

Controlling light emission and detection using subwavelength interlayers

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Hossam Elmitwalli- (aka Galal)

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Betreuer und Gutachter: Prof. Dr. Mario Agio

Gutachter: Prof. Dr. Carsten Rockstuhl

Prüfer 1: Prof. Dr. Carsten Busse

Prüfer 2: Prof. Dr. Peter Haring Bolivar

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Peace be upon my father, bless my mother.

Abstract

Light emission and detection are basic processes at the core of applications in optics and photonics, such as lighting, sensing and telecom. Despite extensive work on the design of light-matter interfaces, the exchange of electromagnetic radiation with matter is still a challenge. Here, we show how subwavelength interlayers can lead to light outcoupling efficiencies approaching 100% in combination with strong directional emission, specifically from materials with a large refractive index. We also highlight potentials for enhanced light detection and control, via structural reciprocity. Our findings are particularly relevant for semiconductor-based nanophotonic devices, which typically suffer from a large mismatch with respect to free-space and guided modes.

Zusammenfassung

Lichtemission und -detektion sind grundlegende Prozesse, die im Zentrum von Anwendungen in der Optik und Photonik stehen, wie beispielsweise Beleuchtung, Sensorik und Telekommunikation. Trotz umfangreicher Arbeiten zum Design von Licht-Materie-Schnittstellen stellt der Austausch elektromagnetischer Strahlung mit Materie nach wie vor eine Herausforderung dar. Hier zeigen wir, wie Subwellenlängen-Zwischenschichten zu einer Lichtauskopplungseffizienz von nahezu 100 % in Kombination mit einer starken gerichteten Emission führen können, insbesondere bei Materialien mit einem hohen Brechungsindex. Wir heben auch das Potenzial für eine verbesserte Lichtdetektion und -steuerung, durch strukturelle Reziprozität hervor. Unsere Ergebnisse sind besonders relevant für halbleiterbasierte nanophotonische Bauelemente, die typischerweise unter einer großen Diskrepanz zwischen Freiraum- und geführten Moden leiden.

List of publications

Patents

1. EP3865860: Device for ultra-bright directional light emission
H. Galal (granted 02.05.2024)
2. EP3327426: Device for beaming of light
H. Galal, M. Agio (granted 12.02.2020)

Journal publications and preprints

3. The TRANSGUIDE: Ultra-bright directional light emission from any refractive index material
arXiv:2003.11913 (2020)
4. Highly efficient light extraction and directional emission from diamond color centers using planar Yagi-Uda antennas
arXiv:1905.03363 (2019)
5. Highly efficient light extraction and directional emission from large refractive-index materials with a planar Yagi-Uda antenna
Opt. Mater. Express 7, 1634-1646 (2017)

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Chapter 1

Introduction

Light sources and detectors constitute foundational building blocks of emerging technologies, as they enable the generation, manipulation, and measurement of light. Improvements in the performance of these components contributed substantially to the development of applications essential to our everyday lives, namely illumination, communication, and imaging. Beyond that, quantum mechanics is driving the demand for light sources and detectors. A variety of nanoscale platforms, such as semiconductor nanowires [1], quantum dots and nanocrystals [2,3], organic molecules [4], and color centers in solids [5], have found a potential role in creating and detecting single photons and quantum states of light. These capacities are crucial for quantum communication, quantum cryptography, and quantum information processing.

1.1 Light sources and detectors

Emission and absorption of light waves are reciprocal processes. In principle, many optoelectronic components can both emit and detect light. However, in common practice, they are usually optimized for one of these two functions. Consider, as an example, a Light Emitting Diode (LED) emits light in a forward-bias setting, meanwhile functions as a photodiode when configured in reverse-bias. The underlying emission-absorption mechanisms relating to the physical conversion of charges into photons, vice versa, are beyond the scope of this thesis work. Here, the focus is rather towards the exchange of light between the optical component and the surrounding interfacing medium.

1.2 Quantum emitters

A quantum emitter is recognized as a nanoscale system with discretized energy levels. A single photon with a well-defined wavelength is ideally released upon relaxation from a high to low energy state. Emerging quantum applications demand specific photon properties in order to render the full potential of quantum light. Here are key aspects [6] unleashing potentials in communication, computing, sensing, and imaging:

Single-photon emission

Unlike classical light emitters, the emission profile of quantum emitters comprises a single photon per time instant. This photon distribution is known as antibunching.

Indistinguishability

The emitted photons are ideally identical in all degrees of freedom, most importantly frequency and polarization.

Spectral purity

Especially in well-isolated systems, the linewidth of the emitted photons can be nearly monochromatic.

Emission rate control

The environment can modify the spontaneous emission rate of a quantum emitter, via the Purcell effect. For instance, placing an emitter in an optical cavity enhances or suppresses emission.

Coherence

Interactions with the environment via phonon-coupling and noise eventually degrade the coherence of the emitted photons.

Directional emission

Funneling the photon emission into specific structural modes allows for the modification of spatial distribution of the photons. This is realized in practice by coupling a quantum emitter to nanostructures such as waveguides and antennas.

The latter aspect is more related to the structural setting of the emitter, be it quantum or classical, and has been the main focus of this thesis work. One should keep in mind that emerging quantum systems, likewise classical light sources and detectors, are more oriented towards semiconductors and diamond; which further exacerbates the challenges associated with directional emission. This shall be elaborated upon in the upcoming sections.

1.3 Interface mismatch

Refractive index mismatch is a major issue in relation to light extraction and light coupling within an optical component. When the refractive indices of the active material, i.e. the material where photon creation-absorption takes place, and the surrounding medium differ, this can significantly impair the performance of an optical component. While the discussion here evolves around light emission, the general behavior can be extended to light detection, with the reversibility of optical phenomena in mind. However, the latter topic shall be addressed thoroughly elsewhere in an appropriate context within this thesis work. The following discussion gives a brief demystification of common light-matter interfacing encounters.

Figure 1.1 depicts a straightforward ray-optics scenario. A person standing in open air, along the x-axis, is observing a light source (1) emitting light rays (2), (3), (4). The source is embedded in a homogeneous glass medium (5). Along the interface between glass and air, oblique light rays no longer follow a straight path, instead, Snell's Law comes into play. Two behaviors stand out. First, some rays diverge away from the observer, towards the y-axis. Second, other light rays do not manage to make it out of the glass. The latter translates from a critical angle derived from the refractive indices of both interface materials. In the case of a glass-air interface, the critical angle reads $\sim 42^\circ$. That said, the observer perceives the light source with less brightness and with a relatively larger spatial spread. Replacing glass with diamond, ray divergence increases owing to diamond's relatively larger refractive index. Meanwhile, the critical angle falls to $\sim 25^\circ$, with light trapping becoming more significant. Overall, the light source is further dimmed.

On a microscopic scale, if the thickness of the active medium (6) were to be on the order of the wavelength of the emitted light, in-plane waveguide effects become more prominent and further trap a considerable amount of light, giving rise to modal propagation along the y-axis.

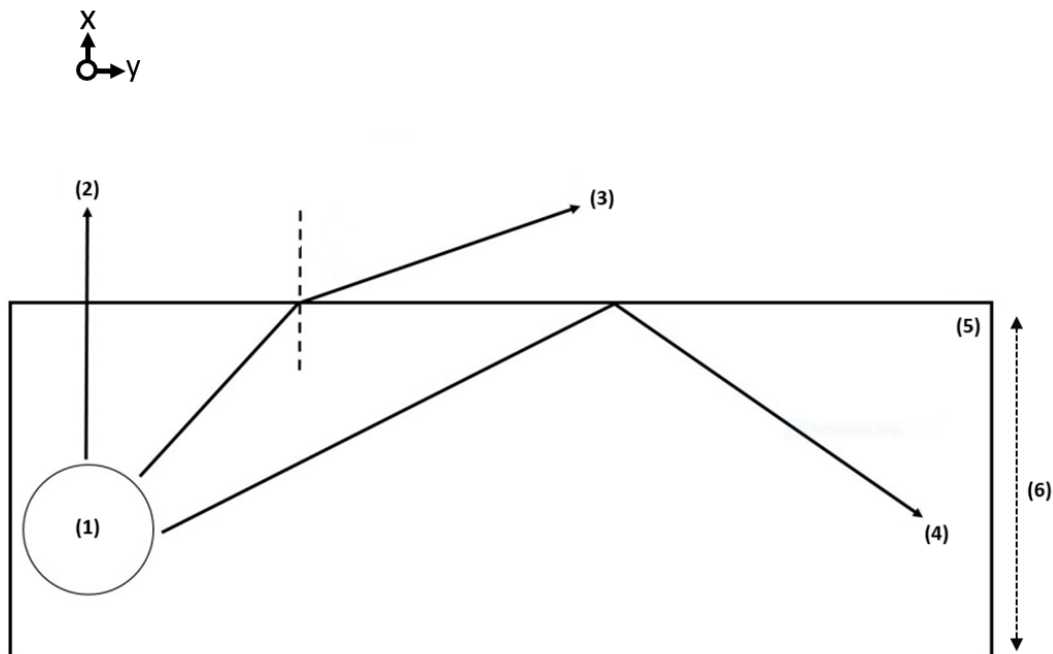


Fig. 1.1 Ray optics depiction of an interface mismatch. A light source simplified with 3 monochromatic rays is embedded in a homogenous glass medium, refractive index ($n_{glass} = 1.5$). Background medium is air, refractive index ($n_{air} = 1$). Dimensions are not to scale.

Solution-wise, advanced nanofabrication and sophisticated external optics are likely required to overcome these issues. Examples include a variety of dielectric [7,8] and metallic [9–13] antenna structures, waveguides [14–16], cavities [17–19], gratings [20,21], photonic crystals [22], solid immersion lenses [23,24] and metasurface [25]. Even though the conceived solutions put forward so far have shown great promises, each comes with its own limitations; most commonly performance, scalability, and robustness. Meanwhile, here in this work, we have taken a different direction by adopting a completely planar approach, refraining from over-engineered architectures.

It is worth mentioning that the main demanding application remains free-space light emission-detection, where interface mismatch is at its peak contrast, and eventually most solutions fall short. In what remains of this chapter we selectively highlight the most relevant and recent state of the art techniques, in order to give more perspective.

1.4 State of the art review

Solid immersion lens

Structuring the surface, i.e. the interface, of the active medium is one common practice that relies on altering Snell’s law for each light path. Typically, a lens curvature is etched with respect to the position of the emitter within the active medium, rendering the lens’ crucial parameters, namely the focal length and the aperture. As a result, a collimated light beam emerges from the active medium. Ideally, the lens should be accompanied by a reflective structure from the opposite side, in order to redirect the emitter’s counter emission towards the lens. Additional optical coatings can be applied to the lens’ surface in efforts to mitigate Fresnel reflections. All together, this has been demonstrated for a diamond single-photon source within the context of a quantum network application [27]. Even though, the reported light extraction efficiency stands around 10%. One possible root cause could be that the misalignment of the lens with respect to the quantum emitter is inevitable, especially with the difficulty in handling diamond nano-fabrication processes. This emphasizes the importance of large technological tolerance margins.

Gratings

Diffraction gratings follow within the same context as solid immersion lens; however, in way of patterning the interface with wavelength tailored (periodic) features. In turns, this demands even more stringent precision positioning of the emitter with respect to the grating geometry. Bullseye is a popular geometry, and has demonstrated promises when accompanied with a reflecting structure from the opposite side [28], as the case with a solid immersion lens. The bandwidth of the emitter is conceived to be truncated by the grating, and higher order emission diffraction side lobes flare at large angles.

Cavities

Cavities come in various curved and planar variants. The Fabry-Perot Etalon is the optical planar version, with the advantage of flexibility in implementation. Overall, the basic idea of a cavity is to trigger a standing wave, for a specific operational wavelength, between the two cavity reflecting facets. This so-called cavity resonant mode reinforces itself in specific locations within the cavity, where ideally the emitter is to be positioned. In that case, the emitter is visualized to be riding the cavity mode, leading to enhancements in light extraction, for example. The cavity mirrors could be metallic or dielectric. Either way, the spacing between the two mirrors maintains a relationship with respect to the operational wavelength, i.e. multiples of half a wavelength order.

There have been cavity implementations, also on diamond [29], where emitter positioning sensitivity has been questioned. Amongst the additional issues of cavities is bandwidth modulation. Typically, cavities limit the bandwidth, as a function of the reflectivity of the mirror facets. There have also been interesting efforts in combining cavities with gratings [30]. This, however, tightens further the technological tolerance margin.

Antennas

Antennas have first emerged for radio-frequency applications. Leading on, it has been a common practice to extend their applicability, for example to the VIS-IR bandwidth, by downscaling their geometrical dimensions comparably to the operational wavelength. Optical antennas, typically made from metals and dielectrics, support resonances that depend on their geometrical size, shape, and material. These resonances determine how efficiently they can handle light. The Yagi-Uda antenna has gained reputation for its selective directionality in emitting and receiving electromagnetic radiation. Curto et al. demonstrated a nano version of

the Yagi-Uda antenna, where they implemented the antenna elements using nanoparticles [9]. The light emitter was a quantum dot, coupled to one of the nanoparticles. Implementation of the antenna was in a way that light emission propagates along the surface; parallel to the substrate. The proximity of the light to the substrate imposes limitations on the light utilization options. Checcucci et al. have followed up on this work and put forward a more compact version [26], subject topic of chapter 2.

Waveguides

The deliberate design of a leaky waveguide has been perceived by Lee et al. as a potential solution to outcouple light from an emitter; in their case a single molecule quantum emitter [31]. With the aid of a reflecting mirror from one side of the waveguide and collection through an oil-immersed objective from the other side, they were able to demonstrate near unity collection efficiency. However, the radiation pattern of the system is not practical for coupling with low NA optics. Moreover, their experimental setting is not suited for free-space emission applications. With that said, this state of the art is particularly relevant for chapter 4 of this thesis work.

To this extent, none of the reviewed techniques could check all boxes. This brings us to the conceptual approach of this research work.

1.5 Thesis outline

The framework of this research builds upon the planar Yagi-Uda antenna work of Checcucci et al. [26], which was originally conceived for low refractive index active medium, i.e. values on the order of glass.

Part 1

Our first solution is an advanced version of the planar Yagi-Uda antenna, extending its applicability to large refractive index materials. The theoretical background is laid out in chapter 2, followed by the experimental validation in chapter 3. This part stands as a complete proof-of-concept, incorporating theoretical and experimental work back-to-back, and has been extended to other light emitting platforms via cited external collaborations.

Part 2

Further development, the second solution addresses the limitations of the latter advanced planar Yagi-Uda antenna by implementing waveguide theory. A detailed theoretical elaboration is introduced in chapter 4. However, preceding chapters serve as a foundational build-up for the conceived waveguide-based enhancement. Based upon, one can safely extend the validity of the experimental merits from the advanced planar Yagi-Uda antenna to the waveguide-based antenna.

1.6 Supplementary reading

Given that the core of this thesis work originates from the Yagi-Uda antenna, we wrap up this section with key highlights of the said antenna. Detailed elaborations are to follow accordingly.

Yagi-Uda antenna

The radio-frequency architecture of the Yagi-Uda antenna developed around the concept of two sets of components: reflecting and directing elements; with the signal sender/receiver (i.e. dipole) in between. The most popular arrangement comprises one reflecting element and an array of directing elements, as depicted in Fig. 1.2. Considering the antenna operational in sending mode, the signal from the dipole bounces along the reflector element and subsequently undergoes channeling through the directing elements. Likewise, in reception, the director elements pick up the oncoming signal; channeling it through the reverse path. The dimensions of the individual elements are ideally aligned with the operational wavelength of the signal.

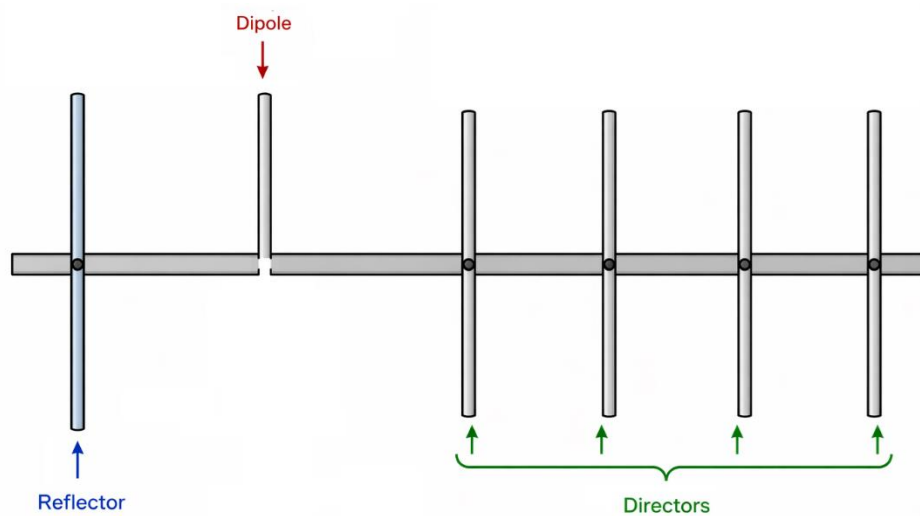


Fig. 1.2 Radio-frequency architecture of the Yagi-Uda antenna (top-view). The reflector element stands as a single element while the director comprises an array of four identical element. A common practice, the length of the director elements are slightly shorter than the reflector element. Signal generator/receiver connects along the dipole.

With that, further insights into dipolar nanoscale emitters, planar antennas, and waveguide theory are reviewed in the context of two patent disclosures, enclosed in the Appendix.

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Chapter 2

Interlayer planar Yagi-Uda antenna

The potential of planar structures in beaming light emission was originally conceived on single molecules, in the work of Checcucci et al. [1]. Essentially, the approach relies on the concept of an optical Yagi-Uda antenna [2], where reflector and director elements are implemented using thin metal films. However, the existence of surface plasmon polaritons (SPPs) at the interface between the metal films and the dielectric layers poses an insoluble limitation on the outcoupling efficiency. Coming up, we formulate a simple strategy that accounts for SPP modes, leading to an overall significant enhancement in light emission, and extends the versatility of the planar approach to other material systems such as diamond and semiconductors. Likewise, absorbers, by invoking reciprocity.

A European patent has been granted in recognition of this work, where the author is the first inventor.

Patent disclosure [EP3327426 - Device for beaming of light] is enclosed in the Appendix.

2.1 Antenna configurations

A dipole emitter positioned a distance d_1 away from a metallic layer, named reflector, induces an image dipole [3]. When the two dipoles radiate with an appropriate phase delay, they give rise to a beaming effect in one direction. This occurs provided that d_1 falls within the range $\lambda/(6n) < d_1 < \lambda/(4n)$, where λ is the emission wavelength and n is the refractive index of the medium hosting the dipole source, named active medium. Further directionality can be obtained by positioning a thin metallic layer in the radiation direction, named director, at a distance d_2 away from the dipole. The distance d_2 is also governed by a simple relationship between d_2 , λ and n [1]. The dipole source can have a horizontal or perpendicular orientation with respect to the layers. However, the latter has a stronger near field that couples a considerable amount of energy to SPP modes present at the reflector and director interfaces and it does not exhibit a single-lobe emission pattern. Therefore, in our study we will consider only a horizontal dipole.

The proposed antenna configuration is generalized in Fig. 2.1 . Figure 2.1(a) is the standard case, where the active medium is placed between two planar metallic layers [1]. Intermediate dielectric layers space the active medium apart from the reflector and director in Fig. 2.1(b) . A further dielectric layer spaces the director from the collection medium in Fig. 2.1(c) . The coordinates of the dipole with respect to reflector and director, d_1 and d_2 respectively, together with the thicknesses and refractive indices of the additional layers, remain the essential design parameters of the antenna. In what follows, we investigate the role of these new dielectric layers in improving the outcoupling efficiency and beaming.

2.2 Outcoupling efficiency and beaming

We first analyze and compare the designs of Figs. 2.1(a) and 2.1(b) . To this purpose we choose a set of parameters that outline the basic concepts behind the improved antenna configuration. Our results are based on a plane-wave expansion of the emission of a Hertzian dipole in a multilayer structure [4], [5].

Figure 2.2(a) illustrates a color center in a diamond membrane coated with two silver films acting as reflector and director; other metals like gold can be used [1]. In Fig. 2.2(b) the structure incorporates two intermediate layers made of glass, which have a refractive index lower than that of the active medium. The layer thicknesses are indicated in the figure caption.

For an emission wavelength $\lambda = 738$ nm, the refractive indices of diamond, glass, and silver are 2.4, 1.5, and $0.033 + 5.1i$ [6], respectively. The antenna designs are evaluated by calculating the total power emitted by the dipole (P_{tot}) in the layered structure and the power transmitted to the collection medium (P_{rad}), both also in terms of power densities as a function of the in-plane wavevector (k_p). The outcoupling efficiency (β) is then given by $P_{\text{rad}}/P_{\text{tot}}$. The radiation pattern is also investigated calculating P_{rad} as a function of the azimuthal and polar angles, respectively ϕ and θ . All curves are normalized to the power emitted in the active layer, considered as a homogeneous infinite medium. Therefore, P_{tot} corresponds to the enhancement of the spontaneous emission rate, which is always of the order of one in the studied configurations. Another relevant quantity is the beaming efficiency (η), which we define as the ratio between the power collected up to a semi-angle of 20° and P_{rad} , corresponding to the power collected by a high-NA single-mode fiber (NA ~ 0.35). We also compute the antenna gain (G), defined with respect to an ideal isotropic radiator, using the formula $G = \beta(4\pi/P_{\text{rad}})P_{\text{max}}$. β is the antenna efficiency (equal to the outcoupling efficiency) and P_{max} is the power radiated in the peak direction. For a dipole in a homogeneous medium $G = 1.5$ or 1.76 dB.

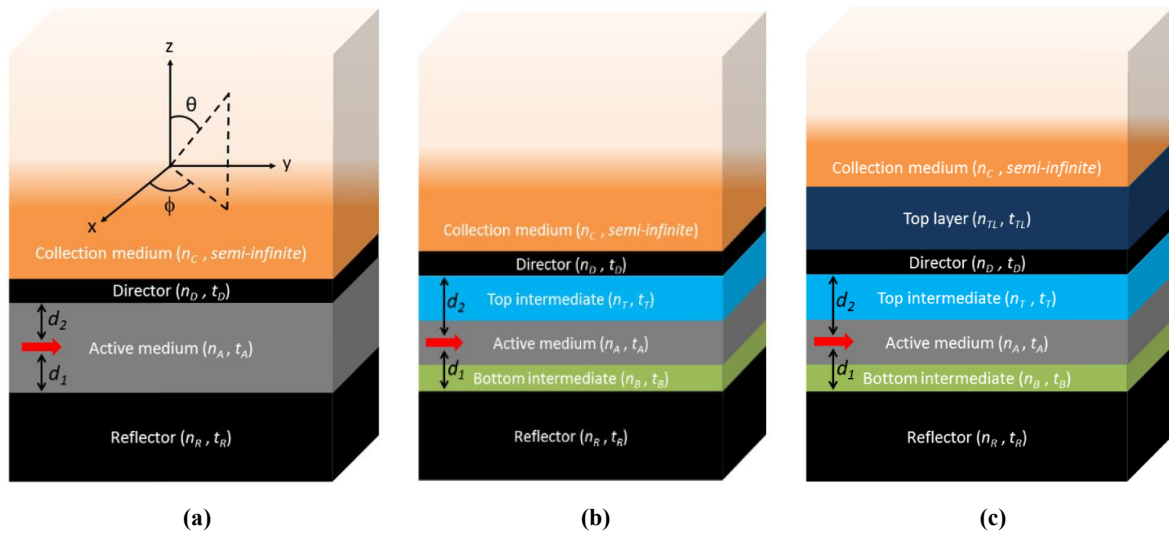
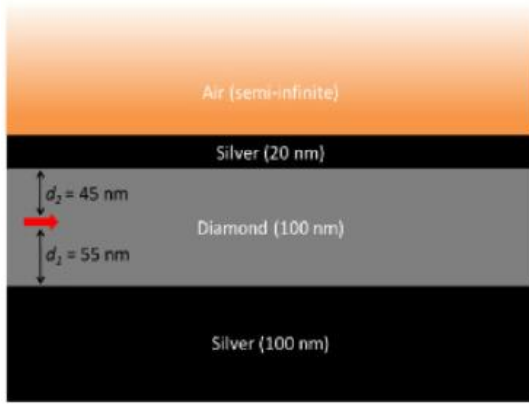


Fig. 2.1 Planar Yagi-Uda antennas. (a) Basic configuration (reflector, active layer and director) and adopted coordinate system. (b) Configuration to improve outcoupling efficiency and directionality (reflector, bottom intermediate layer, active layer, top intermediate layer, director). (c) Configuration to further improve outcoupling efficiency and directionality (reflector, bottom intermediate layer, active layer, top intermediate layer, director, top layer). A horizontal arrow indicates a Hertzian dipole in the active medium placed at a distance d_1 and d_2 from reflector and director, respectively. The refractive indices of the intermediate layers in Figs. 2.1(b) and 2.1(c) must be smaller than the refractive index of the active medium, but not necessarily equal to each other. The refractive index of the top layer should be smaller than the refractive index of the collection medium.

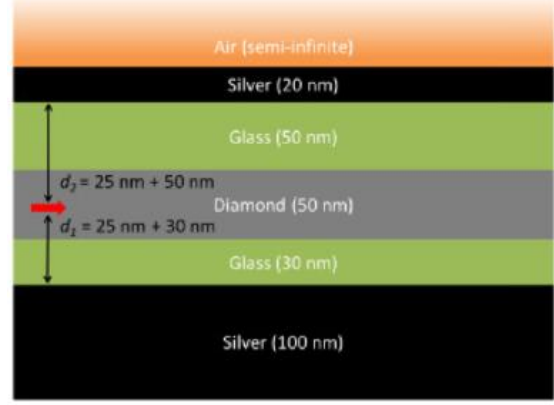
We consider the configuration in Fig. 2.2(a) as a reference, and plot in Fig. 2.2(c) the power density per unit $(dk_p)^2$ associated with P_{tot} (red curve) as a function of the normalized in-plane wavevector k_p/k_0 [4]; where k_0 is the wavevector corresponding to $\lambda = 738$ nm in the collection medium. We notice that the power density is distributed as follows: power radiated in the collection medium peaked at small in-plane wavevectors, for $k_p < k_0$; an SPP mode bound to the director in the collection medium peaked near k_0 , for $k_p > k_0$; two nearly degenerate SPP modes bound to the director in the active medium and to the reflector peaked between $3k_0$ and $3.5k_0$, for $k_p > 2.4k_0$, where 2.4 is the refractive index of diamond, i.e. the active medium. These SPP modes absorb a considerable amount of energy, resulting in $\beta < 50\%$.

The blue curve in Fig. 2.2(c) refers to the power density for the antenna configuration of Fig. 2.2(b). The inclusion of two intermediate layers made of glass significantly suppresses the coupling to SPP modes, as it can be inferred from the reduction of the peaks in the power density. Consequently, P_{rad} increases and β doubles to 82%. In practice, placing the diamond membrane between two glass layers can considerably lower the effective refractive index of the active region (the multi-layer structure between the two metal films), and the diamond-silver interfaces are replaced by glass-silver interfaces. The latter couples less to both types of SPP modes earlier discussed. Moreover, light confinement at the interface (the transverse extension of the SPP electric field component) is inversely proportional to the refractive index of the dielectric interface layer. In that sense, interfacing silver with glass rather than diamond reduces the field in the metal layers and consequently the Joule losses [7].

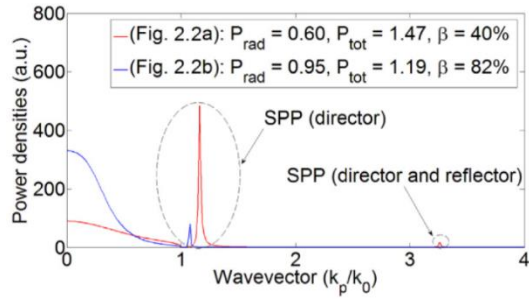
In addition, as better shown in Fig. 2.2(d), turning the design of Fig. 2.2(a) into that of Fig. 2.2(b) narrows the radiation pattern integrated over the azimuthal angle from a half-width at half maximum (HWHM) of 29° to 19° in the polar angle, corresponding to an increase of gain from 6 dB to 12.7 dB. The intermediate layers have another important effect. Figures 2.2(e) and 2.2(f) plot the radiation pattern as a function of ϕ and θ , and show that the configuration of Fig. 2.2(b) yields a profile that is more favorable for coupling light to an optical system with circular symmetry, such as an optical fiber. The stronger beaming effect for the antenna configuration of Fig. 2.2(b) can be intuitively explained by considering that the Fresnel coefficients at the interfaces between the two intermediate layers and the active medium favor the transmission of partial waves having a smaller in-plane wavevector component.



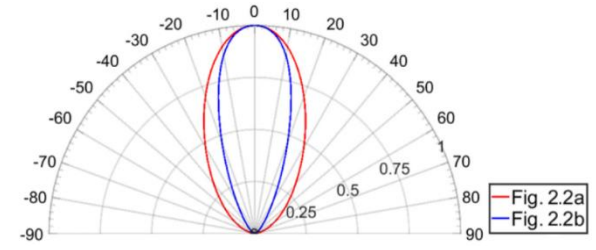
(a)



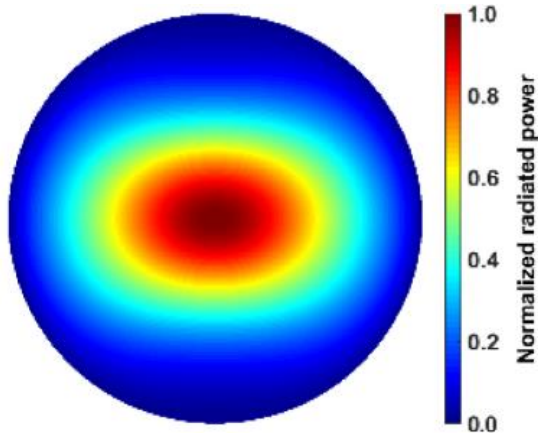
(b)



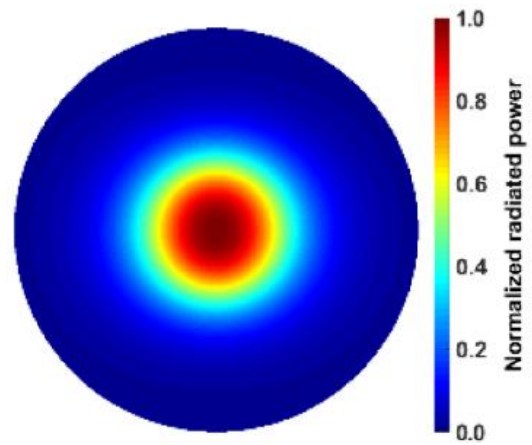
(c)



(d)



(e)



(f)

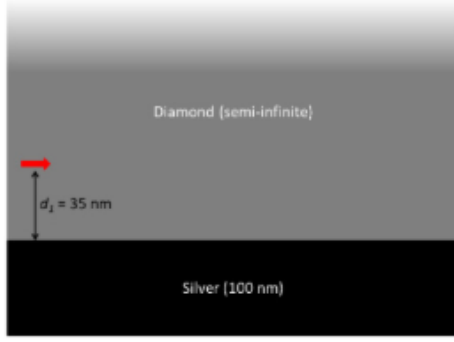
Fig. 2.2 Improving outcoupling efficiency and directionality. (a) Basic antenna configuration (100 nm-thick silver reflector, 100 nm-thick diamond layer, 20 nm-thick silver director). (b) Improved antenna configuration (100 nm-thick silver reflector, 30 nm-thick glass layer, 50 nm-thick diamond layer, 50 nm-thick glass layer, 20 nm-thick silver director). For both configurations the Hertzian dipole is 55 nm from the reflector, and the collection medium is air. (c) Power density for P_{tot} as a function of the in-plane wavevector k_p and (d) Normalized radiation pattern integrated over the azimuthal angle for the configurations depicted in Fig. 2.2(a) (red curve) and Fig. 2.2(b) (blue curve). The peaks in (c) correspond to the excitation of SPPs. (e) and (f) Normalized radiation pattern for the configurations depicted in Fig. 2.2(a) (red curve) and Fig. 2.2(b) (blue curve) with gain 6 dB and 12.7 dB, respectively. The power is normalized with respect to its maximum value.

2.3 Suppressing the excitation of surface plasmon polaritons

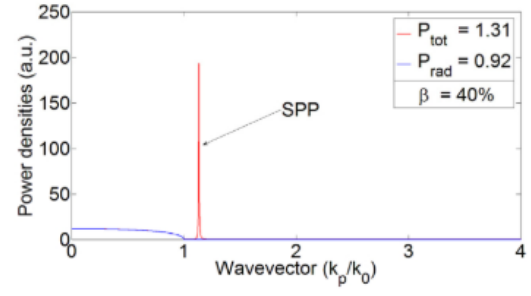
In order to get a better understanding to these findings, we separately consider the effect of the intermediate layers on the reflector and director alone by replacing the diamond layer with a semi-infinite medium having the same refractive index. This configuration rules out the possibility that the diamond membrane may be contributing in some way to the power density with a dielectric guided mode. Here, the distances d_1 and d_2 are chosen such that the dipole is in closer proximity to the reflector and director layers, respectively, thereby making the excitation of SPP modes stronger and thus the action of the dielectric intermediate layers more evident.

Figure 2.3(a) depicts a dipole in diamond near a silver reflector. The corresponding power densities are shown in Fig. 2.3(b). The existence of a peak in correspondence with the SPP mode at the diamond/silver interface reduces the radiation efficiency to 40%. The inclusion on a 30 nm-thick glass layer [see Fig. 2.3(c)] completely suppresses the SPP peak and boosts the radiation efficiency to 99.9%, as demonstrated by the overlapping power densities in Fig. 2.3(d). Note also that the distance d_1 is the same for both configurations.

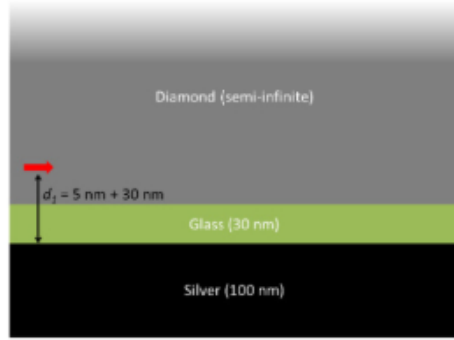
Figure 2.3(e) refers to the director, which is now sandwiched between two semi-infinite media. Here the power densities plotted in Fig. 2.3(f) require more discussion. The one associated with P_{rad} represents the power radiated in the collection medium above the director [see Fig. 2.3(e)], for $k_p < k_0$. Due to the absence of the reflector, the power density associated with P_{tot} includes the power radiated in both upper and bottom semi-infinite media, for $k_p < k_0$, and only in the bottom medium, for $k_0 < k_p < 2.4 k_0$. This explains why β is so small. The peaks near $k_p = k_0$ and $k_p = 3 k_0$ refer to the SPP mode residing in the collection medium (air) and in the active medium (diamond), respectively. In Fig. 2.3(g), a 50 nm-thick glass layer separates the director from the diamond semi-infinite medium. In the corresponding power densities [see Fig. 2.3(h)], the SPP peak related to the SPP mode propagating at the bottom side of the director has been completely removed. However, β remains close to 1% because most of the radiation is directed into diamond downwards.



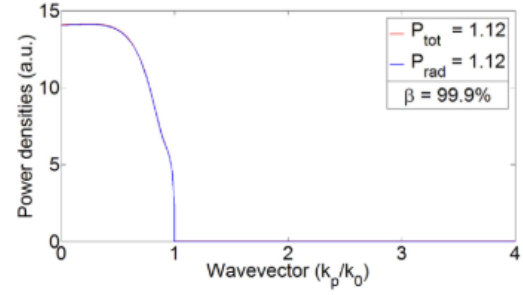
(a)



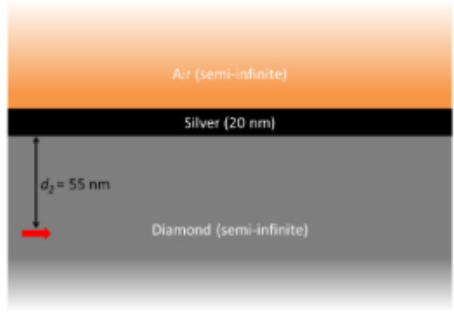
(b)



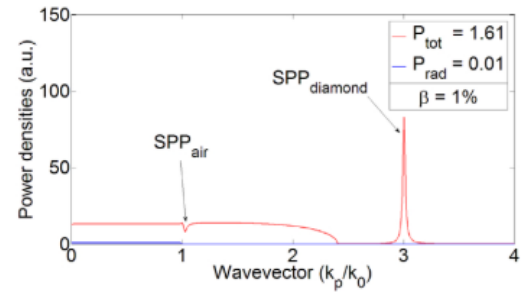
(c)



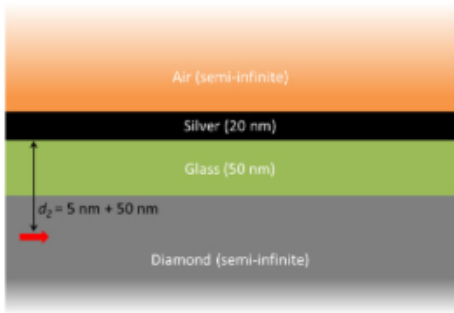
(d)



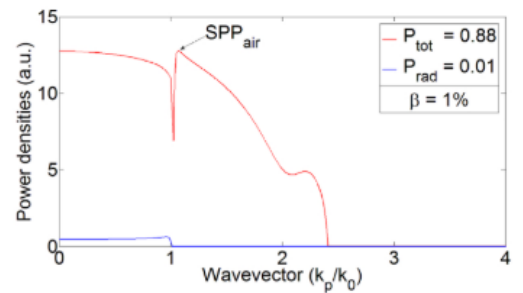
(e)



(f)



(g)



(h)

Fig. 2.3 Suppressing the coupling to SPP modes. Hertzian dipole in diamond near a silver reflector without (a) and with (c) glass intermediate layer. (b) and (d) Power densities for P_{rad} (blue curve) and P_{tot} (red curve) as a function of the in-plane wavevector k_p for the configurations in Figs. 2.3(a) and 2.3(c), respectively. Hertzian dipole in diamond near a silver director without (e) and with (g) glass intermediate layer. (f) and (h) Power densities for P_{rad} (blue curve) and P_{tot} (red curve) as a function of the in-plane wavevector k_p for the configurations in Figs. 2.3(e) and 2.3(g), respectively.

The behavior of the different SPP modes can be interpreted in terms of their dispersion relations. For the reflector, Fig. 2.4(a) respectively considers the SPP modes at the interface between semi-infinite silver and diamond, and silver and glass [see the insets]. By replacing diamond with glass, the wavevector of the SPP mode is lowered to regions closer to the light-line, where the SPP is less confined at the interface and the density of states is closer to that of a plane wave. Altogether, this reduces the weight of the SPP mode relative to radiation modes, which is evident by the suppression of the SPP peak in the power density.

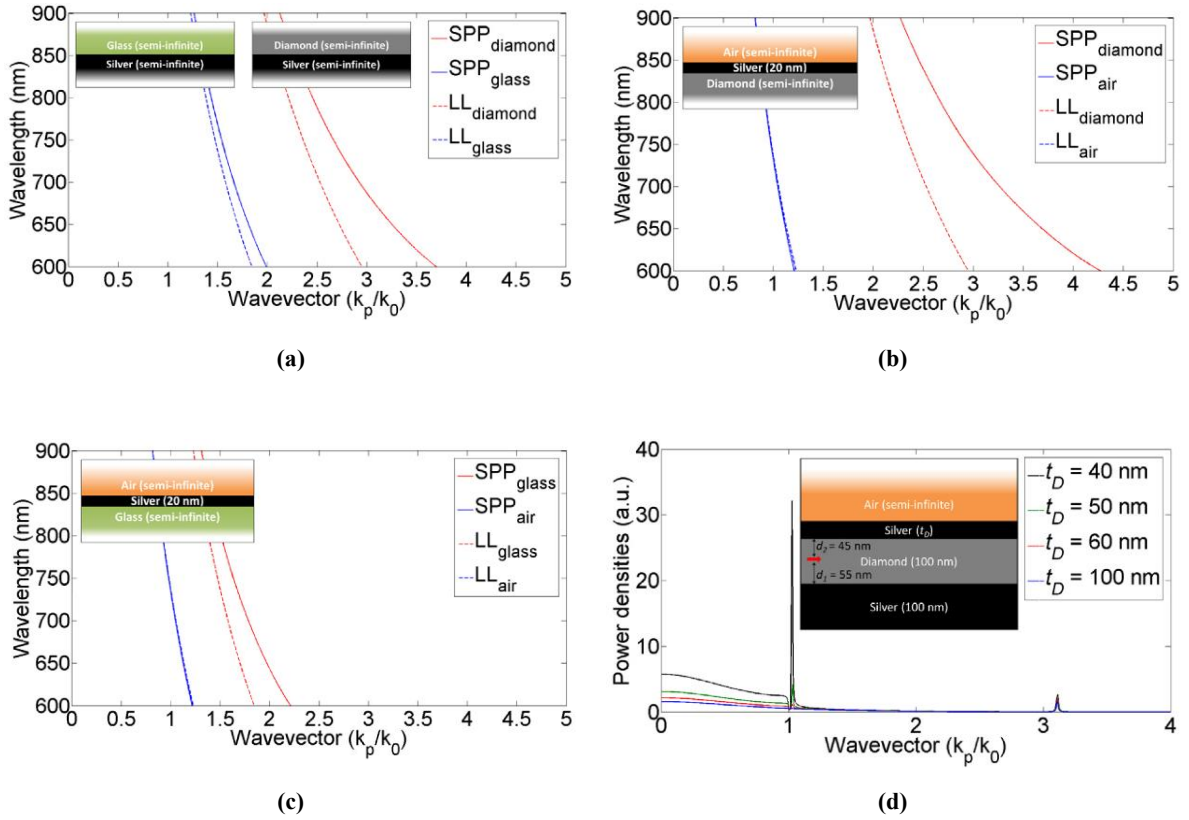


Fig. 2.4 Controlling the SPP dispersion at reflector and director. (a) Dispersion of the SPP mode at the reflector: a glass/silver (blue curve) and at a diamond/silver (red curve) interface. (b) Dispersion of the SPP modes at the director in an air/20-nm silver/diamond layer structure: upper (blue curve) and lower (red curve) hybrid mode. (c) Dispersion of the SPP modes at the director in an air/20-nm silver/glass layer structure: upper (blue curve) and lower (red curve) hybrid mode. The dashed curves represent the light-lines (LL) at each interface. (d) Power density for P_{tot} as a function of the in-plane wavevector k_p for different director thicknesses for the configuration of Fig. 2.2(a). The imaginary part of the dielectric function of silver is much smaller than its real counterpart [6], and therefore has been neglected in the calculation of the SPP dispersion relations.

The director exhibits a similar trend when replacing diamond [Fig. 2.4(b)] with glass [Fig. 2.4(c)]. The structure is considered to be a 20-nm silver film sandwiched between two semi-infinite media. Notice that the finite thickness of the director generates coupling between the two SPP modes (SPP hybridization), which causes a repulsion of the two SPP branches: one is

pushed towards larger wavevectors (red solid curve) and one branch towards shorter wavevectors (blue solid curve), at least in the region close to $\lambda = 738$ nm. This can also be verified by comparing the dispersion relations in Fig. 2.4(a) with those of Figs. 2.4(b) and 2.4(c). The shift in the SPP wavevector to lower values explains the reduction observed for the SPP peak shown in Fig. 2.2(c). We have also investigated the configuration made of a 20-nm silver film placed between air and a glass film on semi-infinite diamond (not shown). By varying the thickness of the glass intermediated layer, the SPP modes can be tuned between the two extreme cases shown in Figs. 2.4(b) and 2.4(c).

The thickness of the director (t_D) has been selectively increased in Fig. 2.4(d) to investigate the role of coupled SPP modes in a thin film [7]. The antenna configuration is similar to that of Fig. 2.2(a), and it is also shown in the inset. The lower SPP mode remains unperturbed by a change in the director thickness. The radiated power of the system drops down when t_D increases, but it is also evident that the peak associated with the upper SPP mode is suppressed, thereby emphasizing that the excitation of this SPP mode due to the finite thickness of the director is responsible for loss in the outcoupling efficiency. Increasing the director thickness indeed eliminates the contribution of the upper SPP mode, but unfortunately at the expense of the transmitted power, hence the outcoupling efficiency.

As shown in Fig. 2.2(c), addition of the intermediate layers strongly affects the SPP modes lying at the interfaces with the active medium and also considerably reduces the amplitude of the SPP mode lying in the collection medium. However, the antenna can be made to radiate more power by engineering the structure in order to further suppress the latter leakage channel in the director, as discussed in the next section.

2.4 Bandwidth, efficiency, and tolerance

The planar Yagi-Uda antenna has been conceived also to operate with a much larger bandwidth in comparison with that of an optical cavity [1]. The question is whether the introduction of intermediate layers somehow affects the bandwidth and, more generally, what kind of tolerance with respect to parameters like wavelength, dipole position one should expect.

Figures 2.5(a) and 2.5(b) illustrate various relevant figures of merit as a function of wavelength for the configurations of Figs. 2.2(a) and 2.2(b), respectively, but with collection in a glass medium ($n = 1.5$) instead of air. For both of them we find similar trends with wavelength,

although the design of Fig. 2.2(b) is clearly more performing in terms of β and η . Specifically, it is found that β is nearly constant to a value close to 90%, while η exhibits a broad peak in correspondence of beaming. The bandwidth, where beaming takes place, is quite comparable for the two situations, although in the case with intermediate layers η can be as high as nearly 70% (values up to 90% can also be obtained, not shown). P_{tot} is larger for the case without intermediate layers, while P_{rad} is almost the same.

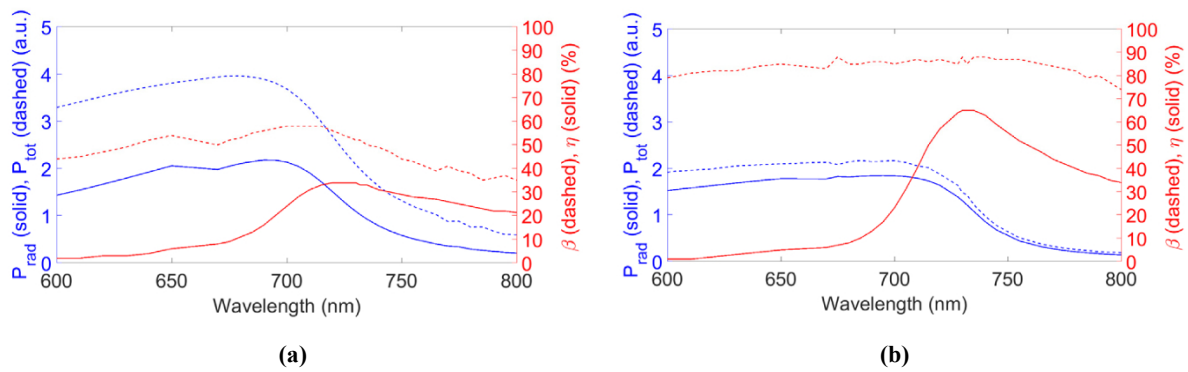


Fig. 2.5 Outcoupling efficiency and beaming. (a) and (b) P_{rad} (blue solid curve), P_{tot} (blue dashed curve), η (red solid curve) and β (red dashed curve) as a function of wavelength for the configurations of Figs. 2.2(a) and 2.2(b), respectively. Material dispersion is taken into account.

A further added value of the intermediate layers is that they make the antenna's figures of merit nearly independent of the dipole's position in the active region. In other terms, the planar Yagi-Uda antenna does not function based on cavity-like nor plasmonics effects, i.e. where the position of the dipole needs to be precisely set in order to maximize the coupling to the electric field of a certain mode. This is illustrated in Fig. 2.6, where the dipole position is swept along the thickness of the diamond layer. In moving from the bottom interface towards the top one, both efficiencies are nearly constant, demonstrating that the dipole can be placed with a precision of about 20-30 nm. Another important benefit of the intermediate layers is the enforcement of a minimum distance between the emitter and the metal surfaces that avoids fluorescence quenching [8].

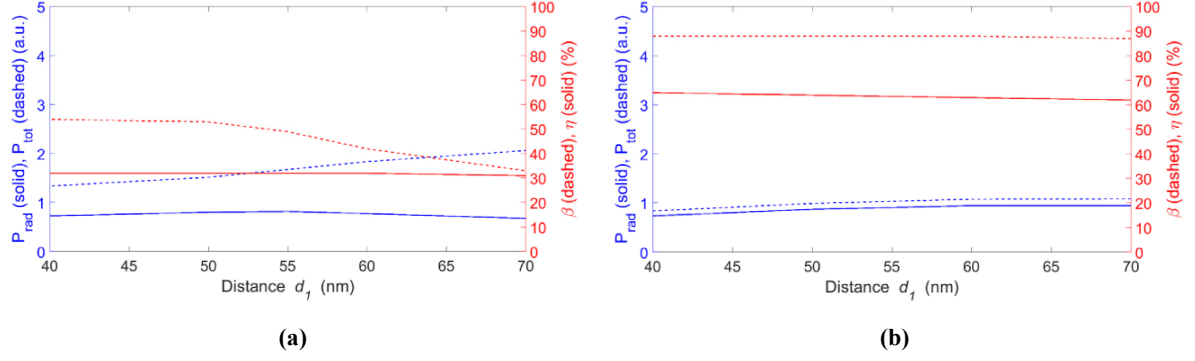
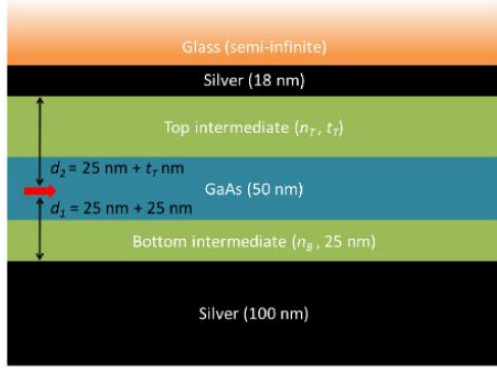


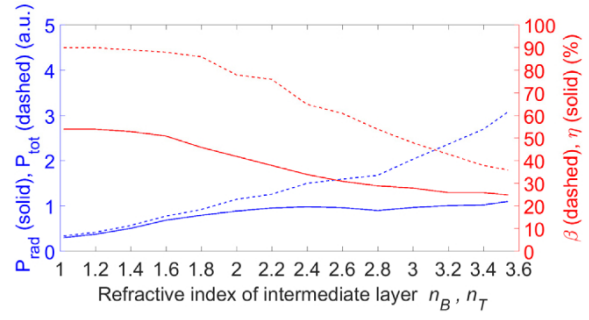
Fig. 2.6 Tolerance with respect to dipole position. (a) and (b) P_{rad} (blue solid curve), P_{tot} (blue dashed curve), η (red solid curve) and β (red dashed curve) as a function of dipole position in the active layer for the configurations of Figs. 2.2(a) and 2.2(b), respectively.

2.5 Refractive index of the intermediate layers

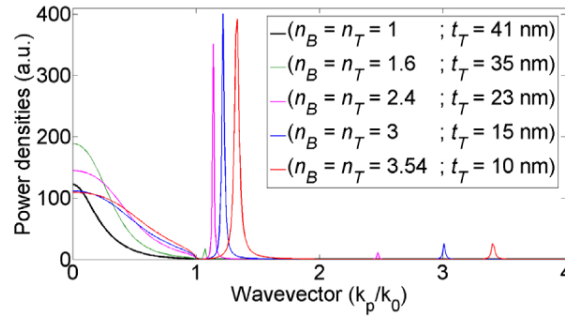
Our scheme can be readily extended to other quantum emitters and materials. As an example, we demonstrate how the outcoupling efficiency of a quantum dot (QD), emitting at $\lambda = 950$ nm in a GaAs membrane, can be significantly enhanced with the aid of our structure. At room temperature, the refractive indices of silver and GaAs at the aforementioned operational wavelength read $n = 0.04 + 6.74i$ [6] and $n = 3.539$ [9], [10], respectively. In the configuration depicted in Fig. 2.7(a), the QD is embedded in a 50 nm GaAs host membrane, sandwiched between two dielectric layers. Figure 2.7(b) illustrates how powers and efficiencies depend on the refractive indices of the bottom (n_B) and top (n_T) intermediate layers. Already for layers made of SiO_2 ($n = 1.451$), the efficiencies β and η have reached 88% and nearly 56%, respectively, corresponding to a gain of 13.4 dB (β and η can respectively reach 90% and 60% with a configuration similar to that of Fig. 2.1(c), not shown).



(a)



(b)



(c)

Fig. 2.7 Refractive index of the intermediate layers and efficiencies. (a) Planar antenna configuration (100 nm-thick silver reflector, 25 nm-thick intermediate layer, 50 nm-thick GaAs layer, intermediate layer with variable thickness, 18 nm-thick silver director). The Hertzian dipole is 50 nm from the reflector and the collection medium is glass. (b) P_{rad} (blue solid curve), P_{tot} (blue dashed curve), η (red solid curve) and β (red dashed curve) as a function of the refractive index of the intermediate layers (n_B , n_T) for the configuration depicted in (a). The thickness of the upper intermediate layer (t_T) is adapted in order to maximize efficiency. The gain is 13.4 dB when the intermediate layers are made of SiO_2 . (c) Evolution of the power density for P_{tot} , as a function of the in-plane wavevector k_p , in response to the change of the effective refractive index on the bottom side of the director. The refractive indices of the bottom and top intermediate layers are the same and simultaneously changed. Accordingly, only the thickness of the top intermediate layer is tuned to maximize β .

The powers instead decrease to values comparable to emission in GaAs treaded as a homogeneous infinite medium. The thickness of the GaAs membrane has been made large enough to give space for positioning the QD a sufficient distance away from the membrane's interfaces, to preserve the QD from quenching and dephasing due to surface states. Although the refractive index of GaAs is much larger than that of diamond, the intermediate layers manage to considerably reduce the effective index of the active region, thereby completely suppressing the SPP modes, as observed for the black curve in Fig. 2.7(c). A HWHM angle of 13° is foreseen for that case.

2.6 Addition of a thin film between director and collection medium

The role of the geometrical parameters in the director region is more complex. Increasing the director thickness compresses the beam waist and, at the same time, reduces β owing to the increased opaqueness of the director. On the other hand, reducing the thickness gives the director more transparency and more light can be coupled out from the structure. Unavoidably, this also decreases the control of the director and the radiation pattern develops a broader beam waist. Moreover, we have shown that the peak associated with the SPP mode in the collection medium is very sensitive to the width t_D of the director [see Fig. 2.4(d)]. A straightforward way to suppress the coupling to this mode has been to increase t_D , which has proven to be an inefficient option as it unavoidably compromises the outcoupling efficiency. In other words, since β depends both on the transmittance of the director and on the coupling to the SPP mode in the collection medium, a trade-off seems necessary in order to maximize β .

With a low-refractive index dielectric layer, such as low-index SiO_2 ($n = 1.05$) [11] or silica aerogel ($n = 1.02$) [12] or air ($n = 1$), placed between the director and a collection medium made of glass ($n = 1.5$) for example, the aforementioned competing effects can be settled and the figures of merit can be boosted to values never attainable before. Furthermore, this layer, if chosen to be silica aerogel, preserves the silver layer from oxidation, which can severely deteriorate the antenna's performance by changing the director thickness and introducing a high-refractive index epi-oxide layer.

In practice, the coupling to the SPP mode in the collection medium can be modified in a straightforward manner by varying the refractive index on the upper side of the director. As it can be inferred from Fig. 2.4(c), for a collection medium made of glass the addition of a thin air layer after the director transforms the SPP mode into a radiative one. Its dispersion relation lies between the light lines in air and glass. If the air layer is thin in comparison to the lateral extension of the SPP mode, the dispersion curve is near to the glass light line. Consequently, the SPP peak in the power density is smeared out by the large radiation losses. As the thickness of the air layer gets larger, the mode gradually shifts towards the light line in air and the SPP peak re-emerges in the power density causing a narrow secondary lobe in the radiation pattern.

In Fig. 2.8 we address the role of the top layer, first shown in Fig. 2.1(c), through two selective configurations, where in the first one we boost the outcoupling efficiency to 92%, and in the second to 94%; the HWHM angle can be tightened down to 12° and 6° , respectively. Further enhancements are foreseen with judicious choice of material and thickness. A comparison is

drawn in Figs. 2.8(a) and 2.8(b) based on the figures of merit for the configuration of Fig. 2.2(b), for which the collection medium is glass ($n = 1.5$) or silicon nitride ($n = 2$), respectively, and the layer that separates it from the director is air. The thickness of this layer is scanned from 0 to 400 nm, which affects more the efficiencies than the powers. Notice that β tends to decrease when η increases and vice versa. Moreover, the combination of a collection medium with a large refractive index with a low-index thin layer can make the emission pattern very narrow, as shown in Fig. 2.8(b). There is an optimal thickness, which weakly depends on the antenna parameters and on the wavelength.

The impact of the top layer, specifically on the upper SPP mode, can be observed in Figs. 2.8(c) and 2.8(d), where the power densities are plotted for different values of the top layer thickness (t_{TL}). The top layer thickness, in conjunction with the refractive index of the collection medium, can be exploited to tune the effective index on the topside of the director. In this way, one can have control on the remaining SPP contribution observed earlier, Fig. 2.2(c) (red curve), in a more practical way without having to change the fixed design parameters of the antenna (refractive index and thickness of the intermediate layers); as explained in Fig. 2.7(c) for GaAs. It has been observed that the SPP diminishes and shifts towards smaller wavevectors, and the mode eventually becomes radiative ($k_p < k_0$). For example, a 50 nm top layer effectively suppresses the SPP mode, as shown by the green curves in Figs. 2.8(c) and 2.8(d). Increasing the thickness beyond 190 nm gives the SPP modes a radiative nature; identified by the weak side-lobes in Figs. 2.8(e) and 2.8(f) that result from the merging of the SPP mode with the central radiated lobe, where the radiation pattern integrated over the azimuthal angle is plotted as a function of the polar angle. Despite these additional lobes, the central lobe becomes narrower and, consequently, η increases. For $t_{TL} = 50$ nm the gain is 16.1 dB and 18.4 dB, respectively. Simultaneous variation of the effective refractive index on both sides of the director will not be covered in the paper; however, this approach allows for efficiencies superior to that obtained with the former approaches, for example, η reaches 90%.

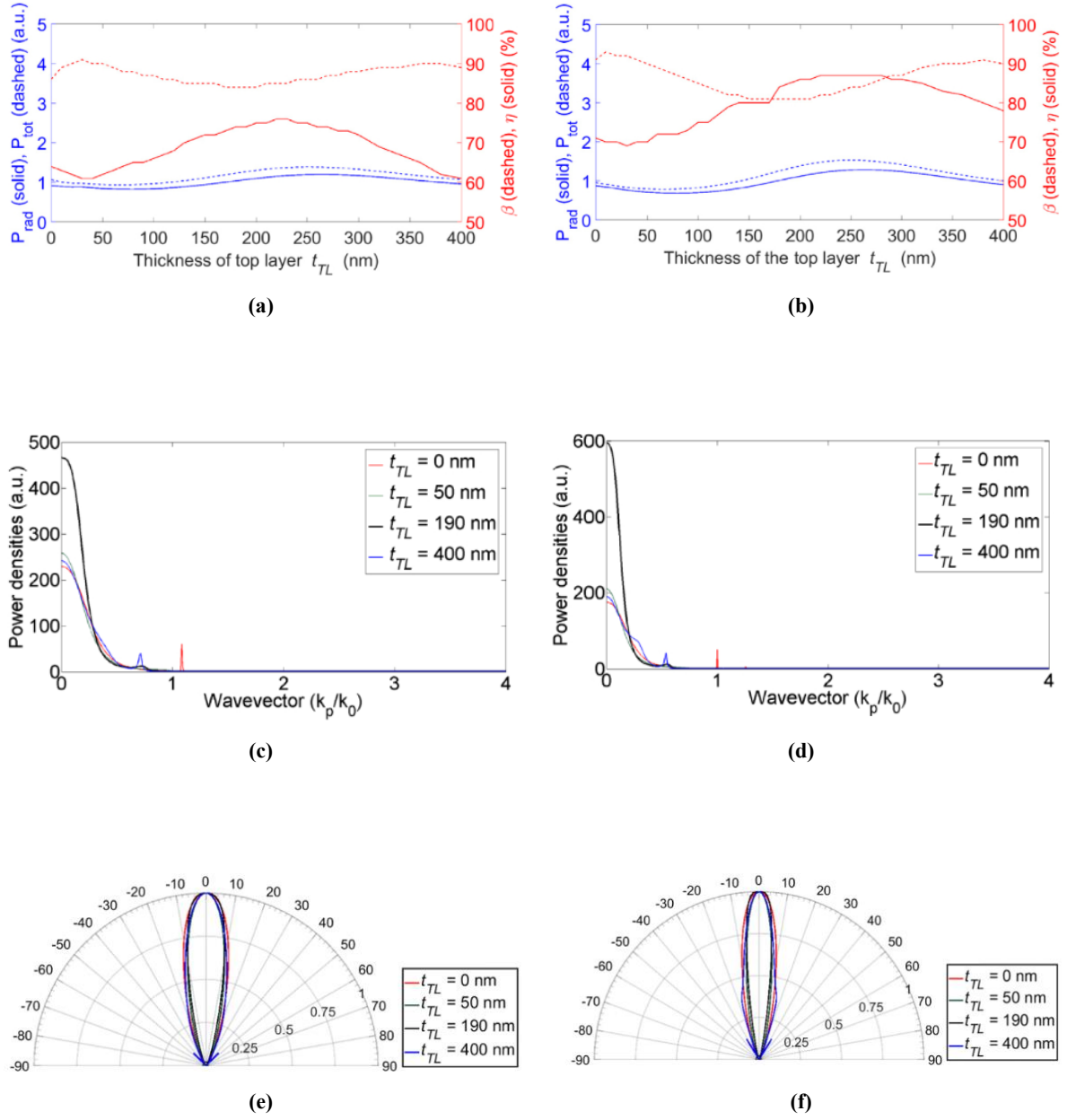


Fig. 2.8 Narrowing the emission pattern and collection medium. (a) and (b) Antenna configuration (100 nm-thick silver reflector, 30 nm-thick glass layer, 50 nm-thick diamond layer, 50 nm-thick glass layer, 20 nm-thick silver director, air layer of variable thickness) with glass and silicon nitride as collection medium, respectively. The Hertzian dipole is 55 nm from the reflector. (c) and (d) P_{rad} (blue solid curve), P_{tot} (blue dashed curve), η (red solid curve) and β (red dashed curve) as a function of thickness of the air top layer for the configurations depicted in Figs. 2.8(a) and 2.8(b), respectively. (e) and (f) Normalized radiation pattern, integrated over the azimuthal angle, as a function of thickness of the air top layer for the configurations depicted in Figs. 2.8(a) and 2.8(b). For $t_{\text{TL}} = 50$ nm the gain is 16.1 dB and 18.4 dB, respectively.

The increased directionality, observed along the thickness range $t_{\text{TL}} = 100$ nm to 300 nm, can be attributed to the fact that the low index top layer together with the relatively higher index collection medium function as a planar lens. Light transmitted from the director and traversing a low index medium (top layer) is refracted according to Snell's law when entering the collection medium. Therefore, the divergence of the emitted light can be made minimal with a

large refractive index contrast between the two media and with an appropriate thickness for the top layer. In this context, the interface between the two layers has only one normal to it. On the contrary, a solid immersion lens (SIL) has the opposite refractive index contrast and its curved interface has an infinite number of normals. Our conceived planar lens, in its simplest form, can be a tunable-thickness air gap. The practicality of this configuration allows for recalling the efficiencies plotted in Figs. 2.8(a) and 2.8(b) readily without having to reconfigure the main structure of the antenna. Tight HWHM angles down to 1.9° are foreseen when coupling to high refractive index materials, like silicon.

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Chapter 3

Experimental validation

Here we highlight how with the inclusion of tens to hundreds of nanometers of silica, a low-refractive index transparent material compatible with many industrial platforms, the emission profile of SiV color centers in diamond can be significantly enhanced. Our original approach has been followed up for other systems, such as SnV in diamond [1], self-assembled quantum dots [2] and V2 centers in silicon carbide [3].

3.1 Selective antenna designs

The foreseen enhancement, basically, is an exploitation of the first order mode of the interlayered planar Yagi-Uda antenna, where the thickness of the host medium in correlation with the thicknesses of the low-refractive index layers must be quite small. For some applications; for example: LEDs and lasers; more space can be required between the two antenna metal elements (reflector and director) for the incorporation of supporting layers, such as charge or transport layers, and in this case, one can take advantage of the antenna's higher order modes. These modes, in fact, are more promising if higher emission directionality is favorable. On the other hand, their light extraction efficiencies are inferior to their first order counterparts. The reason being is that; thicker active media, the overall layers bounded between the antenna's two metallic elements, beyond a certain thickness threshold support guided modes and trap a considerable amount of the emitted light [4]. However, with the knowledge of the structure's dispersion, one can make the coupling to these guided modes minimal by tuning the thickness of the individual active medium layers.

As a start, we briefly review the general antenna architecture shown schematically in Fig. 3.1(a), which consists of metallic reflector and director layers and of low-refractive index layers to space the host medium from the antenna's metallic elements; with an additional low-refractive index layer directly on top of the director. The intermediate layers and the top layer are independent of each other and can be used separately. However, together they can push the overall light emission efficiency to unprecedented values [ch.2], [5]. The emphasis here is to demonstrate the antenna's potential in light emission enhancement from color centers, without emphasizing on driving its performance towards the peak limit.

We verify the scheme on 110 nm thick diamond membranes, designated as Reference (Ref), see Fig. 3.1(b); in two selective antenna configurations, Antenna design 1 (Ant1) and Antenna design 2 (Ant2), as depicted in Figs. 3.1(c) and 3.1(d) respectively. Throughout our calculations we consider the SiVs as horizontally oriented Hertzian dipoles, positioned in the diamond membrane at $d = 30$ nm within a ± 25 nm pitch. For the antenna configurations, the dipole's distance from the reflector (d_1) and the director (d_2) fulfill the relationship: $p\lambda/(6n) < d_1, d_2 < p\lambda/(4n)$; where λ is the emission wavelength, n is the refractive index of the active medium, and p is the mode order. The design of Ant1 is within the higher order range, with $p = 3$; while design Ant2 exploits the first order mode, with $p = 1$. The refractive indices of diamond, silica, and silver at 738 nm read: 2.4, 1.45, and $0.033+5.1i$, respectively [6]. The collection and the

background media are air, and the fluorescence is collected from the director side. Results are based on a plane-wave expansion of the dipole's emission in a multilayer structure [7], [8].

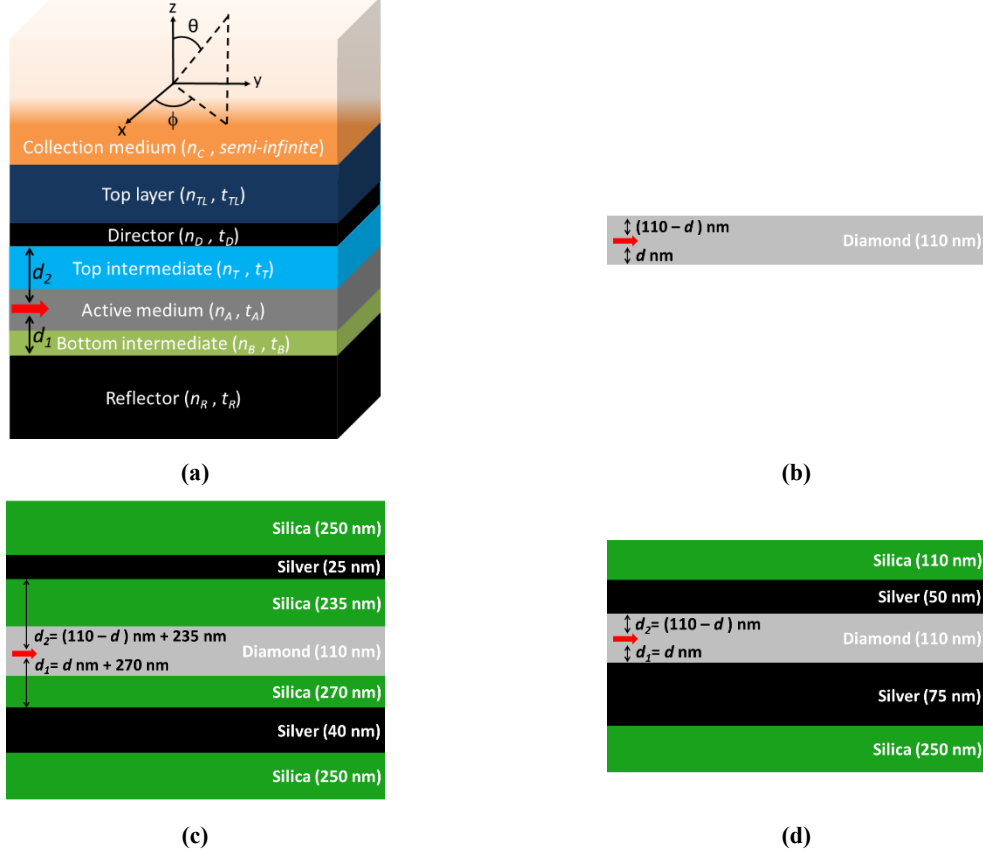


Fig. 3.1 Selective antenna design samples. (a) Advanced configuration of the planar Yagi-Uda antenna (reflector, bottom intermediate layer, top intermediate layer, director, top layer). Active medium hosting a horizontally oriented Hertzian dipole emitter (red arrow). The emitter is positioned a distance (d_1) from the reflector and a distance (d_2) from the director. (b) Reference design (Ref): a bare 110 nm thick diamond membrane, with a SiV emitter modelled as a horizontally oriented Hertzian dipole (red arrow), positioned a distance (d) from the bottom diamond interface. (c) Antenna design 1 (Ant1): silica top and bottom intermediate layers, and silver reflector and director; have been applied to the bare membrane Ref. The silica layers on top of the director and beneath the reflector are for the protection of the silver layers, and not part of the antenna's actual design. (d) Antenna design 2 (Ant2): silver reflector and director have been applied directly to the bare membrane Ref without intermediate layers. A top layer from silica has been used. This layer also serves for the protection of the silver layer, together with the silica layer beneath the reflector.

Designs Ant1 and Ant2 are not the advanced (complete) version of the antenna scheme. In Ant1, Fig. 3.1(c), only intermediate layers are incorporated; and the two 250 nm silica layers on top of the director and below the reflector are solely for technological reasons, to protect the silver layers from oxidation. While in Ant2, Fig. 3.1(d), intermediate layers are not used; instead, the thickness of the top protective silica layer has been reduced to 110 nm. This layer not only protects the silver director but also serves as the top layer, and in conjunction with the collection medium tunes the dispersion of the director [ch.2], [5]. Ideally the thickness of the reflector

should be in bulk range, but in the two designs it has been slightly reduced to allow for some transparency, in case of optically pumping the emitters from that side. These amendments, whether the protective layers or the reduction in the reflector's thickness, have no impact on the antenna's performance.

In assessment of the two different antenna designs, we recall two figures of merit: the outcoupling efficiency (β) and the beaming efficiency (η) [ch.2], [5]. β is given by $P_{\text{rad}}/P_{\text{tot}}$: where (P_{tot}) is the total power emitted by the dipole in the layered structure, and (P_{rad}) is the power transmitted to the collection medium; both in terms of power densities as a function of the in-plane wavevector (k_p). By calculating P_{rad} as a function of the azimuthal and polar angles, ϕ and θ respectively (see Fig. 3.1a), η is given by the ratio between the power collected up to a semi-angle θ of 20° and P_{rad} ; corresponding to the power collected by a high-Numerical Aperture (NA) single-mode fiber (NA ~ 0.34). Ant1 features a very high directional emission profile, with η approaching 90 % and the emission pattern funneled into a single lobe having a radiation Half Angle (HA) at Full Width Half Maximum (FWHM) as tight as 8° ; in conjunction β shows values around 10 %. On the other hand, design Ant2 exhibits a higher extraction efficiency, with β in the range 40 – 60 %; and η in the vicinity of 62 % with a 15° HA single-lobe. Overall, and in comparison with Ref, both Ant1 and Ant2 show a significant enhancement in the measured fluorescence signal; whether translating from the strong light extraction or beaming effect, or the combination of both.

3.2 Sample fabrication

A cross-section schematic of the fabricated antenna samples, particularly Ant1, is shown in Fig. 3.2(a). The different color layers are in correspondence with that in Fig. 3.1(c); however, the scaling of the antenna elements in both figures are not informative. The fabrication process starts with the growth of the polycrystalline diamond membranes (grey) on a silicon substrate (yellow), owing to the latter's flat surface. The membranes' bottom surface is then exposed by etching a hole thoroughly through the silicon substrate, via Reactive Ion Etching (RIE), leaving the diamond membrane suspended in air. SiV color centers are then created in a controlled manner through a $5 \times 10^7 \text{ cm}^{-2}$ Si ion fluence implantation, followed by thermal annealing [9], [10]. The silica (green) and silver (black) layers are then coated using an Edwards electron beam evaporator. One side of the antenna is coated at a time. The sample is left to cool down before it can be flipped to coat the other side of the antenna.

After applying the complete antenna structure to the suspended diamond membrane, the overall multilayer stack takes a curvature as shown in Fig. 3.2(a). This bending applies to both Ant1 and Ant2, and presumably, is a resultant of the asymmetry in the deposited layers on both sides of the membrane, and due to the discrepancy in thermal constants of the individual materials; especially that a cool down period interposed the coating of the two antenna sides. One must carefully control temperature gradients to avoid snapping the membrane.

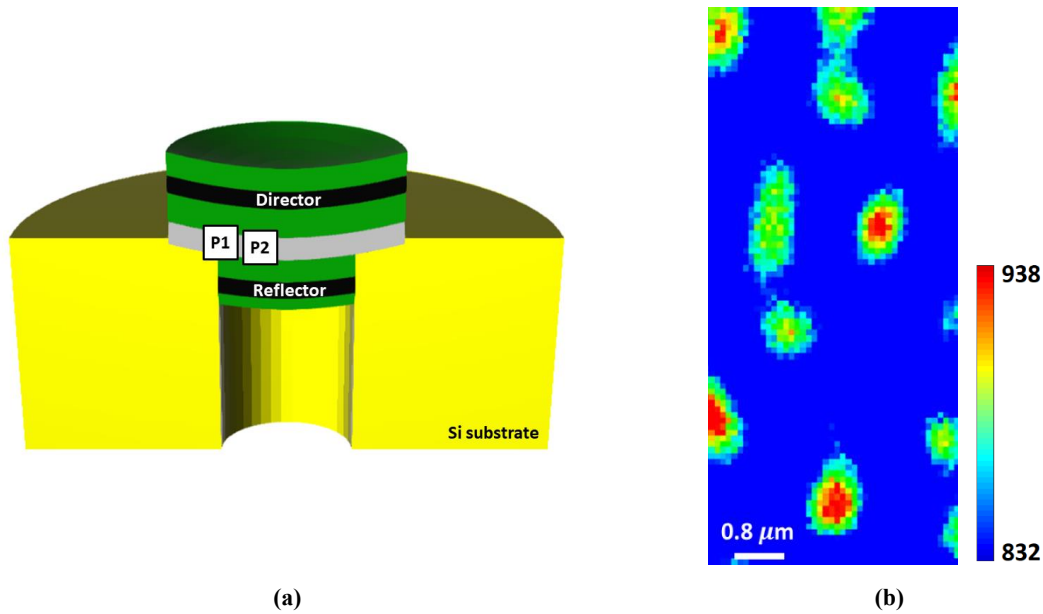


Fig. 3.2 Sample Ant1. (a) Cross-section schematic. The diamond membrane (grey) is suspended on an annular silicon substrate (yellow). Silica layers (green) and silver layers (black) are deposited on the suspended membrane to construct the design shown in Fig. 3.1c. Points (P1 and P2) mark roughly the locations on the sample where the fluorescence measurements were taken. (b) A fluorescence image for sample Ant1, showing an ensemble of eight emitters with varying brightness (red: in focus; green out of focus).

3.3 Results and discussions

The three samples Ref, Ant1, and Ant2 were optically characterized using a 656 nm laser (PicoQuant, PDL 800-D, LDH-D-C-660), in a home-built confocal microscopic [11]. The fluorescence signal is collected by means of an air objective lens and it undergoes necessary filtering before detection on the instruments (camera (Princeton Instruments, ProEM-HS: 512 BX3, back-illuminated electron multiplying CCD (EMCCD) camera); spectrometer (Andor, Shamrock 500i) equipped with an EMCCD camera (Andor, Newton 970, A-DU970P-BVF); photodiode (APD) (Micro Photon Devices, 50 cps dark count, < 50 ps jitter) and time-interval analyzer of a time-correlated single photon counter (TCSPC) (PicoQuant, PicoHarp 300)).

Fluorescence imaging

Firstly, we performed fluorescence imaging to characterize the emitters in the antenna structure. The bending of the diamond membrane downwards, reported in Fig. 3.2(a), is also evident in the fluorescence images (not shown). At (P1), the edge of the silicon substrate partially blocks the light; while by moving towards the center of the membrane, at (P2), the region close to the center of the membrane appears defocused. Hence, one must readjust the depth position of the objective when moving towards the center of the membrane, to observe the emitters. A more focused image view of an emitter ensemble, also from design Ant1, is shown in Fig. 3.2(b). The fluorescence map indicates that the emitters are sufficiently separated to be able to address single SiV centers, as recently reported [12]. Here, we took advantage of the fluorescence imaging to identify the location of the emitters to investigate the functionality of the antenna.

Back focal plane imaging

Next, angular information on the emitters' radiation profile has been extracted from the Fourier plane, using Back Focal Plane (BFP) imaging. Theoretical calculations expect a single-lobe radiation pattern for Ref, Ant1, and Ant2; however, with significant distinctions in directionality: $HA \sim 40^\circ$ and $\eta \sim 12\%$; $HA \sim 8^\circ$ and $\eta \sim 86\%$; $HA \sim 15^\circ$ and $\eta \sim 62\%$; respectively. In case of Ref, the radiation HA shows strong dipole-position dependency, while this is not the case for both antenna designs. The three sub-figure columns in Fig. 3.3 correspond to the structures shown in Figs. 3.1(b), 3.1(c), and 3.1(d), i.e. Ref, Ant1, and Ant2, respectively. The first sub-figure row in Fig. 3.3 is the theoretical far field power radiation pattern; followed by the BFP images of selected emitters, in the second row; and comparisons between theory and experiment in terms of the radiated power and the radiation angles are drawn, along the last row. Color map scaling in Figs. 3.3(d), 3.3(e), and 3.3(f) are only for clarification, and should not be confused and used to compare the brightness of the emitters. The pixel scaling in the BFP images for the three samples is not the same. Neighboring emitters in Figs. 3.3(e), 3.3(f) have been masked out, for the demystification of the results.

Despite the distribution in the emitters' position, due to the statistical nature of the implantation process, good agreement between theory and experiment can be overall remarked in Fig. 3.3, which emphasizes on the antenna's robustness in accommodating technological imperfections.

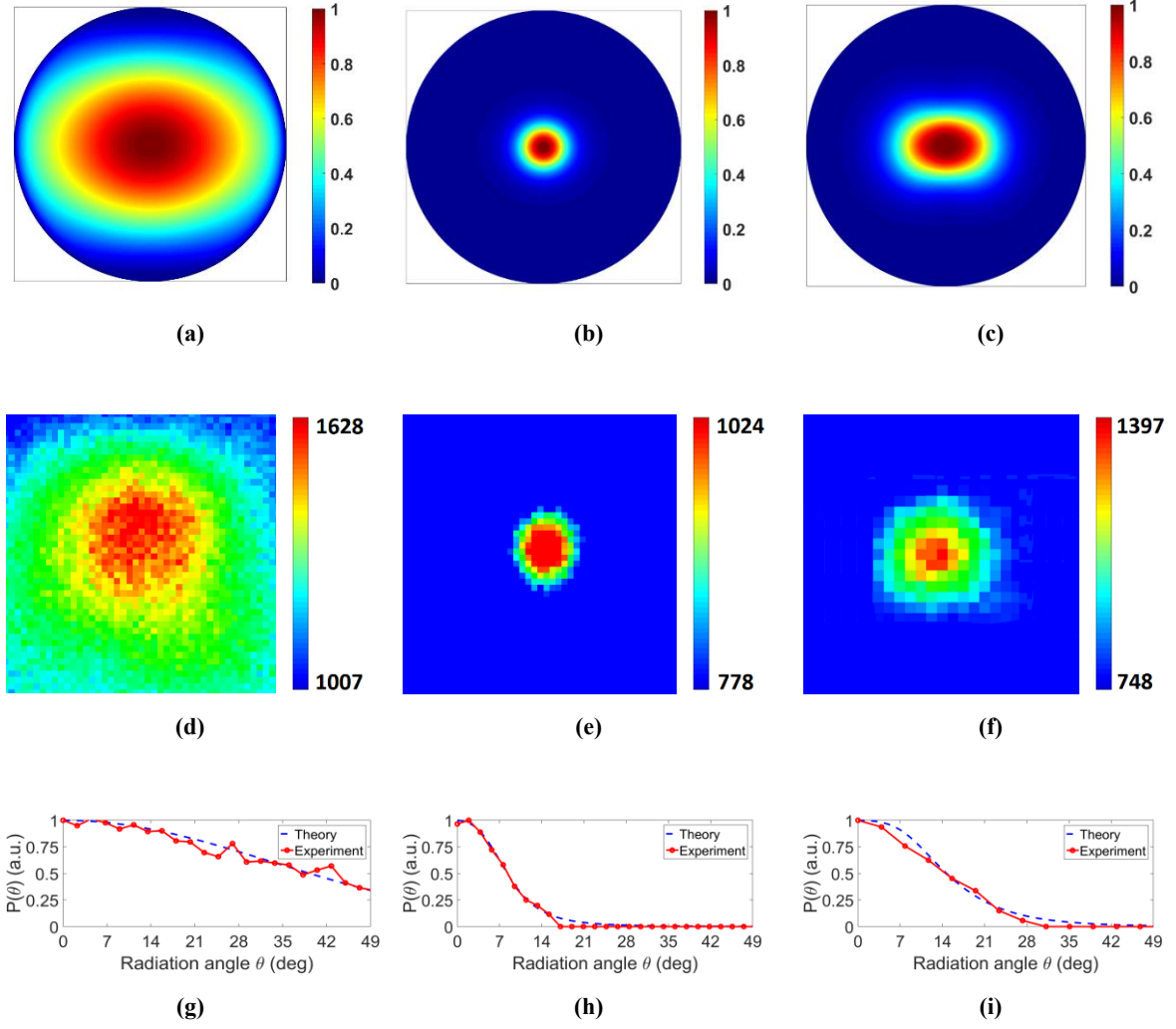


Fig. 3.3 Theory vs. experiment. (a), (b), and (c) Theoretical far field power radiation pattern, on a normalized scale; for Ref, Ant1, and Ant2 respectively. (d), (e), and (f) BFP images for the radiation pattern of Ref (scale: 46 x 46 px, 2.25°/px), Ant1 (scale: 54 x 54 px, 1.9°/px), and Ant2 (scale: 26 x 26 px, 3.9°/px) respectively. Color mapping scales in the three BFP images are not informative on the emitters' brightness. Neighboring emitters in (e) and (f) masked out. (g), (h), and (i) The radiation half angle θ versus the normalized radiated power, theory vs experiment, for Ref, Ant1, and Ant2 respectively.

Fluorescence count rate

Next, we investigate the overall enhancement in emission count rate, namely $\beta \times \eta$, for Ant1 and Ant2 in two different types of measurements; shown in Figs. 3.4(a), 3.4(b) respectively. The samples are excited from the director side, and the fluorescence signal is collected with the same objective. In the first configuration, the laser power (P_{Laser}) used to excite Ref and Ant1 is the same; however, the pump power (P_{Pump}) for Ant1 is much weaker than that for Ref, owing to the director's high reflectivity ($R \sim 0.89$). While in the second configuration, P_{Laser} is adjusted to maintain the same P_{Pump} for both Ref and Ant2. The emission count rate from Ref is already very weak, especially with a low P_{Pump} , and therefore a higher numerical aperture objective has been utilized in the latter configuration. We remind that the antenna works only

for emitters with Horizontal (H) dipole orientations. Vertical (V) dipoles will be completely quenched, and only the in-plane component of Diagonal (D) dipoles will survive, as illustrated in Figs. 3.4(a), 3.4(b) [ch.2], [4], [5]. The polycrystalline nature of the diamond membrane does not give preference to a certain dipole orientation. Statistically, we can assume a one-third probability of occurrence for each dipole orientation, H, V, and D. More emitters will be effectively active in case of Ref, and accordingly, one would expect a higher count rate than for Ant1 and Ant2.

The spectral emission count rate of Ant1 versus Ref is plotted in Fig. 3.4(c), on a normalized scale, in observation of the antenna's beaming effect dispersion. In Fig. 3.4(d), Ant2 and Ref are plotted with their actual count scales, for emphasis on the discrepancies in count rates. With Ref in red and Ant1 in blue, Fig. 3.4(c), one can already remark the submersion of Ref's 738 nm ZPL in a broad background emission. This background originates from impurities incorporated during the growth process of the membranes, and due to the polycrystalline nature of the membranes [9]. Along the full spectral range, three different behaviors stand out with respect to Ant1's response, indicated with the black arrows: the short-wavelength range background emission is enhanced; the long-wavelength range background is quenched; and the ZPL is ~5 nm blue shifted. The background modulation has been studied in [5]. This collective behavior translates from the broadband operation of the antenna; the beaming effect already starts earlier before the ZPL, peaks at the ZPL, and then ramps down onwards. As for the ZPL spectral shift, the membrane bending reported earlier is a result of the strain build up within the membrane. The different materials deposited on the membrane exert a tensile/compressive force on the membrane. With the membrane suspended in air, it relaxes to the strain with a slight curvature, and takes the shape of a meniscus structure, like that in Fig. 3.2(a). Near the edges of this structure, the curvature (strain) is maximum, while the curvature (strain) is minimal towards the center. By sampling measurements along the in-plane of the membrane, and in moving from the edge to the center of the membrane; Ant1's ZPL experiences a maximum blue shift near the edge, cyan plot Fig. 3.4(e), and converges (red shifts) to Ref's ZPL (red dashed plot) in proximity to the center (along the black arrow). Similar spectral shifts have been reported in SiVs, upon the application of an external strain in a controlled manner [13], [14].

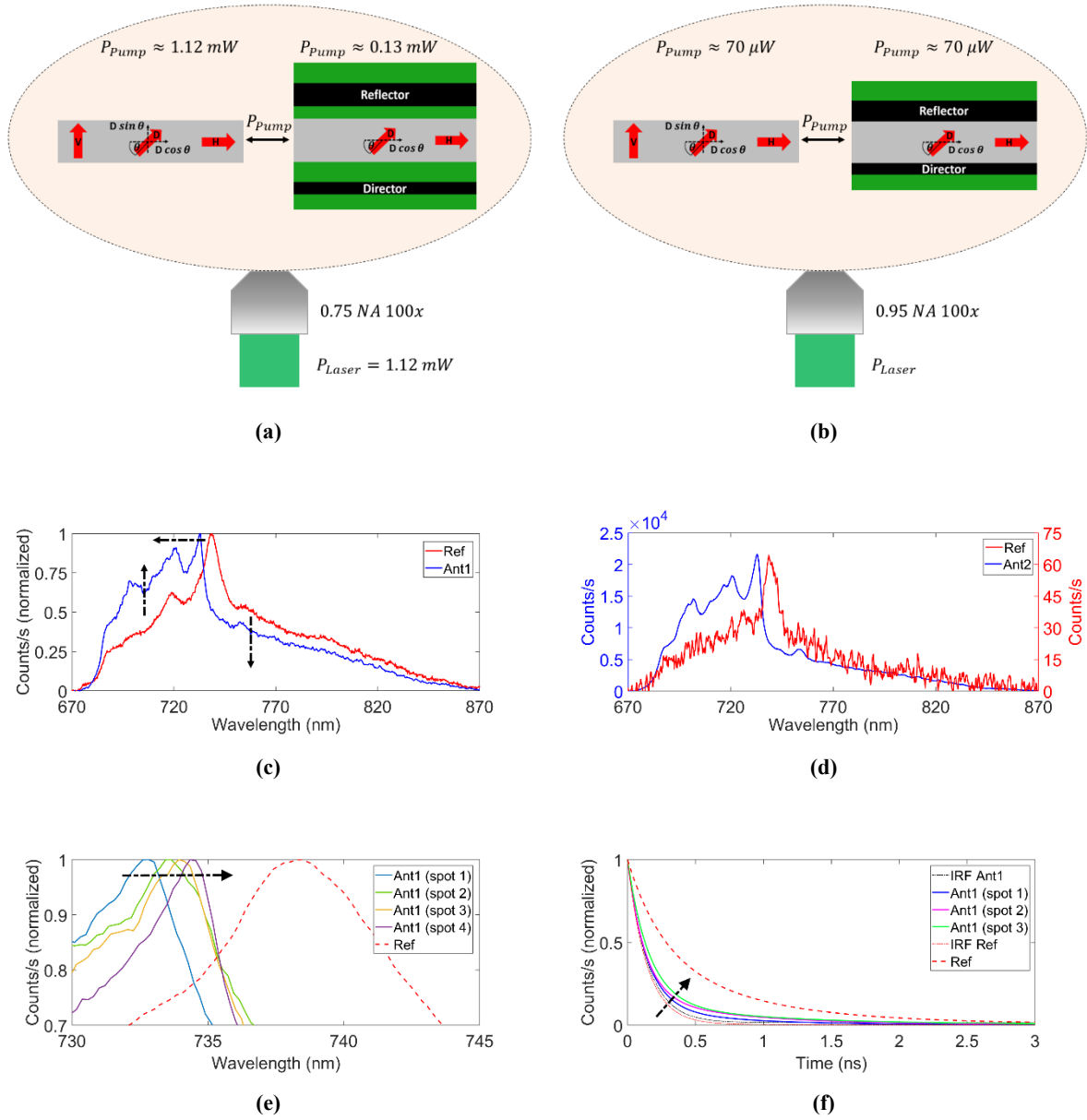


Fig. 3.4 Fluorescence count rate. (a) Experimental aspects of the measurements performed individually on Ref and Ant1 (same P_{Pump}), 0.75NA-100x ZEISS objective used. The corresponding results are shown in (c). (b) Experimental aspects of the measurements performed individually on Ref and Ant2 (same P_{Pump}), 0.95NA-100x Olympus objective used. The corresponding results are shown in (d). (c) Count rate spectral response for Ref vs Ant1, on a normalized scale. Vertical black arrows indicate the background modulation for Ant1 with respect to Ref; horizontal black arrow indicates the blue shifting of the ZPL of Ant1. (d) Count rate spectral response for Ref vs Ant2, on actual scale. The response of Ref is projected on the right y-axis, while the response of Ant2 is projected on the left y-axis. (e) ZPL spectral shift measurements for Ant1; performed by measuring four spots, starting from the edge of the membrane (spot 1) and by moving towards the center of the membrane (spot 4). The ZPL for Ref is in red dashed plot. Black arrow indicates the direction towards the center of the membrane. (f) Lifetime measurements for Ant1; performed by measuring three spots, starting from the edge of the membrane (spot 1) and by moving towards the center of the membrane (spot 3). The Ref lifetime and the instrument response function are the dashed and dotted red curves, respectively. Black arrow indicates the direction towards the center of the membrane.

The inhomogeneous strain argument has also been registered in lifetime measurements, for Ant1. However, the intention here is not to study the lifetime dynamics, but to visualize the spectral shift from different perspectives. The lifetime of Ref and Ant1 were measured at different times, with the corresponding Instrument Response Function (IRF) of each marked in dotted plots, shown in Fig. 3.4(f). For Ant1, the lifetime is shortest at the membrane's far edge, blue plot, and by moving towards the center of the membrane (following the arrow) it converges towards that for Ref, red dashed plot. Additional band-pass filters have been utilized to filter out the background emission.

Coming back to the count rate measurements for Ant2, Fig. 3.4(b); the same P_{Pump} allows us to assess the enhancement in count rate on a one-to-one basis. Again, we stress on the point that, more emitters are contributing to the overall count rate in case of Ref. The high numerical aperture objective used specifically in this measurement does not improve the photon collection for Ant2; because already its emission profile is highly directional. In fact, the radiation angles in case of Ref are very broad, and a high-NA objective will certainly account for this divergence and deliver a higher count rate. In practice, we can extend the 0.34 NA collection efficiency η to a 0.75 NA and a 0.95 NA objective lens, $\eta_{0.75}$ and $\eta_{0.95}$ respectively. In terms of numbers: $\eta_{0.75} \sim 54\%$ and $\eta_{0.95} \sim 90\%$, for Ref; $\eta_{0.75} \sim 96\%$ and $\eta_{0.95} \sim 100\%$ for Ant2. The results are shown in Fig. 3.4(d), with the response of Ref in red projected on the right y-axis; and Ant2 in blue projected on the left y-axis. The Ref ZPL registers a count rate of ~ 60 cps, at the best. On the other side, the blue shifted Ant2 ZPL registers a count rate of more than 21000 cps. This corresponds to an enhancement by more than 333 times, with the same P_{Pump} and with a fewer number of emitters. It is also worth mentioning; in spite that Ref was pumped ~ 9 times harder than Ant1 in the experimental configuration of Fig. 3.4(a), and with a fewer number of emitters, Ant1 still shows ~ 3 times higher count rate than Ref.

There have been efforts to characterize a single emitter for the three samples. However, unlike single crystalline diamond, the bare polycrystalline diamond membranes inherently exhibit a strong background emission superimposed on the ZPL, which can be mitigated by growing thicker diamond films followed by back-thinning [12]. Furthermore, with the application of the antenna, the background is strongly amplified and diminishes the observation of a dip in the second order correlation measurements [15].

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Chapter 4

Transfer Waveguide (TRANSGUIDE)

This section advances upon the learnings of chapter 2. The novel waveguide-based approach theoretically proposed in this monography renders light extraction efficiencies superior to its interlayered planar Yagi-Uda antenna counterpart, with emphasis on free-space emission. Prospects for enhanced light detection have also been touched upon within the context.

A European patent has been granted in recognition of this work, where the author is the unique inventor.

Patent disclosure [EP3865860 - Device for ultra-bright directional light emission] is enclosed in the Appendix.

4.1 The waveguide paradox

Waveguides have long been known for guiding light along their axes. Here, they are used differently, and it shall be shown that they hold as much promises from their sides. Three simple plain waveguides: the Source; the Gate; and the Drain are packed one upon another, on the Forward-bias layer, to form a transistor-like architecture referred to as the Transfer Waveguide (TRANSGUIDE), schematically shown in Fig. 4.1.



Fig. 4.1 Scheme outline. Flat waveguides packed on a reflecting layer, forming a three-stage stack (cross-section view).

Essentially, light is emitted within the Source waveguide, from emitters with their dipole orientation parallel to the Gate waveguide's axis. The Forward-bias is a reflecting layer that directs the emitted photons towards the Drain waveguide. The overall structure is designed to support a photon flow from the Source to the Drain, i.e. along the tunnel.

The following discussions are highlights on how a three-stage stack, with waveguide building blocks constructed from very simple materials; can bring light sources, whether classical or quantum, to another level. In laying down the concepts, the Silicon Vacancy (SiV) color center in diamond is adopted as the light emitting platform, with an operational wavelength of 738 nm [1]. However, TIR due to diamond's high-refractive index will be addressed in a different manner to what we have seen so far throughout the previous chapters. As simple as it gets; by putting plain oxide layers together, for example, a practical solution to this longstanding problem will be tailored in the upcoming examples. The proposed layered structure is free of any advanced nanostructures or engineered metamaterials, and offers a broad technological tolerance margin. The refractive indices of TiO_2 , ZnO , Al_2O_3 , SiO_2 , diamond, and silver at the aforementioned wavelength read: 2.54 [2], 1.97 [3], 1.76 [4], 1.45 [5], 2.4 [6], and $0.033+5.1i$

[7], respectively. Choice of materials is solely for outlining the working concept and is not restricted. Outperforming results are conceived with selective material combinations.

4.2 Leakage tunneling

Imaginary-Source

To this extent, as far as understood, any of the three waveguides is typically comprised of a core and a cladding, with the cladding consisting of a lower part and an upper part. With reference to the configuration shown in Fig. 4.2(a), the Source's core and cladding are defined from the same material; meaning that, there is no refractive index contrast between them. The Source, in this case, is considered imaginary since its core and cladding are merged together; this implies that imaginary physical interfaces define the boundaries between them. Presumably, the emitters are located in close proximity to the center of the Source, marked with the origin of the coordinate system. The Gate functions in a similar manner to an Insulator Metal Insulator (IMI) waveguide. In this arrangement, the Gate is merged; meaning that the Gate's lower cladding is merged with the Source's upper cladding, i.e. same material. On the other side of the Gate, a typical dielectric waveguide serves as the Drain. A real physical interface draws the boundary between the Gate and the Drain, via the refractive index contrast between their contiguous claddings. Dimensions of the individual waveguides can be read in the caption of Fig. 4.2.

Tolerances, in terms of the Light Extraction Efficiency (LEE) and the Radiation Half Angle (RHA), are analyzed along the z-coordinate up to ± 20 nm emitter position displacement (Δd) from the origin, shown in Fig. 4.2(b). Lateral displacements, along the x and y coordinates, are completely irrelevant owing to the structure's translational symmetry. The figure of merit LEE is defined as: the Power Radiated from the Drain along the z-coordinate in the forward direction (P_{rad}) divided by the Total Power emitted by the dipole within the Source (P_{tot}). The radiation pattern is quantified by the RHA measured at half-maximum. Whether moving towards the Gate ($+\Delta d$) or towards the Forward-bias ($-\Delta d$), the LEE remains in the vicinity of 78% with a 27° RHA single-lobe pattern. Reminding that, the background medium is air, i.e. free-space emission. Not shown in Fig. 4.2(b), the Purcell factor takes values between 1 and 2.

The modes supported in this arrangement are plotted in Fig. 4.2(c). Radiative modes are identified with real effective refractive index values $\text{Re}(n_{\text{eff}}) = [0:1]$, while non-radiative

modes feature a $\text{Re}(n_{\text{eff}}) > 1$ (shaded area in Fig. 4.2(c)). In this context, non-radiative modes can be thought of as loss channels. The behaviors of these non-radiative modes are understood from the successive field profiles shown in Fig. 4.2(d)-(g). In Fig. 4.2(d), due to the finite thickness of the diamond layer, the two Surface Plasmon Polariton (SPP) modes at each of its interfaces merge together within the diamond layer, giving rise to a hybrid guided mode in the Source. SPP is considered an interesting phenomenon; however, for light emitting devices it can be bothersome. The second mode, in Fig. 4.2(e), is guided in the Gate. This mode is partially converted into a TIR contribution along the TiO_2 - SiO_2 transition. A similar TIR contribution could also be seen earlier in Fig. 4.2(d). The two remaining modes in Fig. 4.2(f),(g) are guided in the Drain: the first is a fundamental mode concentrated in the core, while the second is a higher order mode in the cladding. The cladding mode is capped with a TIR contribution along the SiO_2 -air transition. The tunneling from the Source to the Drain's cladding, under the gating effect, can be clearly remarked in Fig. 4.2(g).

Real-Source

A noticeable difference between this arrangement and the previous one is the physical structure of the Source. Here in Fig. 4.3(a), there is a refractive index contrast between the Source's core and cladding; implying that, real physical interfaces define the boundaries between them. As in the previous example, the emitters are initially positioned close to the center of the Source. The Gate is again merged; however, this time the Gate's lower cladding is SiO_2 instead of diamond.

Let us take a look at the tolerance plot shown in Fig. 4.3(b), where the robustness of the modified Source structure is investigated. Apparently, the figures of merit LEE and RHA show higher emitter position insensitivity close to 90% and 19°, respectively. The radiated power is funneled into a symmetric single-lobe, with Purcell factor values between 1 and 2 (not shown).

Overall, from Fig. 4.3(c)-(g); the hybrid Source guided mode becomes leakier, stepping down. With the electric field concentrated in the Source's cladding, more light is transferrable from the Source to the Drain.

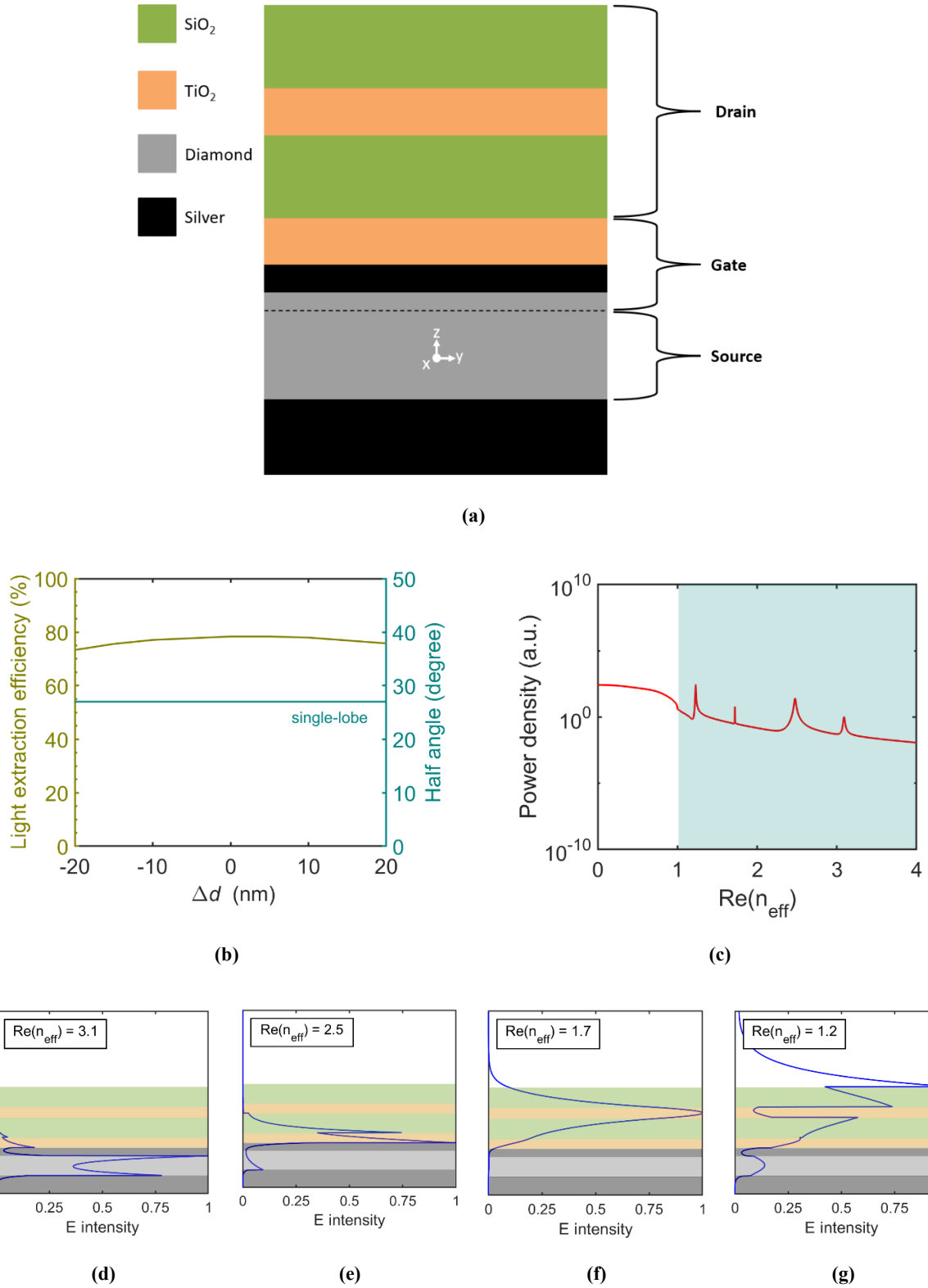
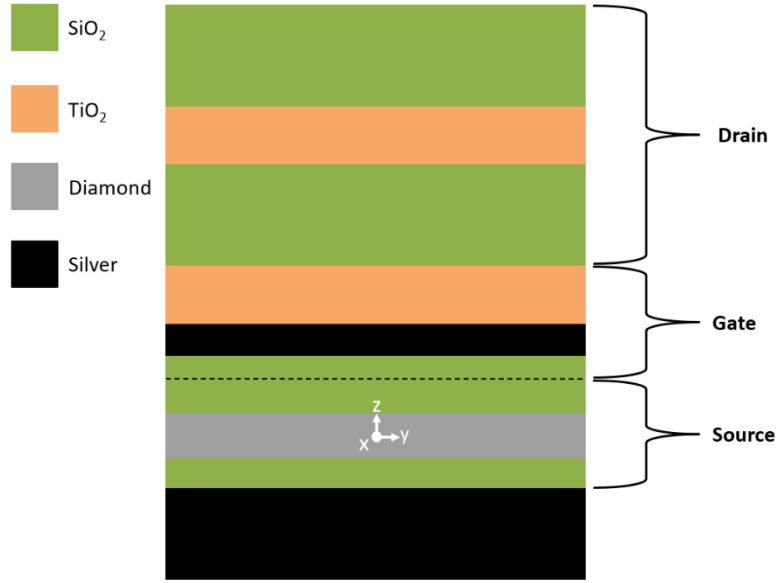
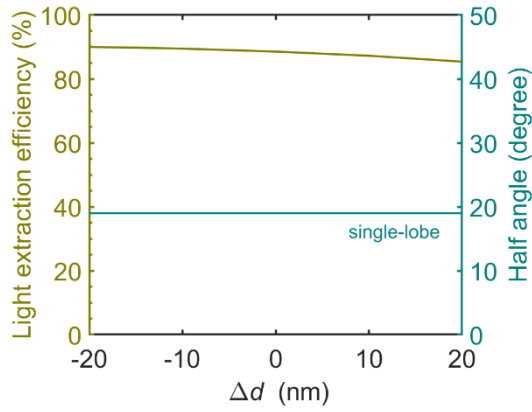


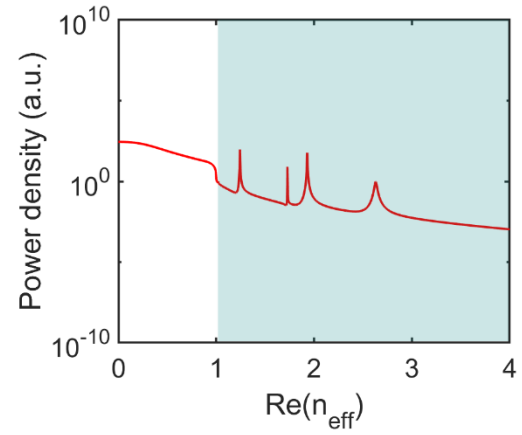
Fig. 4.2 Imaginary-Source merged-Gate configuration (free-space emission). (a) Stack dimensions: [Forward-bias: (100 nm)], [Source: (25 nm, 50 nm, 25 nm)], [Gate: (10 nm, 45 nm, 58 nm)], [Drain: (112 nm, 58 nm, 112 nm)]. Coordinate system origin marks the center of the Source. (b) Figures of merit as a function of the emitter position displacement from the center of the Source. (c) Power density, on a logarithmic scale, as a function of the real effective refractive index. (d)-(g) Normalized modal field distributions of the four non-radiative modes shaded in (c). Color mapping is in correspondence with (a).



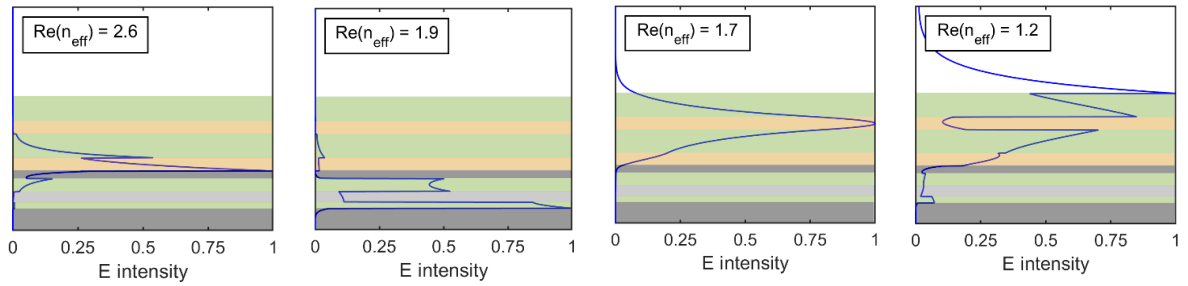
(a)



(b)



(c)



(d)

(e)

(f)

(g)

Fig. 4.3 Real-Source merged-Gate configuration (free-space emission). (a) Stack dimensions: [Forward-bias: (100 nm)], [Source: (30 nm, 50 nm, 30 nm)], [Gate: (31 nm, 35 nm, 62 nm)], [Drain: (112 nm, 58 nm, 112 nm)]. Coordinate system origin marks the center of the Source. (b) Figures of merit as a function of the emitter position displacement from the center of the Source. (c) Power density, on a logarithmic scale, as a function of the real effective refractive index. (d)-(g) Normalized modal field distributions of the four non-radiative modes shaded in (c). Color mapping is in correspondence with (a).

4.3 Pinching

Now that we have identified the dominant loss channels, herein we take a look at the main radiant modes. At first, consider the imaginary-Source merged-Gate configuration's radiant mode plotted in Fig. 4.4(a). The Source's field tunnels its way through the Gate, and ends up stored in the Drain's cladding. Notice that the mode is pinched twice: once in the core of the Gate, and a second in the core of the Drain. A pinch is technically a tightening of the light's path; in the same sense as, a pinch for the charge carriers in a Field Effect Transistor (FET). The Drain has been configured not to hold on to the mode for long, and eventually the light bursts into free-space.

A similar scenario takes place in Fig. 4.4(b), for the real-Source merged-Gate configuration; however, this time the Source's field is heavily depleted, with an additional pinch in the Source's core. The higher LEE delivered by this configuration, as compared to the former, translates from the enhanced mode tunneling and pinching.

The corresponding electric field cross-sectional mappings shown in Fig. 4.4(c),(d) illustrate the light transfer along the tunnel, and the eventual burst into free-space. For the latter configuration, the Drain appears fuller while the Source is almost completely drained. Obviously, the burst is seeded from the Drain, and is pinched in the three waveguide cores. Even though the emitters are incubated in the Source, their light emission rather builds up in the Drain. The light radiated from the Drain, visualized in the far-field, is shown directly beneath in Fig. 4.4(e),(f); with the left-panels for the examples under consideration, and the right-panels for selective designs featuring different pinching effects. The idea here is to show that pinching is capable of routing and reshaping the emission beam profile. The RHA can readily be reduced, for example, from 27° to 15° , in Fig. 4.4(e); and from 19° to 12.5° , in Fig. 4.4(f). Tighter angles are realizable.

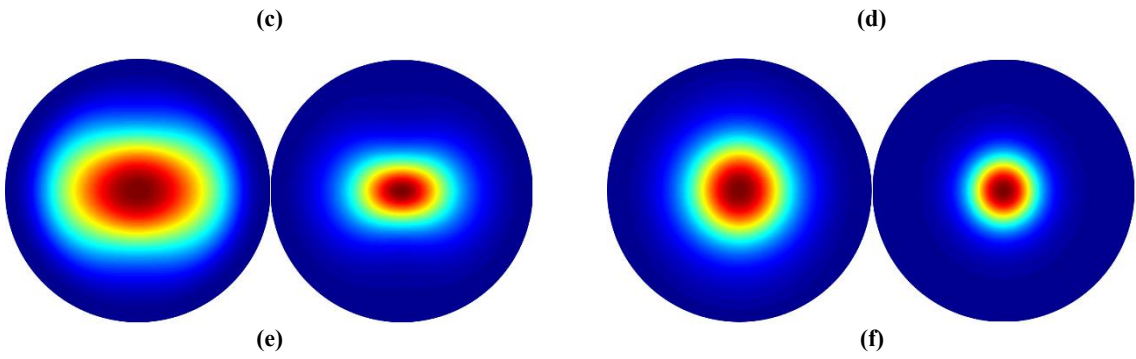
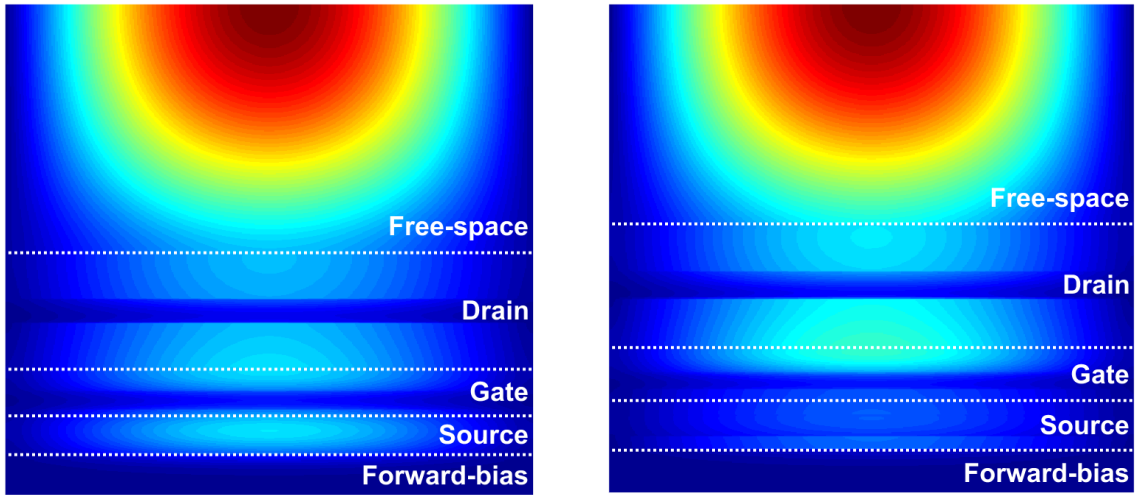
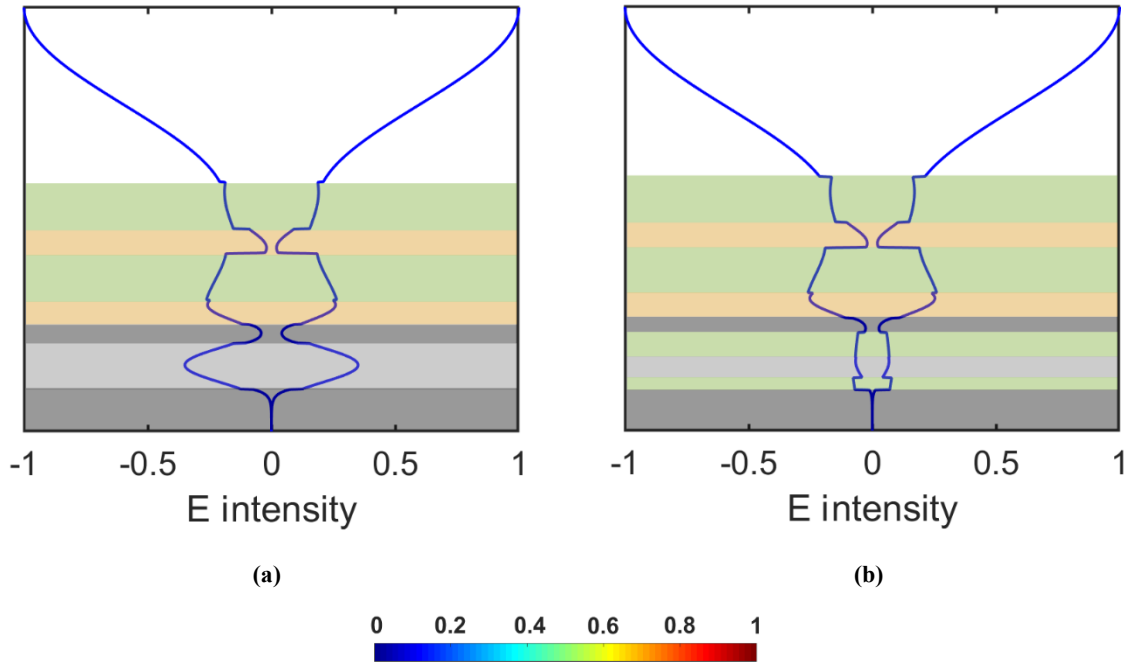


Fig. 4.4 Radiated power (free-space emission): imaginary-Source vs real-Source. (a), (b) The main radiant mode for the configurations with an imaginary-Source merged-Gate and a real-Source merged-Gate, respectively. Color mapping is in correspondence with Fig. 4.2(a) and Fig. 4.3(a), respectively. (c), (d) Normalized electric field magnitude cross-sections for (a) and (b), respectively. (e) (left) Normalized far-field radiation pattern for (a); (right) for a configuration similar to (a) but featuring a different pinching factor. (f) (left) Normalized far-field radiation pattern for (b); (right) for a configuration similar to (b) but featuring a different pinching factor. All scales are normalized.

4.4 Gate trenching

One of the Gate's functionalities is to regulate the light transfer between the Source and the Drain. In the two previous examples, the Gate was merged with the Source. Here in Fig. 4.5, we will consider something different: physically detaching the Source from the Gate. This is realized by using a different material for the Gate's lower cladding; where in Fig. 4.5(a) the diamond lower cladding is replaced with ZnO for the imaginary-Source configuration, and in Fig. 4.5(b) the SiO₂ lower cladding is replaced with Al₂O₃ for the real-Source configuration. The overall refractive index profiles of the structures are depicted in Fig. 4.5(c),(d) respectively. For both configurations, the Gate's upper cladding remains TiO₂. The impact of the Gate trenching is addressed in Fig. 4.5(e),(f); with the earlier merged-Gate plots recalled from Fig. 4.2(b) and Fig. 4.3(b), respectively. The free-space LEE approaches 81% for the imaginary-Source trenched-Gate configuration; and 91% for the real-Source trenched-Gate configuration, exhibiting a flatter plateau response.

In this context, two arguments might arise. First; the enhancement in the LEE delivered by switching from an imaginary-Source (Fig. 4.2(a)) to a real-Source (Fig. 4.3(a)), might be misinterpreted as a result of the suppression of SPPs in response to the inclusion of low-refractive index layers, i.e. replacing the silver-diamond interfaces in the former case with silver-SiO₂ interfaces in the latter case. The LEE plots in Fig. 4.5(f) prove this argument wrong. This is understood from the fact that, Gate trenching the real-Source configuration is equivalent to replacing the silver-SiO₂ interface with a silver-Al₂O₃ interface; bearing in mind that Al₂O₃ has a higher refractive index than SiO₂. Even when the dipole emitter approaches the Gate, i.e. (+ Δd), the LEE for the trenched-Gate case increases with respect to the merged-Gate case. One would have expected it to rather decrease [ch.2], [8].

The other argument that might come into mind; Gate trenching the imaginary-Source configuration of Fig. 4.2(a) with ZnO in Fig. 4.5(a), can be visualized as replacing the silver-diamond interface in the former with a silver-ZnO interface in the latter. Since the refractive index of ZnO is lower than that for diamond, it makes sense that the LEE is higher for the ZnO trenched case; owing to the less coupling to SPPs [ch.2], [8]. However; this perception is misleading, because, trenching the Gate with an even lower refractive index material, such as SiO₂, deteriorates the LEE rather than enhancing it.

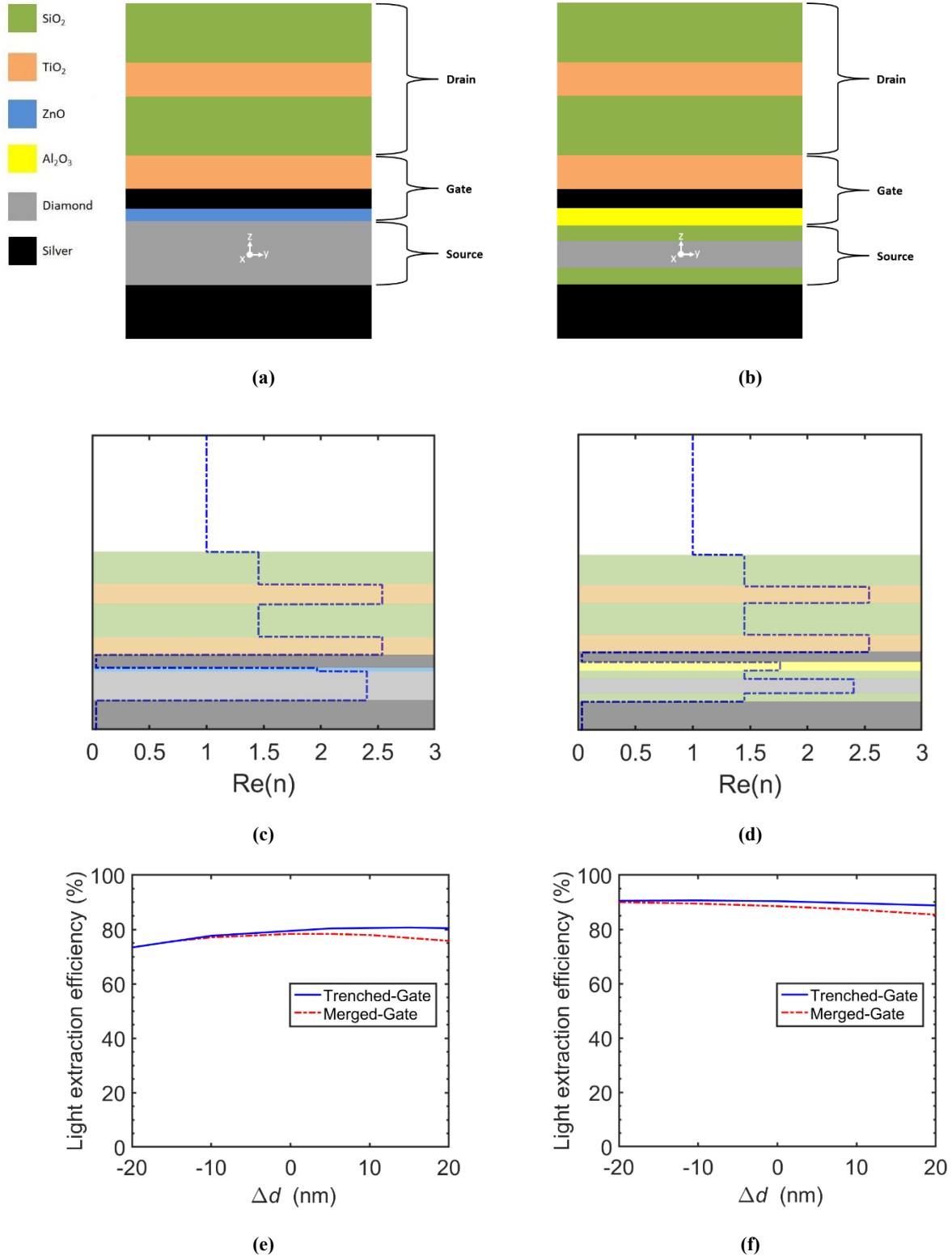


Fig. 4.5 Gate trenching (free-space emission). (a) Imaginary-Source: the Gate's lower cladding and the Source's upper cladding are different materials. Configuration dimensions: [Forward-bias: (100 nm)], [Source: (25 nm, 50 nm, 25 nm)], [Gate: (12 nm, 45 nm, 62 nm)], [Drain: (112 nm, 68 nm, 112 nm)]. (b) Real-Source: the Gate's lower cladding and the Source's upper cladding are different materials. Configuration dimensions: [Forward-bias: (100 nm)], [Source: (30 nm, 50 nm, 30 nm)], [Gate: (29 nm, 35 nm, 62 nm)], [Drain: (112 nm, 58 nm, 112 nm)]. (c), (d) Refractive index profiles of the configurations in (a) and (b), respectively. Layer color mapping is in correspondence with (a) and (b). (e), (f) Comparisons between the Trenched-Gate configurations and the Merged-Gate configurations (plots recalled from Fig. 4.2(b) and Fig. 4.3(b)) in terms of the LEE as a function of the emitter position displacement from the center of the Source, for the configurations in (a) and (b).

From here, I would like to emphasize on the fact that, the TRANSGUIDE's potentials are higher when the individual waveguides are well defined. It has got nothing to do with the suppression of SPPs by the inclusion of low-refractive index layers; one can already see that the effective refractive index values are high enough to provoke strong SPPs. After all, the three waveguides have been stitched together in a way, such that all competing loss channels are settled down.

4.5 State of the art

The literature trend so far has been to incorporate nanostructures or engineered materials in light emitting devices, taking advantage of the latest advances in nanofabrication. It turns out that; this just makes the whole process more complex and adds up additional bills. Even the reported free-space LEEs have not really benefited from that sophisticated technology; in fact, image blurring and diffraction in illumination applications [9] and bandwidth modulation are a symptom. All this comes at the expense of the radiation pattern, requiring additional external-integrated optics to account for the large radiation angle spans and the distorted beam profile. In practice, the spatial positioning of the dipole light emitters with respect to the incorporated nanostructures becomes very critical; thereby, further tightening the technological tolerance margin.

In a different direction, we have earlier shed light on the planar Yagi-Uda antenna, chapter 2 and 3. Let us take it on a one-to-one comparison with the TRANSGUIDE. The planar Yagi-Uda antenna, when applied to a 100 nm diamond active medium, struggles with a 40% free-space LEE [ch.2], [8]. One step further, the advanced interlayered version of the said antenna, applied to a 50 nm diamond active medium, the free-space LEE saturates close to 80% [ch.2], [8]. When it comes to the TRANSGUIDE; we have already witnessed free-space LEEs near 81% on that 100 nm diamond active medium, and 91% on that 50 nm diamond active medium. This superiority comes in response to stitching two symmetric dielectric waveguides together by means of an antisymmetric plasmonic waveguide.

Technically speaking, the interlayered scheme in [ch.2], [8] principally relies on the suppression of SPPs with the inclusion of very low-refractive index layers, ideally $n \approx 1$. Such stringent requirement makes the scheme highly restrictive and inapplicable to free-space emission applications; especially with the fact that typical charge-transport material layers feature a relatively high-refractive index. Meanwhile, the TRANSGUIDE has no problems with SPPs, and is comfortable with high-refractive index materials.

4.6 Medium vs free-space emission

At this stage, the free-space LEE exceeds 90% with the promoted leakiness of the Source. The power contributions of the four non-radiative modes (Fig. 4.2(c)-(g) and Fig. 4.3(c)-(g) are negligible compared to the radiant continuum. That said, if these modes were to be plotted on a linear scale, most of them would even be hardly seen. However; out of the four, the Drain mode $\text{Re}(n_{\text{eff}}) = 1.2$ amounts for the largest share, with a significant amount of the modal power seized in the Drain's cladding. With reference to Fig. 4.2(g) and Fig. 4.3(g) one can see that, in the latter case, more light builds up in the Drain's cladding. For both cases, the mode is capped with a TIR contribution.

Interfacing the Drain's outermost cladding with a material, having a relatively higher refractive index; sets the aforementioned Drain mode free. This is demonstrated in Fig. 4.6(a),(b), with the blue plots representing the real-Source trenched-Gate configuration of Fig. 4.5(b) packaged in epoxy or silicone gel ($n = 1.5 - 1.55$); while the red dashed plots are for free-space background. The shaded area in Fig. 4.6(a) marks the non-radiative modes for the packaging plot. As a result, the Drain's cladding mode is completely converted into a radiant mode, and the Drain's remaining guided core mode is further weakened; giving rise to a 92% LEE, at least for this configuration. The origin of this 1–5% incrementation is depicted in Fig. 4.6(b). The Source in turn is evacuated and more light is transferred along the tunnel, with an exponential field rise in the Drain's outermost cladding. At the packaging's interface, TIR no longer exists, and the mode bursts out of the Drain. The LEE, in packaging and in free-space, as a function of the emitter position displacement (Δd) is plotted in Fig. 4.6(c),(d); for the imaginary-Source and for the real-Source both trenched-Gate configurations, respectively. To mention, however, the LEE for the inferior imaginary-Source trenched-Gate configuration approaches 86% in packaging.

We are now left with three non-radiative modes, one of which has already been strongly weakened. With the careful tailoring of the materials and design, we can further weaken or even get rid of the leftover non-radiative modes.

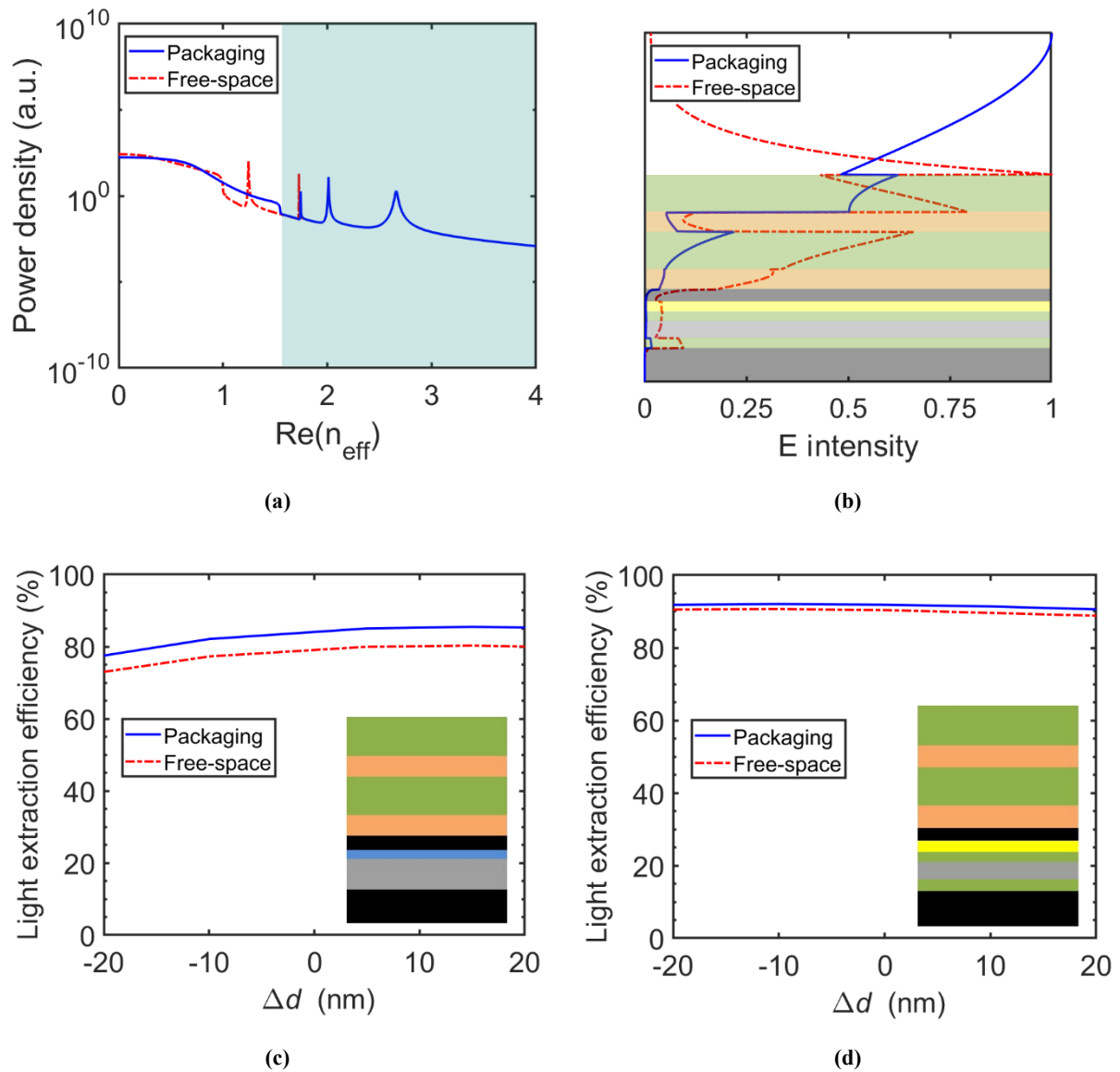


Fig. 4.6 Packaging (blue) vs free-space (red) emission. (a) Power densities as a function of the real effective refractive index, for the real-Source trenched-Gate configuration. Shaded area marks the non-radiative modes for the packaging plot. (b) Transformation of the Drain's guided cladding mode, for the real-Source trenched-Gate configuration. Normalized scale. (c), (d) The LEE, packaging vs free-space; as a function of the emitter position displacement from the center of the Source for the imaginary-Source trenched-Gate and the real-Source trenched-Gate configurations, respectively.

Before we move on to the next section, let me come back to the earlier SPP argument and wrap it up with the two real-Source trenched-Gate packaged examples shown in Fig. 4.7. The cyan plot is a ZnO trench, while the yellow plot is the Al_2O_3 trench recalled from Fig. 4.6(d). Even though ZnO has a higher refractive index than Al_2O_3 , the ZnO trench LEE picks up a $\sim 3\%$ and hits a plateau near 95%.

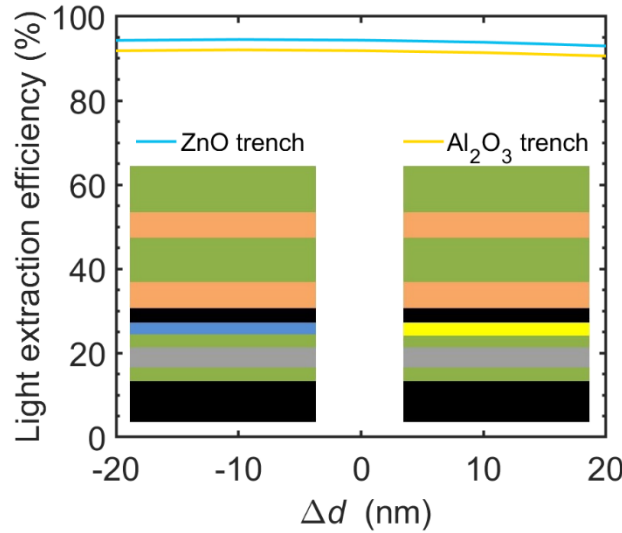


Fig. 4.7 Real-Source Gate trenches (packaging emission). The LEE as a function of the emitter position displacement from the center of the Source. The two plots are real-Source trenched-Gate configurations, with the yellow Al_2O_3 plot recalled from Fig. 4.6(d).

4.7 Reciprocity

Light detection applications, or to say fluorescence and energy conversion systems, are more sensitive to the light's electric field component. Nanostructures have been explored for this purpose, with focus on mediating light-matter interactions through enhancing the electric field strength. Polarization plays an important role, where ideally the incoming light's electric field has to maintain a certain alignment with respect to the nanostructure. Typically, electric field augmentation is spatially limited to superficial nanometers-size “hotspots” around sharp edges or within gaps [11]. Most literature studies in this regard assume an ideal scenario, where the incoming light beam is a well-defined polarization plane wave. In real-life, the beam can arrive with any permissible polarization state, with a finite spot-size that is unnecessarily uniformly distributed; this is a common practice, for example, in LiDAR and sensing applications. Non-uniform exposure can lead to dramatic outcomes and unexpected suppressions [12]; especially

when the nanostructure is arranged in a periodic array, exploiting collective interference effects [11].

In what follows, and by invoking reciprocity, we take a look into what the TRANSGUIDE offers in this regard.

Beam exposure

An efficient light-matter interface would be one that: first, does not waste the incoming light beam by being specific for certain polarization components while transparent for others; second, is independent of the spot-size and the profile of the incoming light beam. To address these issues, a randomly polarized Gaussian profile will be considered for exposure. The numerical aperture of a Gaussian beam is a very critical parameter, and directly relates to the beam profile specifications: spot-size, amplitude distribution, divergence angle, etc.

Now that we have agreed to a realistic exposure, recall the real-Source trenched-Gate design that we came across earlier in Fig. 4.5(b). The structure is exposed to the incoming Gaussian beam head-on, over free-space, as shown in Fig. 4.8(a). For the sake of highlighting the TRANSGUIDE's reciprocity, assume that probing the SiV color center under resonant-excitation is of interest; regardless of whether or not it is physically feasible. The 738 nm wavelength Gaussian beam pump is shone on the Drain, with the SiV presumably located at the center of the Source waveguide, i.e. the origin.

The electric field is observed over an xy-plane, known as the focal plane, located at the center of the Source waveguide. For this argument, we will recall the “normalized electric energy density” factor [13,14]. The reference scenario would be when the incoming beam interacts with the diamond active medium standalone, i.e. the grey slab in Fig. 4.8(a); and in this case we can define a corresponding reference normalized electric energy density factor (F_o). The other scenario would be when the incoming beam interacts with the complete layered structure shown in Fig. 4.8(a), giving rise to a corresponding normalized electric energy density factor (F). The enhancement factor is of interest, quantified by (F/F_o).

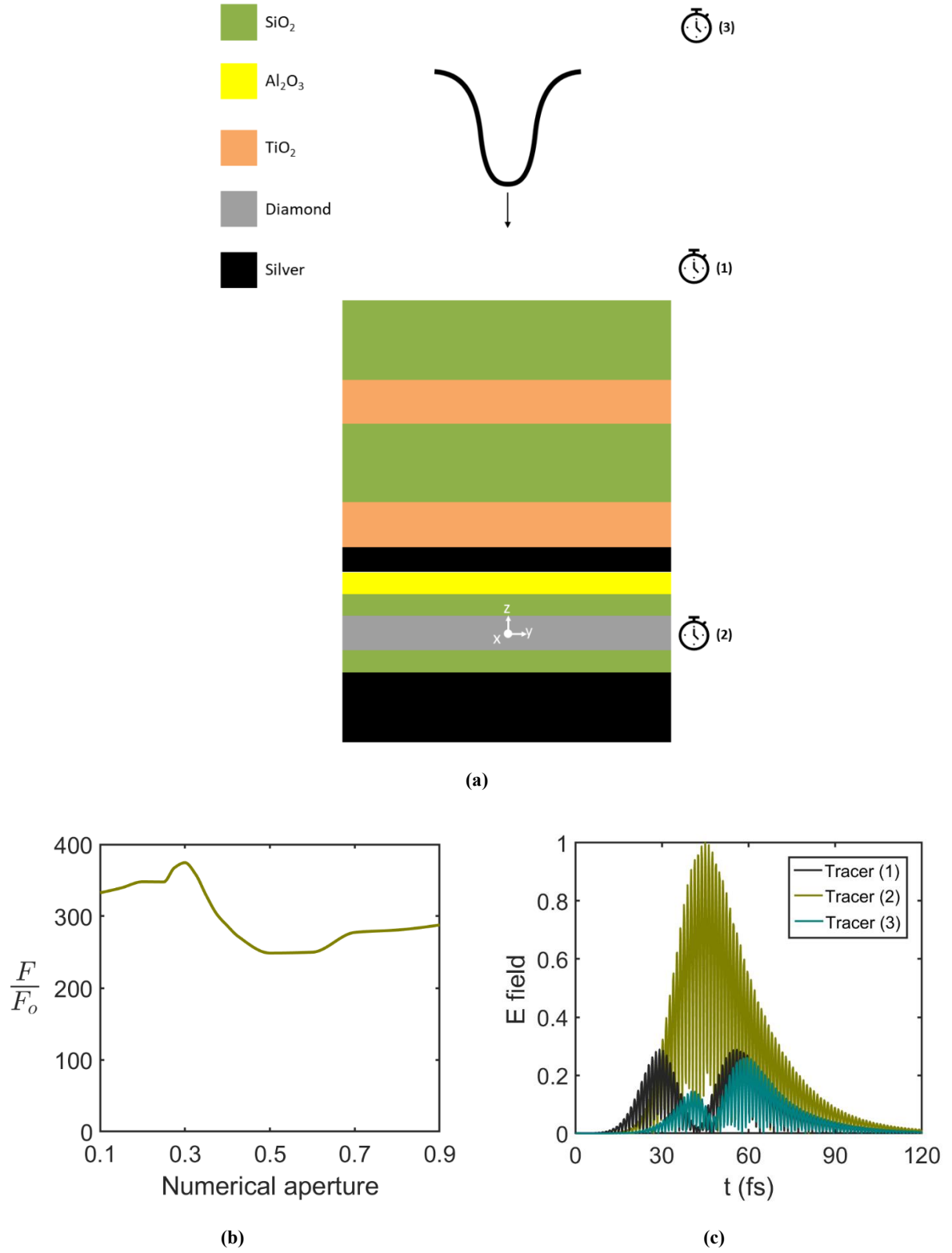


Fig. 4.8 Free-space Gaussian beam exposure. (a) A real-Source trenched-Gate configuration exposed to a 738 nm wavelength arbitrary polarization Gaussian beam, along the (-ve) z-axis. The structure's design parameters can be read in the caption of Fig. 4.5(b). The coordinate system marks the center of the Source waveguide, where ideally the xy-focal plane is located. (b) The enhancement factor computed over the focal plane in response to the beam's numerical aperture values. (c) Round-trip response for the 0.3 numerical aperture incident Gaussian beam. Tracer locations are pointed out in (a).

As the beam's numerical aperture varies, the enhancement factor easily maintains values above 200, shown in Fig. 4.8(b). This response applies to any beam polarization, since the TRANSGUIDE structure is rotationally symmetric around the z-axis. The peak in the vicinity of ~ 0.3 numerical aperture emphasizes on the scheme's reciprocity. This can be understood by referring back to the structure's principle design, where the outgoing light beam in essence was meant to be emitted from the Drain along the (+ve) z-axis with a RHA on the order of 19° (comparable to ~ 0.3 numerical aperture). With the incoming beam following the same trajectory of the outgoing beam, the structure's maximum potential can be reproduced. The Gate, in practice, is a two-way port. This enhancement is not locally limited to the focal plane; in fact, it extends over the entire volume of the Source waveguide's core, in agreement with what perceived earlier. The broadband nature of the scheme extends its applicability beyond resonant-excitation applications (see for example Fig. 4.9(c)).

Virtual-dipole

In order to have a better understanding of the waveguides' responses to the incoming beam, maybe we should consider tracing the beam at different time frames. Carrying out this analysis for a 0.3 numerical aperture would probably be ideal for observing the structure's reciprocity. Three beam tracers are placed at the different locations, pointed out to in Fig. 4.8(a): tracer (1) along the z-axis between the Gaussian beam aperture and the TRANSGUIDE, tracer (2) at the center of the Source waveguide, and tracer (3) along the z-axis behind the Gaussian beam aperture. The picked-up signals are plotted on a normalized scale in Fig. 4.8(c).

The plot from tracer (1) is the event onset, where the impinging pulse is registered as the first packet around 30 fs. While this packet continues its way propagating along the (-ve) z-axis, it is partially back-reflected of the Gate; and accordingly, the reflected portion propagates backwards along the (+ve) z-axis and is registered around 40 fs on tracer (3). The portion of the beam that experienced no reflection ends up in the Source's core. This portion is significantly enhanced and is the only packet registered by tracer (2), around 45 fs. Since diamond is a transparent material, and in this particular study we have not defined any dipolar system to absorb the incoming light; the packet is released back to where it came from. On its return journey, it is first registered around 56 fs on tracer (1) and later on around 60 fs on tracer (3). Notice that the packet's form resembles a dipolar-exponential-decay lifetime envelope, and is preserved at all three registered instances. This packet is a signature of the TRANSGUIDE's

reciprocity. Back-reflected light, more or less, has the same symmetric envelope as the incident light pulse, but with a weaker amplitude.

A final point-out on Fig. 4.8(c). The earlier discussions have repeatedly stressed on the necessity that the dipole emitters maintain an in-plane polarization within the Source, otherwise no light would be emitted in the forward direction. The fact that the incident light pulse was efficiently emitted back again into free-space with the same wavelength implies that, a virtual in-plane electric dipole had been created in the Source. Had the dipole's polarization been out-of-plane, no light in essence would have been registered on tracer (1) and subsequently on tracer (3). There is no way that light can propagate in the forward direction, apart from the incident light back-reflection, unless an in-plane dipole near-field emerges within the Source. The incident light's pulse dynamics tailor the virtual-dipole's oscillatory strength and lifetime. The electric dipolar energy, as observed on tracer (2), can be maximized, for example, in response to the incoming light's pulse duration. The ability to register a light signal as a virtual-dipole and recover it back again can be practical for sensing and memory applications. From a different perspective, this interchangeability can open prospects for cavityless stimulated emission.

4.8 Quantum and classical light emitting platforms

With the elapsed SiV color center in diamond highlights, the TRANSGUIDE's underlying physics should be clear by now. This brings us to a more of an applied discussion, where in what remains of this text, we project the previous findings on selective light emitting platforms.

Near-infrared light emitters

This section takes us a bit deeper into the near-infrared region, and explores the TRANSGUIDE's potentials with even higher refractive index materials.

Cubic silicon carbide (3C-SiC) has emerged as a promising single photon emitter platform along the telecom range [15]. In Fig. 4.9(a), the transistor-like architecture is applied to a 3C-SiC active medium, where it is demonstrated that ultra-bright directional light emission is realizable in spite of the material's high-refractive index, $n \approx 2.55$ [16]. A 50 nm 3C-SiC core is sandwiched in a SiO₂ cladding. The light emitting dipoles can be anywhere within the active

medium, no restrictions on their locations; the only requirement is parallelism to the Gate. In the bandwidth plot shown in Fig. 4.9(c), the free-space LEE hits a plateau around 92%, with the Purcell factor maintaining values between 1 and 2.

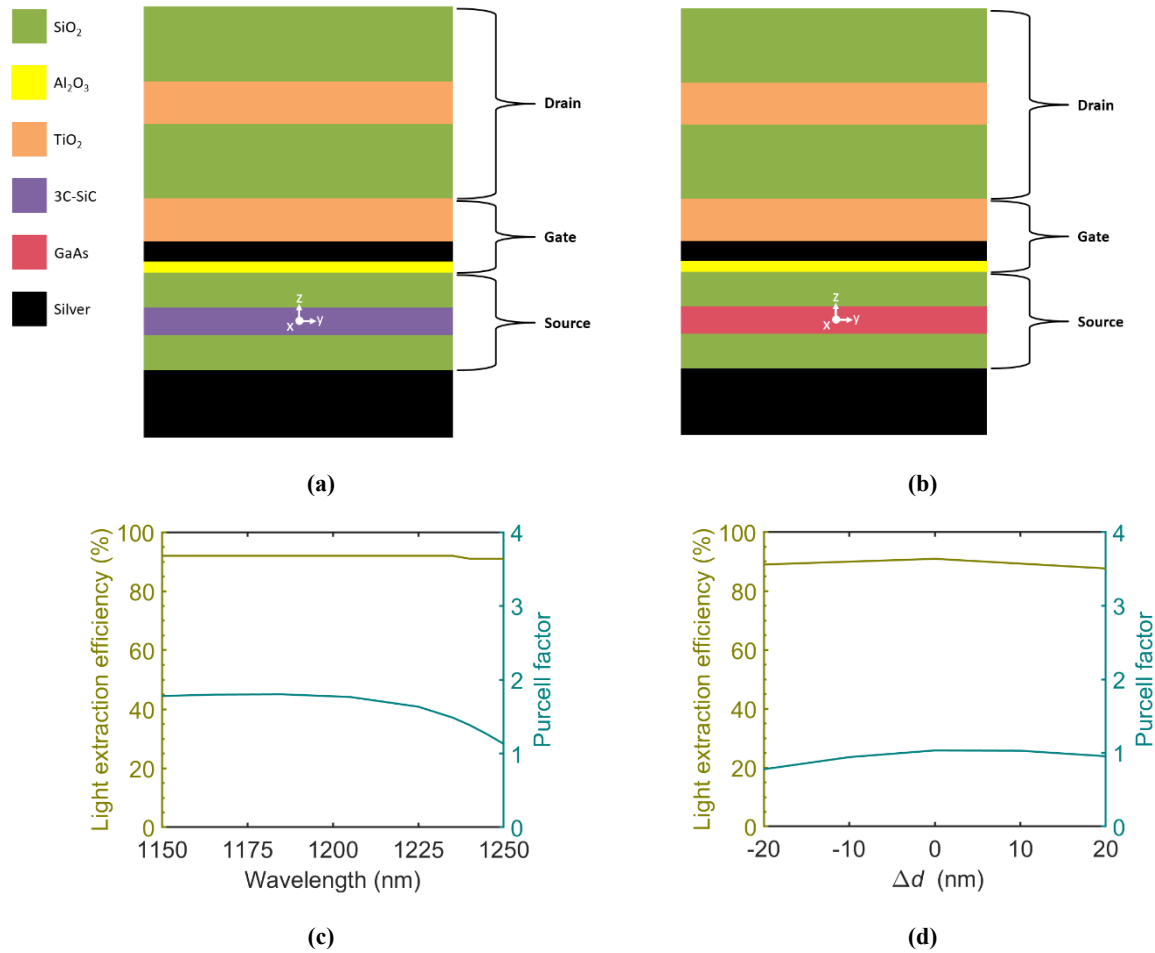


Fig. 4.9 Near-infrared emitters (free-space emission). (a) A 3C-SiC thin film in a real-Source trench-Gate configuration; dimensions: [Forward-bias: (100 nm)], [Source: (114 nm, 50 nm, 114 nm)], [Gate: (14 nm, 25 nm, 115 nm)], [Drain: (200 nm, 111 nm, 200 nm)]. (b) A QD embedded in a GaAs thin film, in a real-Source trench-Gate configuration; dimensions: [Forward-bias: (100 nm)], [Source: (30 nm, 50 nm, 30 nm)], [Gate: (11 nm, 35 nm, 81 nm)], [Drain: (149 nm, 80 nm, 149 nm)]. (c) The free-space LEE and the Purcell factor as a function of the emission wavelength. (d) The free-space LEE and the Purcell factor as a function of the emitter position displacement from the center of the Source. The QD emits at $\lambda = 950$ nm.

Before going through the next example on semiconductor Quantum Dots (QDs), it makes sense to first identify the relevant state of the art in this regard; namely the GaAs planar antenna system from [ch.2], [8]. It should be noted that the reported $\sim 86\%$ LEE, utilizing SiO₂ intermediate layers, considers emission through a semi-infinite glass collection medium, with the refractive index of GaAs reading $n = 3.539$. When switching to free-space emission, it starts to get tricky, and the antenna's free-space LEE drops to 80%. With that in mind; on the

other hand, when applying the TRANSGUIDE to the aforementioned system, considering the configuration shown in Fig. 4.9(b), different behaviors come into play. The corresponding emitter position dependency plot shown in Fig. 4.9(d) demonstrates how, the free-space LEE can hit 91% towards the center of the Source, accompanied with Purcell factor values on the order of 1.

The reported LEE values, whether for 3C-SiC or GaAs, consider free-space emission. In an appropriate material packaging, the LEE is likely to pick up additional percents. With these figures in mind, one can already vision the enhanced brightness and radiation profile that await LEDs.

Low-refractive index active media

So far, all previous highlights have been on high-refractive index light emitting platforms. The TRANSGUIDE also holds promises for low-refractive index material-based applications, such as biosensing and Organic Light Emitting Diodes (OLEDs). Hereunder, I give an idea of what you can expect in this regard.

Consider the dibenzoterrylene (DBT) molecules system reported in [10]. The corresponding authors conclude that their planar antenna approach is strongly limited by SPP losses; that said, it should not come as a surprise that their antenna's free-space LEE is no more than 60%. By reconfiguring their antenna system into a TRANSGUIDE, SPP losses will no longer be a concern.

The TRANSGUIDE configuration shown in Fig. 4.10(a), takes into account the same system parameters as in [10]: namely, an $n = 1.5$ anthracene (Ac) layer containing DBT molecules emitting at 785 nm. With the molecules' dipole orientation parallel to the Gate, the LEE exceeds 93% for free-space emission, and 97% for emission through glass. The radiated power is funneled into a single-lobe, shown in Fig. 4.10(b), with the RHA on the order of 19° and 14° , respectively.

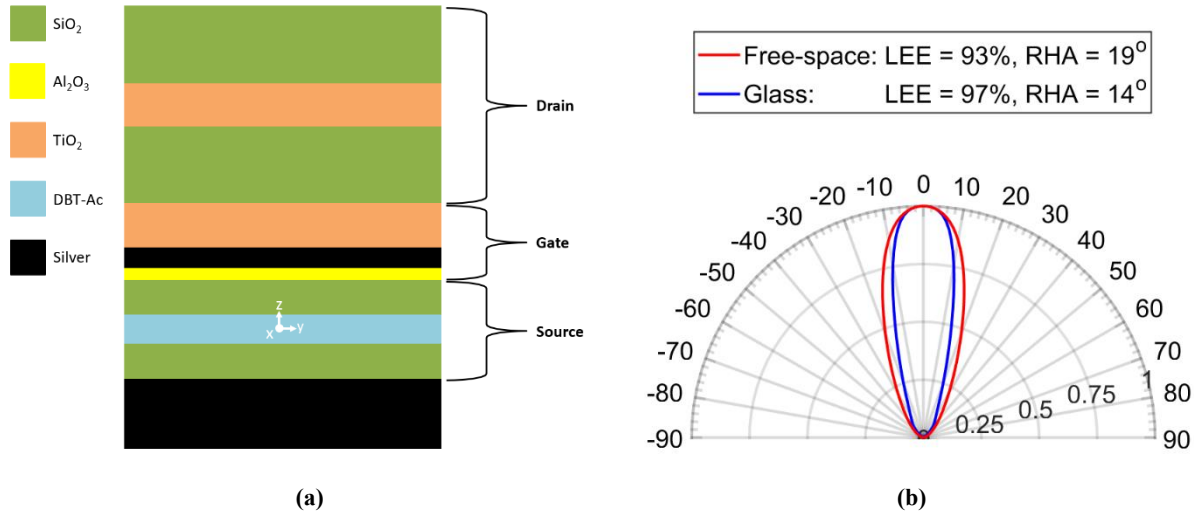


Fig. 4.10 DBT molecules emitting at 785 nm. (a) DBT-Ac layer in a real-Source trench-Gate configuration; dimensions: [Forward-bias: (100 nm)], [Source: (78 nm, 50 nm, 78 nm)], [Gate: (17 nm, 30 nm, 68 nm)], [Drain: (120 nm, 63 nm, 120 nm)]. These dimensions apply explicitly to free-space emission. (b) Normalized radiation pattern polar plot, free-space vs glass ($n = 1.5$) background. Legend: corresponding light extraction efficiency and radiation half angle.

Overall, we are already very close to a 100% LEE, and we should be able to come even closer.

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Chapter 5

Conclusion

We have demonstrated two simple strategies to overcome the poor light emission brightness in any material, irrespective of its refractive index value. In a completely flat configuration, and just with several ultrathin layers, the light extraction and the directionality efficiencies can simultaneously be brought to unprecedented values. The flexibility of the schemes, offering different operational mode regimes, the applicability to different materials at different wavelengths, and the robustness against technological imperfections, hold promises for quantum technologies and also for many light emission applications such as LEDs.

We have also shed light on the schemes' reciprocity and prospects for enhanced light absorption in biosensing and IR detection.

Even though the potentials of the TRANSGUIDE have been revealed so far on a theoretical level, our positive experimental proof-of-concept for the interlayered planar Yagi-Uda antenna serves for the TRANSGUIDE as well.

Diamond is a tough material to handle. In the early days of this research work, single crystal diamond membranes with thicknesses on the order of tens of nanometers were not attainable. This explains why we could not pick up meaningful quantum light signatures from our proof-of-concept demonstrations. However, our work has been followed upon, where a research group at the University of Chicago has been able to readily produce transferable quantum-grade diamond membranes within the thickness range of our work [1]. This achievement paves the way for further integration of diamond in quantum applications.

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Appendix

Two European patent disclosures enclosed.

Status of both patents:

Granted – no opposition filed against – enforced

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(54) **DEVICE FOR BEAMING OF LIGHT**

VORRICHTUNG ZUR BÜNDELUNG VON LICHT

DISPOSITIF POUR CONCENTRER LA LUMIÈRE

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(73) Proprietor: **Universität Siegen**
57076 Siegen (DE)

(72) Inventors:
• **Elmitwalli, Hossam**
57072 Siegen (DE)

• **Agio, Mario**
570724 Siegen (DE)

(74) Representative: **Michalski Hüttermann & Partner**
Patentanwälte mbB
Speditionstraße 21
40221 Düsseldorf (DE)

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Description

[0001] The present invention relates to a device for beaming of light emitted by light sources. More in detail, the present invention relates to a device with an improved antenna configuration of a planar optical antenna which allows beaming light emitted from various light sources, including light-emitting devices (LEDs), fluorescent markers and single-photon sources.

[0002] Light emission and light absorption are two basic processes at the core of many important applications, such as lighting, sensing and telecom. Despite the enormous progress, designing, manufacturing and testing, nanophotonics concepts that interface tiny sensing volumes to low NA (Numerical Aperture) collection optics (e.g. optical fibers), still require a substantial research effort.

[0003] There have been several interesting proposals to improve the collection efficiency of nanoscale light emitters, although only recently the attention has moved to concepts inherited from antenna theory. One of the most exciting advances in nano-optics has been the concept, design and application of optical antennas, or nano-antennas, which represent the most sophisticated tool to enhance and direct light emission from a nanoscale source. The amount of research activity on optical antennas has grown very rapidly in the last few years, and currently spans a broad range of areas, including optics, physics, chemistry, electrical engineering, biology, and medicine, to cite a few.

[0004] In the research to achieve the above-mentioned object, the goal of the inventors has been the design, manufacture and experimental investigation of optical antennas that are able to channel molecular fluorescence into a narrow radiation cone. This was thought in order to allow efficient collection by a fibre probe placed in the far field, hence opening the pathway to single-molecule detection with low-NA optics. Optical antennas offer great flexibility in engineering the radiation pattern. From the prior art devices for beaming and collection of light emitted by light sources with a planar structure that beams the emission of single molecules are known.

[0005] CN 104 101 588 A discloses an integrated seawater chlorophyll microfluidic chip sensor capable of enhancing the anti-interference ability and improving the fluorescence detection efficiency adopts the technical scheme that the integrated seawater chlorophyll microfluidic chip sensor is characterized by consisting of a Si-PIN detector (1), a 6H-SiC/TTO/SiO₂ layer (3), a reflecting and welding layer (4), an LED chip (5), a glass plate (6), a PDMS microfluidic channel (7) and a coated reflector (8), wherein the Si-PIN detector (1), the 6H-SiC/ITO/SiO₂ layer (3), the reflecting and welding layer (4), the LED chip (5), the glass plate (6), the PDMS microfluidic channel (7) and the coated reflector (8) are sequentially connected from bottom to top. The invention also discloses a method for manufacturing integrated seawater chlorophyll microfluidic chip sensor.

[0006] US 2006/231781 A1 discloses a radiation image information detecting panel. A laminate comprises a stimuable phosphor layer, which is capable of storing radiation image information, and which is capable of emitting light of an intensity proportional to the radiation image information when being exposed to secondary stimulating rays, a response speed converting fluorescent substance layer, which is capable of converting the light emitted by the stimuable phosphor layer into light having a life time longer than a light emission life time of the light emitted by the stimuable phosphor layer, and a photo-conductor layer, which is capable of exhibiting electrical conductivity when being exposed to the light obtained from the conversion performed by the response speed converting fluorescent substance layer. The laminate and an electroluminescent layer, which is capable of emitting the secondary stimulating rays with voltage application, are overlaid one upon the other and combined with each other into an integral body.

[0007] WO 2016/166130 for example discloses a device constituted by a planar optical antenna which allows to beam and collect light emitted from various light sources. This device relies on the concept of an optical Yagi-Uda antenna, where reflector and director are implemented using thin metal films. A dipole emitter positioned a distance d_1 away from a metallic layer, named reflector, induces an image dipole. To obtain further directionality a thin metallic layer in the radiation direction, named director, at a distance d_2 away from the dipole is positioned. However, the efficiency of such devices could still be improved. In particular, the excitation of surface plasmon polaritons (SPPs) at metal-dielectric interfaces represents a major loss channel, which limits the outcoupling efficiency.

[0008] Therefore, the object of the present invention is to provide a device for beaming of light emitted by a light source with an enhanced antenna configuration of a planar optical antenna to improve outcoupling efficiency and directionality.

[0009] This object is addressed by the subject matter of claim 1. Preferred embodiments are described in the sub claims.

[0010] According to the disclosure a device for beaming of light emitted by a light source, the device comprising a reflector layer and a director layer, wherein a dipole emitter or an absorber is positioned at a distance d_1 away from the reflector layer, wherein the director layer is positioned in the radiation direction of the dipole emitter or in the absorption direction of the absorber, respectively, wherein the director layer is positioned at a distance d_2 away from the dipole emitter or the absorber, respectively, between a medium hosting the dipole emitter or the absorber, respectively, together with a collection medium, characterized in that between the reflector layer and the host medium a first intermediate layer is provided and between the host medium and the director layer a second intermediate layer is provided.

[0011] By including intermediate layers to space the

host medium apart from the reflector or director, respectively, the excitation of SPP modes can be suppressed. The suppression of the excitation of the SPP modes leads directly to an increase in the outcoupling efficiency and an improved directionality. Not only dipole emitters but also absorbers for the collection of light can be placed in the host medium. When one or more absorbers are placed in the host medium light sources emitting at wavelength λ are corresponding to the one or more of the absorbers.

[0012] Advantageously, d_1 is chosen within the range $\lambda/(6n) \leq d_1 \leq \lambda/(4n)$, where λ is the emission or absorption wavelength and n is the effective refractive index of medium composed by the host and the first intermediate layer. It has been found that an especially preferred working distance for the dipole emitter or absorber from the director layer is in the range $\lambda/(6n) \leq d_2 \leq \lambda/(4n)$, where now n is the effective refractive index of the medium composed by the host and the second intermediate layer.

[0013] According to one preferred embodiment of the invention the refractive indices of the first intermediate layer and second intermediate layer are both smaller than the refractive index of the host medium. The inclusion of two intermediate layers with a refractive index smaller than the refractive index of the host medium can significantly suppress the coupling to SPP modes, which are responsible for limitation on the outcoupling efficiency. The refractive index of the first intermediate layer and the refractive index of the second intermediate layer can be but do not have to be equal to each other. Moreover, these layers can be composite media or multilayer structures as long as their effective refractive index is smaller than that of the host medium. The host medium and the collection medium can also be composite media or multilayer structures.

[0014] According to another preferred embodiment of the invention a top layer is provided between the director layer and the collection medium. The additional top layer may help to further improve the outcoupling efficiency by suppressing the role of SPP in the director and the directionality of the device by narrowing the emission pattern. The top layer plays the role of an integrated flat lens and of the intermediate layer. Therefore the top layer is able to steer an optical ray by a large amount in order to convert a wide radiation pattern into a narrow cone and further suppresses the role of SPP in the director. For example a radiation pattern with a narrow cone is more favourable for coupling light to an optical system with circular symmetry, such as an optical fibre. Moreover, the top can be composite media or multilayer structures as long as their effective refractive index is smaller than that of the collection medium.

[0015] Preferably the refractive index of the top layer is smaller than the refractive index of the collection medium. A further improvement in the outcoupling efficiency and in the directionality, with an even narrower radiation pattern, can be attained by the smaller refractive index of the top layer compared to refractive index of the col-

lection medium.

[0016] Preferably the thickness of the first intermediate layer is chosen in the range from $\lambda/(50n)$ - corresponding to about 10 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(5n)$ - corresponding to about 100 nm for $n = 1.5$ and $\lambda = 738$ nm - preferably from $\lambda/(25n)$ - corresponding to about 20 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(6n)$ - corresponding to about 80 nm for $n = 1.5$ and $\lambda = 738$ nm - and more preferably from $\lambda/(15n)$ - corresponding to about 30 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(10n)$ - corresponding to about 50 nm for $n = 1.5$ and $\lambda = 738$ nm - where n is the effective refractive index of the first intermediate layer. Further enhancements can be achieved with judicious choice of the thickness of the first intermediate layer.

[0017] Preferably the thickness of the second intermediate layer thickness is chosen in the range from $\lambda/(15n)$ - corresponding to about 30 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(4n)$ - corresponding to about 120 nm for $n = 1.5$ and $\lambda = 738$ nm - preferably from $\lambda/(12n)$ - corresponding to about 40 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(5n)$ - corresponding to about 100 nm for $n = 1.5$ and $\lambda = 738$ nm - and more preferably from $\lambda/(10n)$ - corresponding to about 50 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(7n)$ - corresponding to about 70 nm for $n = 1.5$ and $\lambda = 738$ nm - where n is the effective refractive index of the second intermediate layer. Further enhancements can be achieved with judicious choice of the thickness of the second intermediate layer.

[0018] Preferably the thickness of the host medium is chosen in the range from $\lambda/(50n)$ - corresponding to about 10 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(4n)$ - corresponding to about 120 nm for $n = 1.5$ and $\lambda = 738$ nm - preferably from $\lambda/(25n)$ - corresponding to about 20 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(6n)$ - corresponding to about 80 nm for $n = 1.5$ and $\lambda = 738$ nm - and more preferably from $\lambda/(15n)$ - corresponding to about 30 nm for $n = 1.5$ and $\lambda = 738$ nm - to $\lambda/(10n)$ - corresponding to about 50 nm for $n = 1.5$ and $\lambda = 738$ nm - where n is the effective refractive index of the host layer. Further enhancements can be achieved with judicious choice of the thickness of the host layer.

[0019] According to one preferred embodiment of the invention the host medium is made from diamond or GaAs. Further enhancements can be achieved with judicious choice of the material for the host medium.

[0020] According to another preferred embodiment of the invention at least one out of the reflector layer or director layer is made out from aluminium, copper, silver, gold or a combination of thereof.

[0021] According to one preferred embodiment of the invention at least one out of the first intermediate layer or the second intermediate layer is made out from silica, ITO (indium tin oxide) or is an air gap.

[0022] According to another aspect of the invention the top layer is made from silica aerogel or is an air gap.

[0023] According to one aspect of the invention the collection medium is made from glass.

[0024] These and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

[0025] In the drawings:

Fig. 1 shows a cross-sectional view of a layer structure of an embodiment of the present invention; and

Fig. 2 shows a cross-sectional view of a layer structure of another preferred embodiment of the present invention.

[0026] Fig. 1 shows a cross-sectional view of a layer structure 1 in accordance with a preferred embodiment of the present invention. A dipole emitter 5 is positioned at a distance d_1 away from a reflector layer 3 in an host medium 2. The dipole emitter 5 induces an image dipole. When the two dipoles radiate with an appropriate phase delay, they give rise to a beaming effect in one direction.

[0027] Further directionality is obtained by positioning a director layer 4 in the radiation direction at a distance d_2 away from the dipole emitter 5. A horizontal arrow indicates the Hertzian dipole in the host medium 2 placed at a distance d_1 and d_2 from reflector layer 3 and director layer 4, respectively. A first intermediate layer 8 contiguous to the reflector layer 3 and a second intermediate layer 9 contiguous to the director layer 4 space the host medium 2 apart from the reflector layer 3 and director layer 4. The inclusion of the two intermediate layers 8, 9 made e.g. of glass can significantly suppress the coupling to SPP modes and increase the outcoupling efficiency and the directionality.

[0028] Fig. 2 shows a cross-sectional view of a layer structure 1 of another preferred embodiment of the present invention. The cross-sectional view is similar to the view of Fig. 1 whereby an additional top layer 11 spaces the director layer 4 from the collection medium 10. By adding an additional top layer between the director layer 4 and the collection medium 10 the outcoupling efficiency and the directionality of the device can be further improved by suppressing the role of SPP and by narrowing the emission pattern.

[0029] While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description are to be considered illustrative or exemplary and not restrictive; the invention is not limited to the disclosed embodiments.

[0030] Other variations to be disclosed embodiments can be understood and effected by those skilled in the art in practicing the claimed invention, from a study of the drawings, and the description within the scope of the appended claims. In the claims, the word "comprising" does not exclude other elements or steps, and the indefinite article "a" or "an" does not exclude a plurality. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

Any reference signs in the claims should not be construed as limiting scope.

List of reference signs

[0031]

- | | |
|----|---------------------------|
| 1 | layer structure |
| 2 | host medium |
| 3 | reflector layer |
| 4 | director layer |
| 5 | dipole emitter |
| 8 | first intermediate layer |
| 9 | second intermediate layer |
| 10 | collection medium |
| 11 | top layer |

Claims

1. Device for beaming of light, the device comprising a planar optical antenna structure, wherein the planar optical antenna structure comprises from top to bottom in the following order at least a collection medium (10) for collecting light from a director layer (4), a director layer (4) for obtaining directionality of the beamed light, a host medium (2), a reflector layer (3),

wherein a dipole light emitter (5) is positioned in the host medium (2) at a distance d_1 away from the reflector layer (3),

wherein the director layer (4) is positioned in the radiation direction of the dipole light emitter (5), wherein the director layer (4) is positioned at a distance d_2 away from the dipole light emitter (5), **characterized in that**

between the reflector layer (3) and the host medium (2) a first intermediate layer (8) is provided and

between the host medium (2) and the director layer (4) a second intermediate layer (9) is provided.

2. Device according to claim 1, **characterized in that** d_1 (6) is chosen within the range $\lambda/(6n) \leq d_1 \leq \lambda/(4n)$, where λ is the emission wavelength and n is the refractive index of host medium (2).
3. Device according to any previous claim, **characterized in that** the refractive indices of the first intermediate layer (8) and second intermediate layer (9) are both smaller than the refractive index of the host medium (2).
4. Device according to any previous claim, **characterized in that** between the director layer (4) and the collection medium (10) a top layer (11) is provided.

5. Device according to claim 4, **characterized in that** the refractive index of the top layer (11) is smaller than the refractive index of the collection medium (10). 5
6. Device according to any previous claim, **characterized in that** the thickness of the first intermediate layer (8) is chosen in the range from $\lambda/(50n)$ to $\lambda/(5n)$, where n is the effective refractive index of the first intermediate layer. 10
7. Device according to any previous claim, **characterized in that** the thickness of the second intermediate layer (9) is chosen in the range from $\lambda/(15n)$ to $\lambda/(4n)$, where n is the effective refractive index of the second intermediate layer. 15
8. Device according to any previous claim, **characterized in that** the thickness of the host medium (2) is chosen in the range $\lambda/(50n)$ (corresponding to about 10 nm for $n = 1.5$ and $\lambda = 738$ nm) to $\lambda/(4n)$ (corresponding to about 120 nm for $n = 1.5$ and $\lambda = 738$ nm), where n is the effective refractive index of the host layer. 20
9. Device according to any previous claim, **characterized in that** the host medium (2) is made from diamond or GaAs. 25
10. Device according to any previous claim, **characterized in that** at least one out of the reflector layer (3) or director layer (4) is made from aluminium, copper, silver, gold or a combination thereof. 30
11. Device according to any previous claim, **characterized in that** at least one out of the first intermediate layer (8) or the second intermediate layer (9) is made from silica, indium tin oxide or is an air gap. 35
12. Device according to any previous claim, **characterized in that** the top layer (11) is made from silica aerogel or is an air gap. 40
13. Device according to any previous claim, **characterized in that** the collection medium (10) is made from glass. 45

Patentansprüche

1. Vorrichtung zum Abstrahlen von Licht, wobei die Vorrichtung die Struktur einer planaren optischen Antenne aufweist, wobei die Struktur einer planaren optischen Antenne in der folgenden Reihenfolge von oben nach unten mindestens ein Sammelmedium (10) zum Sammeln von Licht von einer Richtschicht (4), eine Richtschicht (4) zum Erhalten eines Richtfaktors für das abgestrahlte Licht, ein Wirtsmedium 50

(2) und eine Reflektorschicht (3) aufweist,

wobei ein Dipol-Lichtemitter (5) im Wirtsmedium (2) in einem Abstand d_1 von der Reflektorschicht (3) angeordnet ist,

wobei die Richtschicht (4) in der Strahlungsrichtung des Dipol-Lichtemitters (5) angeordnet ist, wobei die Richtschicht (4) in einem Abstand d_2 vom Dipol-Lichtemitter (5) angeordnet ist,

dadurch gekennzeichnet, dass zwischen der Reflektorschicht (3) und dem Wirtsmedium (2) eine erste Zwischenschicht (8) angeordnet ist; und

zwischen dem Wirtsmedium (2) und der Richtschicht (4) eine zweite Zwischenschicht (9) angeordnet ist.

2. Vorrichtung nach Anspruch 1, **dadurch gekennzeichnet, dass** d_1 (6) im Bereich $\lambda/(6n) \leq d_1 \leq \lambda/(4n)$ gewählt ist, wobei λ die Emissionswellenlänge und n den Brechungsindex des Wirtsmediums (2) bezeichnen. 25

3. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Brechungsindizes der ersten Zwischenschicht (8) und der zweiten Zwischenschicht (9) beide kleiner sind als der Brechungsindex des Wirtsmediums (2). 30

4. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** zwischen der Richtschicht (4) und dem Sammelmedium (10) eine Deckschicht (11) vorgesehen ist. 35

5. Vorrichtung nach Anspruch 4, **dadurch gekennzeichnet, dass** der Brechungsindex der Deckschicht (11) kleiner ist als der Brechungsindex des Sammelmediums (10). 40

6. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Dicke der ersten Zwischenschicht (8) im Bereich von $\lambda/(50n)$ bis $\lambda/(5n)$ gewählt ist, wobei n der effektive Brechungsindex der ersten Zwischenschicht ist. 45

7. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Dicke der zweiten Zwischenschicht (9) im Bereich von $\lambda/(15n)$ bis $\lambda/(4n)$ gewählt ist, wobei n der effektive Brechungsindex der zweiten Zwischenschicht ist. 50

8. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Dicke des Wirtsmediums (2) im Bereich $\lambda/(50n)$ (entsprechend etwa 10 nm für $n = 1,5$ und $\lambda = 738$ nm) bis $\lambda/(4n)$ (entsprechend etwa 120 nm für $n = 1,5$ und $\lambda = 738$ nm) gewählt ist, wobei n der effektive Brechungsindex des Wirtsmediums ist. 55

9. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** das WirtsmEDIUM (2) aus Diamant oder GaAs besteht.
10. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** mindestens eine Schicht unter der Reflektorschicht (3) und der Richtschicht (4) aus Aluminium, Kupfer, Silber, Gold oder einer Kombination davon hergestellt ist.
11. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** mindestens eine Schicht unter der ersten Zwischenschicht (8) und der zweiten Zwischenschicht (9) aus Siliziumdioxid oder Indiumzinnoxid hergestellt ist oder ein Luftspalt ist.
12. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** die Deckschicht (11) aus Silica-Aerogel hergestellt ist oder ein Luftspalt ist.
13. Vorrichtung nach einem der vorhergehenden Ansprüche, **dadurch gekennzeichnet, dass** das Sammelmedium (10) aus Glas hergestellt ist.

Revendications

1. Dispositif de formation de faisceau de lumière, le dispositif comprenant une structure d'antenne optique plane, où la structure d'antenne optique plane comprend, du haut vers le bas, dans l'ordre suivant, au moins un milieu de collecte (10) permettant de collecter de la lumière provenant d'une couche directrice (4), une couche directrice (4) permettant d'obtenir une directivité de la lumière en faisceau, un milieu hôte (2), une couche réfléchissante (3),
- où un émetteur de lumière dipôle (5) est positionné dans le milieu hôte (2) à une distance d_1 éloignée par rapport à la couche réfléchissante (3),
- où la couche directrice (4) est positionnée dans la direction de rayonnement de l'émetteur de lumière dipôle (5),
- où la couche directrice (4) est positionnée à une distance d_2 éloignée par rapport à l'émetteur de lumière dipôle (5),
- caractérisé en ce**
- qu'une première couche intermédiaire (8) est mise en place entre la couche réfléchissante (3) et le milieu hôte (2) et**
- qu'une deuxième couche intermédiaire (9) est mise en place entre le milieu hôte (2) et la couche directrice (4).**
2. Dispositif selon la revendication 1, **caractérisé en**

ce que d_1 (6) est choisie dans la plage $\lambda/(6n) \leq d_1 \leq \lambda/(4n)$, où λ est la longueur d'onde d'émission et n est l'indice de réfraction du milieu hôte (2).

3. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** les indices de réfraction de la première couche intermédiaire (8) et de la deuxième couche intermédiaire (9) sont tous deux plus petits que l'indice de réfraction du milieu hôte (2).
4. Dispositif selon une quelconque revendication précédente, **caractérisé en ce qu'une** couche de recouvrement (11) est mise en place entre la couche directrice (4) et le milieu de collecte (10).
5. Dispositif selon la revendication 4, **caractérisé en ce que** l'indice de réfraction de la couche de recouvrement (11) est plus petit que l'indice de réfraction du milieu de collecte (10).
6. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** l'épaisseur de la première couche intermédiaire (8) est choisie dans la plage de $\lambda/(50n)$ à $\lambda/(5n)$, où n est l'indice de réfraction effectif de la première couche intermédiaire.
7. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** l'épaisseur de la deuxième couche intermédiaire (9) est choisie dans la plage de $\lambda/(15n)$ à $\lambda/(4n)$, où n est l'indice de réfraction effectif de la deuxième couche intermédiaire.
8. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** l'épaisseur du milieu hôte (2) est choisie dans la plage de $\lambda/(50n)$ (correspondant à environ 10 nm pour $n = 1,5$ et $\lambda = 738$ nm) à $\lambda/(4n)$ (correspondant à environ 120 nm pour $n = 1,5$ et $\lambda = 738$ nm), où n est l'indice de réfraction effectif du milieu hôte.
9. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** le milieu hôte (2) est fabriqué à partir de diamant ou de GaAs.
10. Dispositif selon une quelconque revendication précédente, **caractérisé en ce qu'au moins une** couche parmi la couche réfléchissante (3) ou la couche directrice (4) est fabriquée en aluminium, cuivre, argent, or ou dans une combinaison de ceux-ci.
11. Dispositif selon une quelconque revendication précédente, **caractérisé en ce qu'au moins une** couche parmi la première couche intermédiaire (8) ou la deuxième couche intermédiaire (9) est fabriquée à base de silice, d'oxyde d'étain et d'indium, ou est un

entrefer.

12. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** la couche de recouvrement (11) est fabriquée à base de silice ou est un entrefer. 5
13. Dispositif selon une quelconque revendication précédente, **caractérisé en ce que** le milieu de collecte (10) est fabriqué en verre. 10

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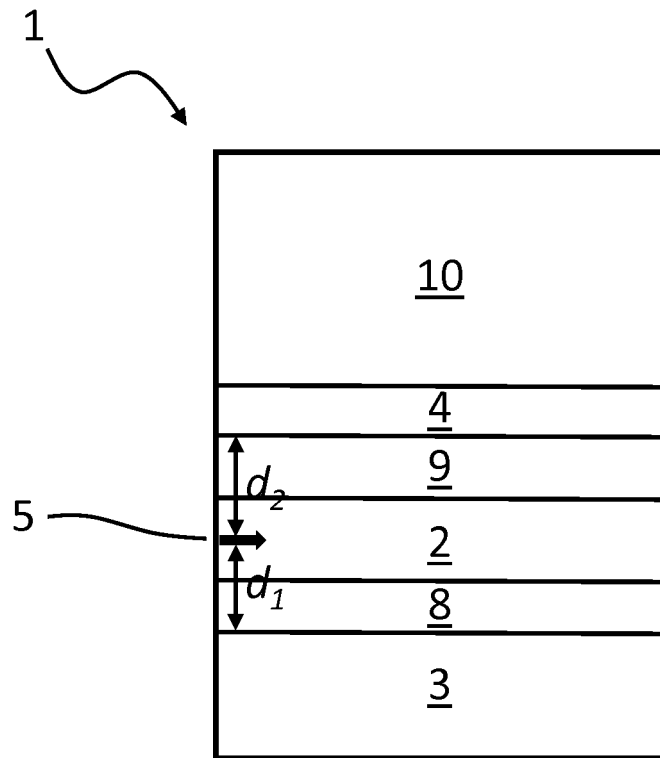


Fig. 1

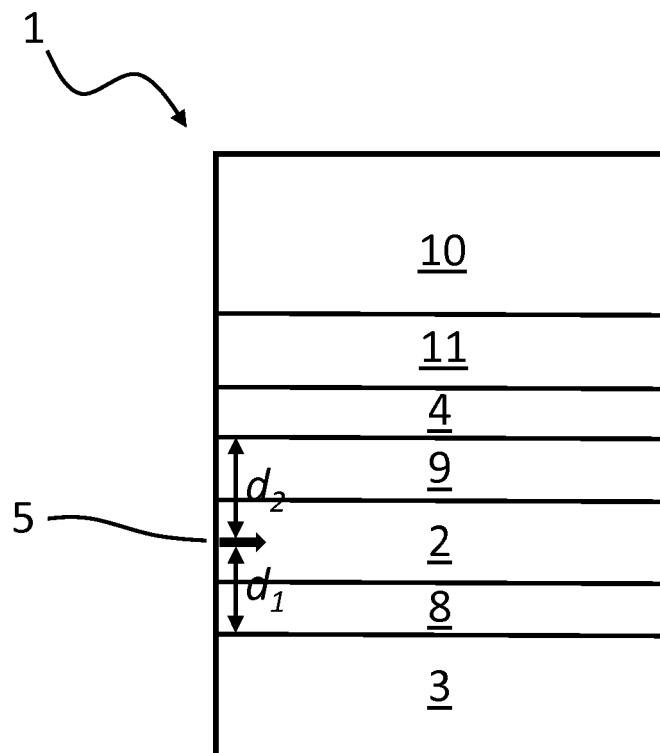


Fig. 2

REFERENCES CITED IN THE DESCRIPTION

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(54) **DEVICE FOR ULTRA-BRIGHT DIRECTIONAL LIGHT EMISSION**

VORRICHTUNG ZUR ULTRAHELLEN GERICHTETEN LICHTEMISSION

DISPOSITIF D'ÉMISSION DE LUMIÈRE DIRECTIONNELLE ULTRA-BRILLANTE

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(73) Proprietors:
• **Elmitwalli (Galal), Hossam**
50825 Köln (DE)
• **Samir, Ahmed**
El Nozha, Cairo 11361 (EG)

(72) Inventor: **Elmitwalli (Galal), Hossam**
50825 Köln (DE)

(74) Representative: **Prüfer & Partner mbB**
Patentanwälte · Rechtsanwälte
Sohnckestraße 12
81479 München (DE)

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Description**Technical problem background**

[0001] Light extraction and directional emission, especially from large-refractive index materials, is a bottleneck for many light emission applications such as Light Emitting Diodes (LED), Lasers, and Single Photon Sources (SPS). A significant amount of light is lost inside the structure of the light emitting device, whether due to Total Internal Reflection (TIR) or due to the presence of metallic elements.

[0002] Consider the scenario depicted in Fig. 1, where a light source (101) is embedded in an active medium (102) having a refractive index larger than 1. The designation "active medium" defines the medium that hosts the light source. The collection medium (100) is free-space with a refractive index equal to 1. For the sake of simplicity, consider that the light source (101) emits the three light rays: (103), (104), and (105). Apparently, the rays undergo different behaviors in response to their different projections. The light ray (103) experiences no modulation, since it is incident normal to the interface between the mediums (102)-(100). The light ray (104) is refracted, and diverges with an angle (106). The light ray (105) is incident at the interface between the mediums (102)-(100) with an angle larger than the critical angle, and undergoes TIR. The light ray (105) is trapped inside the active medium (102), and accordingly, the brightness (i.e. the efficiency) of the light source (101), observed from the collection medium (100), is reduced. The light ray (104) fans out away from the path of the light ray (103), and gives rise to an emission beam with a large divergence angle (i.e. poor collimation). Typically, large numerical aperture optics would be required to handle such beam profile.

[0003] The light extraction efficiency can be defined as: the amount of light that is radiated into the collection medium, divided by the total amount of light that is emitted by the light source within the active medium.

[0004] In the example of Fig. 1, this translates into:

$$\text{Light extraction efficiency} = \frac{\text{ray}(103) + \text{ray}(104)}{\text{ray}(103) + \text{ray}(104) + \text{ray}(105)}$$

[0005] In the relationship above, and by considering the case where the collection medium (100) is free-space, the light extraction efficiency is further defined as the "free-space light extraction". This definition is more specific, and will be recalled often throughout the context of this text since the focus of this patent application is more on free-space emission applications.

[0006] With the simple illustration of Fig. 1 in mind, the problem becomes more challenging when the refractive index discrepancy between the active medium (102) and the collection medium (100) becomes large. According to Snell's law; ray divergence and TIR light trapping are proportional to the refractive index of the active medium (102). High-refractive index materials, such as diamond and semiconductors, are in the heart of many classical-light and quantum-light emitting devices. Thinking of LEDs, lasers, and SPSs; many photonic applications require that the light is emitted into free-space with very high brightness and within a very narrow numerical aperture cone.

[0007] There have been numerous efforts to enhance the light extraction efficiency of light sources. The trend has been to incorporate nano-structures, taking advantage of the latest advances in nanotechnology.

[0008] However; to date, the reported results are not yet to full satisfaction, and the proposed solutions are quite sophisticated and just make the whole process more complex and costly. Furthermore, the light radiation pattern is unavoidably compromised (i.e. does not have a uniform pattern and develops very broad radiation angles and side-lobes).

[0009] A practical solution to this longstanding optical problem would be one that fulfills the following criteria:

1. A near 100% free-space light extraction efficiency.
2. The radiated light should be highly collimated, directional, and single-lobed.
3. The light emitting device structure should be simple and free of any complex architectures, with large tolerance margins to accommodate technological imperfections.
4. The proposed solution should be scalable and applicable to different materials and wavelengths.

[0010] These four requirements, as a whole, are very challenging and have never been met before. However; there have been some interesting trials, where some of the four requirements were partially fulfilled. In the next section, the relevant prior art in this regard is reviewed.

Prior art review

[0011] US 2011/0080738 A1 discloses a light-emitting device having a transparent substrate adjacent to a light-emitting body. The light-emitting substrate has a surface structure defined by dividing the surface into a plurality of linear segments

of width w which are inclined so as to extend in a specific direction in a plane of the surface. Such linear segments are divided into minute regions, each of which is formed by a raised or recessed portion formed in the surface of the transparent substrate. Thereby, the light extraction efficiency can be greatly improved in that extraction of light rays whose incidence angles are greater than the critical angle can be repeatedly realized.

[0012] US 2016/0079566 A1 describes a surface light emitting element including a light emitting layer that emits light, a first electrode layer that is provided on the side of the light emitting layer from which the light is extracted and allows the light that has been emitted by the light emitting layer to pass through, a second electrode layer that is provided on the side of the light emitting layer from which light is not extracted, a light scattering layer that is provided on the side of the first electrode layer opposite to the side on which the light emitting layer is positioned, and a transparent substrate that is provided on the side of the light scattering layer opposite to the side on which the light emitting layer is positioned. In particular, a conductive material in which the real part of a complex dielectric constant is negative is used in the first electrode layer.

Prior art: WO2016166130

[0013] The journal publication [1] covers in details the scientific background for this pending patent application.

[0014] Fig. 2a: It has been suggested in WO2016166130 and in [1] that a Hertzian horizontal dipole emitter (201), hosted in an active medium (202), when placed in close proximity to a highly reflective metal layer (203), an image (204) of the dipole is induced in the metal layer (203).

[0015] Fig. 2b: When the distance d (205) from the dipole emitter (201) to the interface between the layers (202)-(203) is within the limit:

$$\lambda/(6n) < d < \lambda/(4n)$$

[0016] [Where λ is the wavelength of the light emitted by the dipole emitter (201), and n is the refractive index of the active medium (202)]

[0017] Both the dipole emitter (201) and its image (204) radiate in phase; and their corresponding electromagnetic radiations, (206) and (207) respectively, give rise to constructive interference in the far-field spot (208) located in the collection medium (200). This concept has been referred to as dipole-image interference.

[0018] Fig. 2c: By further placing a semi-transparent metal layer (209) between the collection medium (200) and the active medium (202), a second image (210) of the dipole emitter (201) is induced in the semi-transparent metal layer (209). By adjusting the thickness of the active medium (202), the electromagnetic radiation (211) from the second dipole image (210) can be constructively interfered with the electromagnetic radiations (206) and (207). As a result, the radiation pattern, observed from the collection medium (200), develops narrower radiation angles. The configuration with the reflector (203), the active medium (202), and the semi-transparent metal (209) has been conceived by the corresponding inventors-authors as a planar antenna.

[0019] This prior art has severe drawbacks:

1. The light extraction efficiency is highly limited by Surface Plasmon Polariton (SPP) losses at the interfaces between the layers: (202)-(203), (202)-(209), and (209)-(200) [See illustrations (212), (213), and (214) in Fig. 3a.].
2. This approach is not applicable to high-refractive index materials, for example diamond and semiconductors. The reason being, SPP losses are directly proportional to the refractive index of the active medium (202).

[0020] These drawbacks have been conditionally resolved in the successive prior art WO002018096097.

Prior art: WO002018096097

[0021] The journal publication [2] covers in details the theoretical background for this pending patent application. The related experimental results are partially available in the journal preprint [3].

[0022] This prior art also applies the dipole-image interference concept, or the so-called planar antenna, similar to the previous prior art WO2016166130. However, an improvement is introduced, where the SPP losses are considerably reduced; giving rise to a much higher light extraction efficiency as compared to WO2016166130. Accordingly, the approach can, cautiously, be applied to high-refractive index materials such as diamond and semiconductors.

[0023] Fig. 3a: This depiction is an elaboration of the recent argument started in Fig. 2c. At the interface between layers (202)-(203), an SPP loss mode (212) exists. In this context, an SPP is a collective electron oscillation behavior that gives rise to a guided mode(s) along metal-dielectric interfaces. For demystification, an SPP mode is represented in Fig. 3 with a train of shaded diamond shapes. At the interface between layers (202)-(209), a second SPP loss mode

(213) exists. At the interface between layers (209)-(200), a third SPP loss mode (214) exists. The SPP loss modes (212), (213), and (214) are larger when the refractive index of the active medium (202) is high.

[0024] Fig. 3b: By introducing the intermediate layers (215) and (216) as shown, where the refractive indices of these layers have to be lower than the refractive index of the active medium (202), the SPP loss modes (212) and (213) can be reduced.

[0025] Fig. 3c: By further introducing the intermediate layer (217) as shown, where the refractive index of this layer has to be smaller than the refractive index of the collection medium (200), the SPP loss mode (214) can be reduced, provided that, the refractive index of the intermediate layer (217) is on the order of 1. This configuration does not work for free-space emission, since the refractive index of the collection medium (200) has to be much larger than the refractive index of the intermediate layer (217). Note that, in Fig. 3c the collection medium (200) is represented in a different way, with closed boundaries, as an indication that it can no longer be free-space.

[0026] This prior art has some limitations:

1. Since this approach relies on the suppression of SPP losses, the refractive indices of the intermediate layers (215), (216), and (217) have to be very low and chosen in correlation with the refractive indices of the active medium (202) and the collection medium (200). This restriction limits the material choice options and the applicability of the scheme to some operational wavelengths.

2. Even with the reduction of the SPP loss modes (212) and (213), the free-space light extraction efficiency saturates close to 80% [2].

3. With the further reduction of the SPP loss mode (214), in the configuration of Fig. 3c, the light extraction efficiency (this is different from the free-space light extraction efficiency) can reach 90%. However; as mentioned earlier, the configuration in Fig. 3c does not work for free-space emission, since the refractive index of the collection medium (200) has to be very high with respect to the refractive index of the intermediate layer (217).

Prior art summary

[0027] The trend in the two discussed patent pending applications WO2016166130 and WO002018096097, and their corresponding journal publications; has been imaging a dipole emitter in metallic layers, and interfering the dipole with its induced images constructively. The prior art WO002018096097 extended the applicability of this physical concept to high-refractive index material systems by the inclusion of low-refractive index layers, in hope for the reduction of SPP loss modes. However, the promised free-space light extraction efficiencies are on the order of 80%, and the choice of materials and the applicability to other operational wavelengths are highly restricted.

[0028] Therefore, it is the object of the present invention to introduce an inventive physical approach that tackles TIR-light trapping and diverging emission in any refractive index material light emitting platform, in fulfillment of the four industrial criteria listed above. More in precise, the present invention targets applications such as: LEDs, lasers, SPSs, and biomedical sensing; at different operational wavelengths.

Detailed description of the invention

[0029] Waveguides have long been known for guiding light along their axes. Here in the Transfer Waveguide (TRANS-GUIDE) they are used differently; where light is transferred sideways between different waveguide potentials. This invention is named TRANSGUIDE.

[0030] Fig. 4: A photon light emitter (311) is incubated in a waveguide named the source (S). The photon light emitter (311) can be one or more emitters. The designation "source" dates back to the waveguide's hosting for the photon light emitter (311). The source (S) comprises a core (303), a lower cladding (302), and an upper cladding (304); where ideally the photon light emitter (311) is located in the core (303). The source (S) functions in a similar manner to a dielectric waveguide, where the materials and the thicknesses of the source core (303), the source lower cladding (302), and the source upper cladding (304) are chosen such that the source (S) operates in leakage mode. In this context, leakage mode means that the light emitted by the photon light emitter (311) is minimally guided in the direction parallel to the source's core (303); instead, the light escapes from the source waveguide's sides, in the direction normal to the source's core (303). By placing a reflecting layer, named forward-bias (301), contiguous to the source's lower cladding (302), the part of the light that would escape from the source's bottom side will be directed upwards. In this arrangement, the source (S) cannot hold on to the light emitted by the photon light emitter (311), and the light is allowed to escape only from the source's upper cladding (304). The source (S) is a passive element, and does not change the wavelength of the light emitted by the photon light emitter (311). However, the photon light emitter (311) can be passive or active, and can be optically or electrically excited. The main functionality of the source (S) is to deplete the photon light emitter (311).

[0031] Fig. 4: Now that the photons emitted from the photon light emitter (311) can only leave the source (S) from its top side, the source upper cladding (304); an exit terminal is required to control the light's path. The gate (G) is also a

waveguide, and is placed in the light's exit path. Ideally, the gate (G) functions in a similar manner to an antisymmetric Insulator Metal Insulator (IMI) waveguide; with (305) serving as the gate's lower cladding, (306) as the gate's core, and (307) as the gate's upper cladding, respectively. The gate (G) is positioned such that its lower cladding (305) is contiguous to the source's upper cladding (304). The materials and the thicknesses of gate's lower cladding (305), the gate's core (306), and the gate's upper cladding (307) are chosen such that the gate (G) operates in turn-off mode. In this context, turn-off mode means that the gate (G) is transparent with respect to the light emitted by the photon light emitter (311); i.e. supports a minimal guided mode in the direction parallel to the gate's core (306), and gives rise to minimal absorption. This configuration implies that, the light emitted by the photon light emitter (311) traverses the gate (G) in the direction perpendicular to the gate's core (306). The gate (G) is a passive element, and does not change the wavelength of the light emitted by the photon light emitter (311). The main functionality of the gate (G) is to serve as a valve for controlling the light flow out of the source (S). Conductor materials can also be used for the gate's lower cladding (305) and the gate's upper cladding (307).

[0032] Fig. 4: The light that exits the source (S) via the gate (G) is dumped into a third waveguide, called the drain (D), located directly on the other side of the gate (G). The drain (D) is comprised of a core (309), a lower cladding (308), and an upper cladding (310); and is placed such that its lower cladding (308) is contiguous to the gate's upper cladding (307). The drain (D) functions in a similar manner to a dielectric waveguide; where the materials and the thicknesses of drain's lower cladding (308), the drain's core (309), and the drain's upper cladding (310) are chosen such that the drain (D) operates in leakage mode. In this context, leakage mode means that the light emitted by the photon light emitter (311) is minimally guided in the direction parallel to the drain's core (309); instead, the light is allowed to escape from the drain waveguide's sides, in the direction normal to the drain's core (309). The light flow out of the source (S) is stored in the drain (D), in principle, in the drain's lower cladding (308) and in the drain's upper cladding (310). This light buildup in the drain's lower cladding (308) and in the drain's upper cladding (310) eventually bursts, i.e. is released, into the collection medium (300) contiguous to the drain's upper cladding (310). The drain (D) is also a passive element, and does not change the wavelength of the light emitted by the photon light emitter (311). The main functionality of the drain (D) is to create a temporarily light buildup, and follow it with an immediate burst.

[0033] Fig. 4: Overall, the three waveguides are configured not to trap the light emitted by the photon light emitter (311); instead, they pass the light on from their sides to the successive stage. The source (S) is coupled to the gate (G), the gate (G) is coupled to the drain (D), and the drain (D) is coupled to the collection medium (300). The forward-bias (301) ensures a flow of light along the channel, i.e. from the source (S) to the drain (D). Typically, a metallic mirror or a dielectric Bragg mirror would be an option for the forward-bias (301).

[0034] Fig. 5: While the light emitted by the photon light emitter flows from: the source (S), through the gate (G), to the drain (D), ending up in collection medium (300); it is crucial to pinch the light's path along the tunnel. In this context, a pinch means that the electric field intensity is decreased, i.e. approaches zero inside the waveguide core region. Fig. 5a shows an example of a TRANSGUIDE configuration that features ~90% free-space light extraction efficiency. The main radiative mode is plotted in a cross-sectional view of the structure. One can see that the light is pinched three times before it is radiated into the free-space collection medium (300). The first pinch takes place in the source's core, followed by the second pinch in the gate's core, with the third pinch in the drain's core. In Fig. 5b, another example of a TRANSGUIDE configuration is shown; however, this configuration features ~80% free-space light extraction efficiency. The inferior free-space light extraction efficiency, as compared to the configuration of Fig. 5a, is understood from the less number of pinches. The radiated light is only pinched twice: the first pinch is in the gate's core, followed by the second pinch in the drain's core.

[0035] In contrary to the previous discussed prior arts:

- The TRANSGUIDE does not rely on dipole-imaging nor interference effects; and therefore, there are no restrictions on the photon light emitter's position.
- The TRANSGUIDE does not rely on the suppression of SPP losses by the inclusion of low-refractive index materials at the metal-dielectric interfaces; and therefore, high-refractive index materials can be used anywhere without any restrictions.

Invention design considerations

[0036] There are many ways to put the source (S) and the drain (D) waveguides in leakage mode. There are also as many ways to put the gate (G) waveguide in turn-off mode. Here are some examples of possible options:

1. A metallic reflecting layer can serve as the forward-bias (301).
2. The source (S) can be a real-cladding waveguide. Meaning that, the refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are different from the refractive index of the source's core (303); with the option that, the refractive indices of the source's lower cladding (302) and the source's upper cladding

(304) are the same or different. In this context, real-cladding refers to the fact that a real physical interface exists between the core and the cladding since their materials are different.

3. The source (S) can be an imaginary-cladding waveguide. Meaning that, the refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are the same as the refractive index of the source's core (303). In this context, imaginary-cladding refers to the fact that no real physical interface exists between the core and the cladding since their materials are the same. The physical interface in this case is an imaginary design parameter.

4. The gate (G) can be trenched. Meaning that, the refractive index of the gate's lower cladding (305) is different from the refractive index of the source's upper cladding (304). This implies that a real physical interface exists between the source (S) and the gate (G), i.e. between their contiguous claddings. This condition is applicable to the real-cladding source configuration (point 2) and to the imaginary-cladding source configuration (point 3).

5. The gate (G) can be merged. Meaning that, the refractive index of the gate's lower cladding (305) is the same as the refractive index of the source's upper cladding (304). This implies that no real physical interface exists between the source (S) and the gate (G), i.e. between their contiguous claddings. The physical interface in this case is an imaginary design parameter. This condition is applicable to the real-cladding source configuration (point 2) and to the imaginary-cladding source configuration (point 3).

6. The refractive indices of the drain's lower cladding (308) and the gate's upper cladding (307) can be the same or different; i.e. the physical interface between the gate (G) and the drain (D), between their contiguous claddings, can be real or imaginary. This condition can apply to any of the previous configurations.

7. For free-space emission applications the collection medium (300) is considered to be air. However; for non free-space emission applications, i.e. emission through a medium, the refractive index of the collection medium (300) can be equal to or different from the refractive index of the drain's upper cladding (310). This condition can apply to any of the previous configurations.

8. Any of the waveguide cores or claddings can be a single layer or multilayered. In the case of a multilayer, one has to consider the effective refractive index instead.

9. The photon light emitter (311) can be anywhere within the source's core (303).

Invention advantages and comparisons with the prior art

[0037] This section presents selective TRANSGUIDE examples, with emphasis on highlighting the potentials of the invention and how it can confidently outperform any prior art. Performance comparisons are drawn based on a Silicon Vacancy (SiV) color center photon light emitter in a diamond active medium, at a 738 nm operational wavelength.

[0038] The theoretical results to be shown, whether for the TRANSGUIDE or those cited from the prior art, are all based on the same computational approach described in [4] and [5]. The approach has been experimentally verified in [1] and [3].

[0039] Fig. 6, Fig. 7: The photon light emitter (311) is considered initially in the center of the source's core (303). The photon light emitter position displacement Δd (312), with respect to the initial position, is considered along the axis indicated by the double-headed arrow. Positive Δd values correspond to moving towards the gate (G), while negative Δd values correspond to moving towards the forward-bias (301). Solid horizontal lines represent real physical interfaces, while dotted horizontal lines represent imaginary physical interfaces.

[0040] Fig. 6a: This configuration is a real-cladding source featuring a trenched-gate. The refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are the same and are smaller than the refractive index of the source's core (303). This implies that a real physical interface exists between the source's core and cladding. The refractive index of the gate's lower cladding (305) is larger than the refractive index of the source's upper cladding (304). This implies that a real physical interface exists between the gate and the source contiguous claddings. The configuration's design parameters are listed in Table 1. An important aspect of this configuration is that; the interface between the gate's core (306) and the gate's lower cladding (305) is a silver-sapphire interface, respectively.

[0041] Fig. 6b: This configuration is a real-cladding source featuring a merged-gate. The refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are the same and are smaller than the refractive index of the source's core (303). This implies that a real physical interface exists between the source's core and cladding. The refractive index of the gate's lower cladding (305) is the same as the refractive index of the source's upper cladding (304). This implies that an imaginary physical interface exists between the gate and the source contiguous claddings. The configuration's design parameters are listed in Table 1. An important aspect of this configuration is that; the interface between the Gate's core (306) and the Gate's lower cladding (305) is a silver-silica interface, respectively.

[0042] Fig. 7a: This configuration is an imaginary-cladding source featuring a trenched-gate. The refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are the same as the refractive index of the source's core (303). This implies that an imaginary physical interface exists between the source's core and cladding. The refractive index of the gate's lower cladding (305) is smaller than the refractive index of the source's upper cladding

(304). This implies that a real physical interface exists between the gate and the source contiguous claddings. The configuration's design parameters are listed in Table 1. An important aspect of this configuration is that; the interface between the gate's core (306) and the gate's lower cladding (305) is a silver-ZnO interface, respectively.

[0043] Fig. 7b: This configuration is an imaginary-cladding source featuring a merged-gate. The refractive indices of the source's lower cladding (302) and the source's upper cladding (304) are the same as the refractive index of the source's core (303). This implies that an imaginary physical interface exists between the source's core and cladding. The refractive index of the gate's lower cladding (305) is the same as the refractive index of the source's upper cladding (304). This implies that an imaginary physical interface exists between the gate and the source contiguous claddings. The configuration's design parameters are listed in Table 1. An important aspect of this configuration is that; the interface between the gate's core (306) and the gate's lower cladding (305) is a silver-diamond interface, respectively.

[0044] Fig. 8: This plot is a comparison based on the free-space light extraction efficiency, as a function of the photon light emitter displacement Δd (312), drawn between the configurations in Fig. 6a, Fig. 6b, Fig. 7a, and Fig. 7b. For the four examples, the interface between the gate's core (306) and the gate's upper cladding (307) is a silver-TiO₂ interface respectively, while the interface between the gate's core (306) and the gate's lower cladding (305) is different. Refractive indices of TiO₂, diamond, ZnO, sapphire, and silica read: 2.54, 2.4, 1.96, 1.76, and 1.45 respectively.

[0045] Consider for now the configurations of Fig. 6a and Fig. 6b with their corresponding free-space light extraction efficiency plots in Fig. 8. One can see that, as the photon light emitter (311) approaches the gate (G), i.e. positive Δd values, the free-space light extraction efficiency is higher when the refractive index of the gate's lower cladding (305) is larger. This behavior is in complete contradiction with the prior art WO002018096097 and [2]; where they report that the light extraction efficiency increases, provided that, the refractive index of the intermediate layer [Fig. 3c, layer (216)], interfaced with the metal director element [Fig. 3c, layer (209)], is reduced. It should also be noted that, the gate's core (306) from the other side has a very high-refractive index material upper cladding (307), $n_{TiO_2} = 2.54$. Following the same reasoning as in the prior art WO002018096097 and [2], the refractive index of the gate's upper cladding (307) should rather be small and on the order of 1.

	Fig. 6a		Fig. 6b		Fig. 7a		Fig. 7b	
#	Material	Thickness	Material	Thickness	Material	Thickness	Material	Thickness
(300)	Air	Semi-infinite	Air	Semi-infinite	Air	Semi-infinite	Air	Semi-infinite
(301)	Silver	100 nm	Silver	100 nm	Silver	100 nm	Silver	100 nm
(302)	Silica	30 nm	Silica	30 nm	Diamond	25 nm	Diamond	25 nm
(303)	Diamond	50 nm	Diamond	50 nm	Diamond	50 nm	Diamond	50 nm
(304)	Silica	30 nm	Silica	30 nm	Diamond	25 nm	Diamond	25 nm
(305)	Sapphire	29 nm	Silica	31 nm	ZnO	12 nm	Diamond	10 nm
(306)	Silver	35 nm	Silver	35 nm	Silver	45 nm	Silver	45 nm
(307)	TiO ₂	62 nm	TiO ₂	62 nm	TiO ₂	62 nm	TiO ₂	58 nm
(308)	Silica	112 nm	Silica	112 nm	Silica	112 nm	Silica	112 nm
(309)	TiO ₂	58 nm	TiO ₂	58 nm	TiO ₂	68 nm	TiO ₂	58 nm
(310)	Silica	112 nm	Silica	112 nm	Silica	112 nm	Silica	112 nm

Table 1

[0046] For the configurations of Fig. 7a and Fig. 7b with their corresponding free-space light extraction efficiency plots in Fig. 8; a similar behavior can be remarked, where the free-space light extraction efficiency is higher for the trench configuration of Fig. 7a. However, one might argue that the free-space light extraction efficiency increases because the gate-trenching in that case is equivalent to lowering the refractive index of the gate's lower cladding (305), which in turn reduces the coupling to SPP losses. This reasoning is completely wrong; because, if the refractive index of the gate's lower cladding (305) is even further lowered, for example gate-trenching with silica, the free-space light extraction

efficiency decreases instead of increasing. The refractive index of the gate's lower cladding (305) in itself is not important, what matters is the leakage/turn-off and pinching of the waveguides.

[0047] The free-space light extraction efficiencies, shown in Fig. 8, for the configurations in Fig. 7a and Fig. 7b are inferior to those for the configurations of Fig. 6a and Fig. 6b. This is because; grouping the layers together by using a common material compromises the source's leakage operational mode. With reference to Fig. 5b (corresponds to the structure of Fig. 7a), a weak guided mode builds up within the grouped layers (302), (303), and (304). Furthermore, the radiative mode experiences pinches only in the core of the gate and in the core of the drain; lacking a pinch in the source's core (compare with Fig. 5a, corresponding to the structure of Fig. 6a). In spite of that, the free-space light extraction efficiency is more than 80%, which is already much higher than what the prior art WO2016166130 can deliver, and comparable to the prior art WO002018096097. However, layer grouping is a very practical feature. With the current state of the art nanofabrication, realization of very thin active medium layers can be very challenging for some materials. Thickening the active medium by grouping it with adjacent layers can be a solution.

[0048] To summarize, a free-space light extraction efficiency on the order of 90-100% in conjunction with a highly directional single-lobe radiation pattern has never been reported before in any prior art. Table 2 summarizes the relevant efforts in this regard.

Reference		Corresponding patent application	Free-space light extraction efficiency	Radiation pattern Half-Angle (HA) at full width half maximum
Prior art	[1], [2] Fig. 2a	WO2016166130	~40%	Single-lobe pattern, ~29° HA
	[2] Fig. 2b	WO002018096097	~80%	Single-lobe pattern, ~19° HA
	[2], [3] Fig. 1c	WO002018096097	~12%	Single-lobe pattern, ~8° HA
	[2], [3] Fig. 1d	WO002018096097	~54%	Single-lobe pattern, ~15° HA
TRANSGUIDE	Fig. 6a	Present invention	~90%	Single-lobe pattern, ~19° HA
	Fig. 6b	Present invention	~90%	Single-lobe pattern, ~19° HA
	Fig. 7a	Present invention	~78%	Single-lobe pattern, ~27° HA
	Fig. 7b	Present invention	~80%	Single-lobe pattern, ~24° HA

Table 2

[0049] The TRANSGUIDE examples given throughout the context of this text are solely for demonstrating the potentials of the invention, and should not be considered limiting. Further enhancements are foreseen with selective choices of the materials and the design.

[0050] In all previous examples the collection medium (300) was considered free-space, i.e. air. The TRANSGUIDE is also compatible with emission through a medium, and in the case that the refractive index of the collection medium (300) is equal to or larger than the refractive index of the drain's upper cladding (310), the light extraction efficiency adds 2-5% more.

[0051] Another aspect, in all previous TRANSGUIDE examples the active medium was a high-refractive index material. This doesn't mean that the TRANSGUIDE is only applicable to high-refractive index light emitting platforms. In fact, the light extraction efficiency can be as high in low-refractive index material based applications; such as, biosensing and Organic Light Emitting Diodes (OLEDs). The next example demonstrates how the TRANSGUIDE can outperform the prior art even when it comes to low-refractive index active mediums.

Low-refractive index platforms: TRANSGUIDE vs prior art

[0052] Consider the anthracene-dibenzoterrylene (Ac-DBT) molecules system reported in the prior art WO2016166130 and [1], where the inventors-authors introduce an optimal design for their claimed planar antenna structure. However; the theoretical free-space light extraction efficiency for their system is no more than 60%. This shouldn't come as a surprise, since we are already aware that this prior art is struggling with SPP losses.

[0053] By applying the TRANSGUIDE to the said Ac-DBT molecules emitting at 785 nm, see design parameters in

Table 3, the free-space light extraction efficiency can be as high as 93%, with the radiated light funneled into a single-lobe radiation pattern having a 19° HA. Reminding that, these results are also theoretical values, and have been obtained using the same computational approach used in WO2016166130 and [1].

With reference to Fig. 4		
#	Material	Thickness
(300)	Air	Semi-infinite
(301)	Silver	100 nm
(302)	Silica	78 nm
(303)	DBT-Ac	50 nm
(304)	Silica	78 nm
(305)	Sapphire	17 nm
(306)	Silver	30 nm
(307)	TiO ₂	68 nm
(308)	Silica	120 nm
(309)	TiO ₂	63 nm
(310)	Silica	120 nm

Table 3

Waveguide operational modes

[0054] It has been demonstrated throughout the previous examples that, transferring light sideways between different waveguide potentials promises a 90-100% light extraction efficiency, provided that, the waveguides are configured in a certain way: the source (S) and the drain (D) waveguides should be operating in leakage mode; and the gate (G) waveguide should be operating in turn-off mode. These operational modes have already been defined in the previous sections; however, here in Fig. 9 they are illustrated to give more insight into the working principle of the TRANSGUIDE.

[0055] Fig. 9: For the configuration of Fig. 6a, the light emitted by the photon light emitter (311) is plotted as a function of the real-part of the effective refractive index; for two collection medium (300) cases: free-space and medium. Several peaks can be observed for each case; remarking that, the y-axis is on logarithmic scale since the contributions of the peaks between $\text{Re}(n_{\text{eff}}) = [1.5 : 3]$ are very weak that they are hardly visible on a linear scale. The peaks are explained as follows:

- The peak at $\text{Re}(n_{\text{eff}}) = 2.6$ represents the guided light in the source (S). Configuring the source (S) in leakage mode implies minimizing the amplitude of this peak, or even completely suppressing the peak.
- The peak at $\text{Re}(n_{\text{eff}}) = 1.9$ represents the guided light in the gate (G). Configuring the gate (G) in turn-off mode implies minimizing the amplitude of this peak, or even completely suppressing the peak.
- The peaks at $\text{Re}(n_{\text{eff}}) = 1.7$ and $\text{Re}(n_{\text{eff}}) = 1.2$ represent the guided light in the drain (D). Configuring the drain (D) in leakage mode implies minimizing the amplitudes of these peaks, or even completely suppressing the peaks.
- The continuum distribution towards the $\text{Re}(n_{\text{eff}}) = 0$ is more or less the light that is radiated into the collection medium (300).

[0056] The figure plots illustrate how the leakage of the drain (D) is enhanced when the collection medium (300) is changed from free-space to medium; where the peak at $\text{Re}(n_{\text{eff}}) = 1.2$ is completely suppressed and the other peak at $\text{Re}(n_{\text{eff}}) = 1.7$ is further minimized.

[0057] The eventual drain burst discussed earlier, is illustrated in Fig. 10, for the configuration of Fig. 6a. Along the extension direction of the collection medium (300), a very bright intensity light spot could be observed centered directly above the location of the photon light emitters in the source (S). It can also be seen that this bright spot is seeded from

the buildup in the drain (D). Dashed lines mark the structure elements. The pinching is also apparent from the dark-black color mapping that the cores appear in.

Conclusion

[0058] Whether the light emitting platform is a low or high-refractive index material, irrespective of the operational wavelength, a 90-100% light extraction efficiency in conjunction with highly directional emission profiles are realizable in a complete flat ultra-thin architecture.

Description of the figures

[0059]

Fig. 1: Cross-sectional view illustrating the technical background for the problem of total internal reflection light trapping and diverging emission.

Fig. 2: Cross-sectional views outlining the working principle of the prior art WO2016166130.

Fig. 3: Cross-sectional views outlining the working principle of the prior art WO002018096097.

Fig. 4: Cross-sectional view of the TRANSGUIDE.

Fig. 5: The main radiative mode plotted for two different TRANSGUIDE configurations: a) real-cladding source trenched-gate, configuration shown in Fig. 6a, design parameters listed in Table 1; b) imaginary-cladding source trenched-gate, configuration shown in Fig. 7a, design parameters listed in Table 1. The (S), (G), (D) waveguides, the forward-bias (301), and the collection medium (300) structures are overlaid on the plots. Interfaces between the listed structures are marked with dotted lines.

Fig. 6: Cross-sectional views: a) a TRANSGUIDE configuration featuring a real-cladding source trenched-gate; b) a TRANSGUIDE configuration featuring a real-cladding source merged-gate. Dotted lines represent an imaginary physical interface.

Fig. 7: Cross-sectional views: a) a TRANSGUIDE configuration featuring an imaginary-cladding source trenched-gate; b) a TRANSGUIDE configuration featuring an imaginary-cladding source merged-gate. Dotted lines represent an imaginary physical interface.

Fig. 8: Performance plots: the free-space light extraction efficiency as a function of the photon light emitter position displacement Δd (312), for the configurations in Fig. 6 and Fig. 7.

Fig. 9: The light emitted by the dipole light emitter (311) as a function of the real-part of the effective refractive index, plotted for two collection medium (300) cases: free-space and medium. The two plots correspond to the configuration of Fig. 6a, but with the corresponding collection medium.

Fig. 10: The drain burst for the configuration of Fig. 6a plotted on a cross-sectional view of the structure, with the dashed lines marking the interfaces of the elements. The normalized color map bar gives an indication of the light intensity.

Bibliography:

[0060]

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[2] H. Galal and M. Agio, "Highly efficient light extraction and directional emission from large refractive-index materials with a planar yagi-uda antenna," *Opt. Mater. Express* 7(5), 1634-1646 (2017).

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Claims

1. Device for ultra-bright directional light emission, comprising:

a forward-bias layer (301);
a source waveguide (S), incubating one or more photon light emitters (311);
a gate waveguide (G);
a drain waveguide (D); and
a collection medium (300),
overlaid one upon another in this order

wherein the forward bias layer (301) is a reflecting layer,
wherein the source waveguide (S) functions in a similar manner to a dielectric waveguide and wherein the material, the thickness and the effective refractive index of each of the source lower cladding (302), the source core (303), and the source upper cladding (304) are configured such that the source waveguide (S) operates in leakage mode and is coupled to the gate waveguide (G), wherein leakage mode means that the light emitted by the photon light emitters (311) is minimally guided in the direction parallel to the source's core (303) and escapes from the source waveguide's sides in the direction normal to the source's core (303), wherein the gate waveguide (G) functions in a similar manner to an antisymmetric insulator-metal-insulator waveguide and wherein the material, the thickness and the effective refractive index of each of the gate lower cladding (305), the gate core (306), and the gate upper cladding (307) are configured such that the gate waveguide (G) operates in turn-off mode and is coupled to both the source waveguide (S) and the drain waveguide (D), wherein turn-off mode means that the gate (G) is transparent with respect to the light emitted by the photon light emitter (311); i.e. supports a minimal guided mode in the direction parallel to the gate's core (306), in which the light emitted by the photon light emitters (311) traverses the gate (G) in the direction perpendicular to the gate's core (306) and gives rise to minimal absorption,
wherein the drain waveguide (D) functions in a similar manner to a dielectric waveguide, wherein the material, the thickness and the effective refractive index of each of the drain lower cladding (308), the drain core (309), and the drain upper cladding (310) are configured such that the drain waveguide (D) operates in leakage mode and is coupled to both the gate waveguide (G) and the collection medium (300), wherein leakage mode means that the light emitted by the photon light emitters (311) is minimally guided in the direction parallel to the drain's core (309) and escapes from the drain waveguide's sides in the direction normal to the drain's core (309), and
wherein the source waveguide (S), the gate waveguide (G), and the drain waveguide (D) are passive and do not change the wavelength of the light emitted by the one or more photon light emitters (311); and
wherein the photons emitted by the one or more photon light emitters (311) traverse the three said waveguides in the said order, along the direction normal to the three said waveguide cores.

2. Device according to claim 1,

wherein the forward bias layer (301) is a metallic reflector, is a single layer or is multilayered, and has a reflectivity such that the photons emitted by the one or more photon light emitters (311) are transferred in order from the source waveguide (S), to the gate waveguide (G), to the drain waveguide (D), and finally to the collection medium (300).

3. Device according to claim 1,

wherein the source lower cladding (302) is contiguous to the forward-bias (301).

4. Device according to any previous claim,

wherein the one or more photon light emitters (311) are passive or active photon emitters, and can be located anywhere within the source core (303).

5. Device according to any previous claim,
wherein the gate lower cladding (305) is contiguous to the source upper cladding (304).
6. Device according to any previous claim,
wherein the drain lower cladding (308) is contiguous to the gate upper cladding (307), and the drain upper cladding (310) is contiguous to the collection medium (300).
7. Device according to any previous claim,
wherein the collection medium (300) extends in the direction away from the drain upper cladding (310).
8. Device according to any previous claim,
wherein any of the said waveguide cores or claddings, is a single layer or is multilayered.
9. Device according to claim 1,
wherein the effective refractive index of the drain upper cladding (310) is the same as or different from the refractive index of the collection medium (300).
10. Device according to one of the preceding claims,
wherein the collection medium (300) is free space with a refractive index equal to the refractive index of air or is a medium with a refractive index larger than the refractive index of air.
11. Device according to any previous claim,
wherein the effective refractive indices of the source lower cladding (302) and of the source upper cladding (304) are the same as or different from the effective refractive index of the source core (303).
12. Device according to any previous claim,

wherein the effective refractive indices of the source upper cladding (302) and of the gate lower cladding (305) are the same or different or
the effective refractive indices of the gate upper cladding (307) and of the drain lower cladding (308) are the same or different.

Patentansprüche

1. Vorrichtung zur ultrahellen gerichteten Lichtemission, umfassend: eine Flussrichtungsschicht (301);

einen Source-Wellenleiter (S), der einen oder mehrere Photonenlichtemitter (311) enthält; einen Gate-Wellenleiter (G);
einen Drain-Wellenleiter (D); und
ein Sammelmedium (300),
die in dieser Reihenfolge übereinandergestapelt sind,

wobei die Flussrichtungsschicht (301) eine reflektierende Schicht ist,
wobei der Source-Wellenleiter (S) auf eine ähnliche Weise wie ein dielektrischer Wellenleiter funktioniert und wobei das Material, die Dicke und der effektive Brechungsindex von jedem des unteren Source-Mantels (302), des Source-Kerns (303) und des oberen Source-Mantels (304) so konfiguriert sind, dass der Source-Wellenleiter (S) im Leckmodus arbeitet und mit dem Gate-Wellenleiter (G) gekoppelt ist, wobei der Leckmodus bedeutet, dass das von den Photonenlichtemittern (311) emittierte Licht in der Richtung parallel zum Kern (303) der Source minimal geleitet wird und von den Seiten des Source-Wellenleiters in der Richtung senkrecht zum Kern (303) der Source entweicht,
wobei der Gate-Wellenleiter (G) auf eine ähnliche Weise wie ein antisymmetrischer Isolator-Metall-Isolator-Wellenleiter funktioniert und wobei das Material, die Dicke und der effektive Brechungsindex von jedem des unteren Gate-Mantels (305), des Gate-Kerns (306) und des oberen Gate-Mantels (307) so konfiguriert sind, dass der Gate-Wellenleiter (G) im Ausschaltmodus arbeitet und sowohl mit dem Source-Wellenleiter (S) als auch mit dem Drain-Wellenleiter (D) gekoppelt ist, wobei der Ausschaltmodus bedeutet, dass das Gate (G) in Bezug auf das von dem Photonenlichtemitter (311) emittierte Licht transparent ist; d. h. einen minimal geleiteten Modus in der Richtung parallel zum Kern (306) des Gates unterstützt, in dem das von

den Photonenlichtemittern (311) emittierte Licht das Gate (G) in der Richtung senkrecht zum Kern (306) des Gates durchquert und zu einer minimalen Absorption führt, wobei der Drain-Wellenleiter (D) auf eine ähnliche Weise wie ein dielektrischer Wellenleiter funktioniert, wobei das Material, die Dicke und der effektive Brechungsindex von jedem des unteren Drain-Mantels (308), des Drain-Kerns (309) und des oberen Drain-Mantels (310) so konfiguriert sind, dass der Drain-Wellenleiter (D) im Leckmodus arbeitet und sowohl mit dem Gate-Wellenleiter (G) als auch mit dem Sammelmedium (300) gekoppelt ist, wobei der Leckmodus bedeutet, dass das von den Photonenlichtemittern (311) emittierte Licht in der Richtung parallel zum Kern (309) des Drains minimal geleitet wird und von den Seiten des Drain-Wellenleiters in der Richtung senkrecht zum Kern (309) des Drains entweicht, und wobei der Source-Wellenleiter (S), der Gate-Wellenleiter (G) und der Drain-Wellenleiter (D) passiv sind und die Wellenlänge des von dem einen oder den mehreren Photonenlichtemittern (311) emittierten Lichts nicht ändern; und wobei die von dem einen oder den mehreren Photonenlichtemittern (311) emittierten Photonen die drei Wellenleiter in der genannten Reihenfolge entlang der Richtung senkrecht zu den drei Wellenleiterkernen durchqueren.

2. Vorrichtung nach Anspruch 1,

wobei die Flussrichtungsschicht (301) ein metallischer Reflektor ist, eine einzelne Schicht ist oder mehrschichtig ist und ein Reflexionsvermögen aufweist, so dass die von dem einen oder den mehreren Photonenlichtemittern (311) emittierten Photonen in der Reihenfolge von dem Source-Wellenleiter (S) zu dem Gate-Wellenleiter (G), zu dem Gate-Wellenleiter (G), zu dem Drain-Wellenleiter (D) und schließlich zu dem Sammelmedium (300) übertragen werden.

3. Vorrichtung nach Anspruch 1,

wobei der untere Source-Mantel (302) an die Flussrichtung (301) angrenzt.

4. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei der eine oder die mehreren Photonenlichtemitter (311) passive oder aktive Photonenlichtemitter sind, und irgendwo innerhalb des Source-Kerns (303) angeordnet sein können.

5. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei der untere Gate-Mantel (305) an den oberen Source-Mantel (304) angrenzt.

6. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei der untere Drain-Mantel (308) an den oberen Gate-Mantel (307) angrenzt und der obere Drain-Mantel (310) an das Sammelmedium (300) angrenzt.

7. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei sich das Sammelmedium (300) in der Richtung weg von dem oberen Drain-Mantel (307) erstreckt.

8. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei einer der Wellenleiterkerne oder -mäntel eine einzelne Schicht ist oder mehrschichtig ist.

9. Vorrichtung nach Anspruch 1,

wobei der effektive Brechungsindex des oberen Drain-Mantels (310) gleich dem oder verschieden von dem Brechungsindex des Sammelmediums (300) ist.

10. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei das Sammelmedium (300) ein freier Raum mit einem Brechungsindex gleich dem Brechungsindex von Luft ist oder ein Medium mit einem Brechungsindex größer als der Brechungsindex von Luft ist.

11. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei die effektiven Brechungsindizes des unteren Source-Mantels (302) und des oberen Source-Mantels (304) gleich dem oder verschieden von dem effektiven Brechungsindex des Source-Kerns (303) sind.

12. Vorrichtung nach einem der vorhergehenden Ansprüche,

wobei die effektiven Brechungsindizes des oberen Source-Mantels (302) und des unteren Gate-Mantels (305) gleich dem oder verschieden von den effektiven Brechungsindizes des oberen Gate-Mantels (307) und des unteren Drain-Mantels (308) sind.

5

Revendications

1. Dispositif d'émission de lumière directionnelle ultra-lumineuse, comprenant :

10 une couche de polarisation directe (301) ;
un guide d'ondes de source (S), comprenant un ou plusieurs émetteurs de lumière photonique (311) ;
un guide d'ondes de grille (G) ;
un guide d'ondes de drain (D) ; et
un milieu de collecte (300),
15 superposés les uns sur les autres dans cet ordre

dans lequel la couche de polarisation directe (301) est une couche réfléchissante,
dans lequel le guide d'ondes de source (S) fonctionne d'une manière similaire à un guide d'ondes diélectrique
et dans lequel le matériau, l'épaisseur et l'indice de réfraction effectif de chacun de l'habillage inférieur de
20 source (302), du noyau de source (303) et de l'habillage supérieur de source (304) sont configurés de telle
sorte que le guide d'ondes de source (S) fonctionne en mode de fuite et est couplé au guide d'ondes de
grille (G), dans lequel le mode de fuite signifie que la lumière émise par les émetteurs de lumière photonique
(311) est guidée de manière minimale dans la direction parallèle au noyau de source (303) et s'échappe
des côtés du guide d'ondes de source dans la direction normale par rapport au noyau de source (303),
25 dans lequel le guide d'ondes de grille (G) fonctionne d'une manière similaire à un guide d'ondes isolant-
métal-isolant antisymétrique et dans lequel le matériau, l'épaisseur et l'indice de réfraction effectif de chacun
de l'habillage inférieur de grille (305), du noyau de grille (306) et de l'habillage supérieur de grille (307) sont
configurés de telle sorte que le guide d'ondes de grille (G) fonctionne en mode d'éteindre et est couplé à
la fois au guide d'ondes de source (S) et au guide d'ondes de drain (D), dans lequel le mode d'éteindre
30 signifie que la grille (G) est transparente par rapport à la lumière émise par l'émetteur de lumière photonique
(311) ; c'est-à-dire qu'il supporte un mode minimal guidé dans la direction parallèle au noyau de grille (306),
dans lequel la lumière émise par les émetteurs de lumière photonique (311) traverse la grille (G) dans la
direction perpendiculaire au noyau de grille (306) et donne lieu à une absorption minimale,
dans lequel le guide d'ondes de drain (D) fonctionne d'une manière similaire à un guide d'ondes diélectrique,
35 dans lequel le matériau, l'épaisseur et l'indice de réfraction effectif de chacun de l'habillage inférieur de
drain (308), du noyau de drain (309) et de l'habillage supérieur de drain (310) sont configurés de telle sorte
que le guide d'ondes de drain (D) fonctionne en mode de fuite et est couplé à la fois au guide d'ondes de
grille (G) et au milieu de collecte (300), dans lequel le mode de fuite signifie que la lumière émise par les
émetteurs de lumière photonique (311) est guidée de manière minimale dans la direction parallèle au noyau
40 de drain (309) et s'échappe des côtés du guide d'ondes de drain dans la direction normale par rapport au
noyau de drain (309), et
dans lequel le guide d'ondes de source (S), le guide d'ondes de grille (G) et le guide d'ondes de drain (D)
sont passifs et ne changent pas la longueur d'onde de la lumière émise par l'un ou les plusieurs émetteurs
de lumière photonique (311) ; et dans lequel les photons émis par l'un ou les plusieurs émetteurs de lumière
45 photonique (311) traversent les trois dits guides d'ondes dans ledit ordre, le long de la direction normale
par rapport aux trois dits noyaux de guide d'ondes.

2. Dispositif selon la revendication 1,

50 dans lequel la couche de polarisation directe (301) est un réflecteur métallique, est une couche unique ou est
multicouche, et a une réflectivité telle que les photons émis par l'un ou les plusieurs émetteurs de lumière photonique
(311) sont transférés dans l'ordre du guide d'ondes de source (S), au guide d'ondes de grille (G), au guide d'ondes
de drain (D), et finalement au milieu de collecte (300).

3. Dispositif selon la revendication 1,

55 dans lequel l'habillage inférieure de source (302) est contigu à la polarisation directe (301).

4. Dispositif selon l'une quelconque des revendications précédentes,

dans lequel l'un ou les plusieurs émetteurs de lumière photonique (311) sont des émetteurs de photons passifs ou

actifs, et peuvent être situés n'importe où à l'intérieur du noyau de source (303).

- 5
5. Dispositif selon l'une quelconque des revendications précédentes, dans lequel l'habillage inférieur de grille (305) est contigu à l'habillage supérieur de source (304).
6. Dispositif selon l'une quelconque des revendications précédentes, dans lequel l'habillage inférieur de drain (308) est contigu à l'habillage supérieur de grille (307), et l'habillage supérieur de drain (310) est contigu au milieu de collecte (300).
- 10
7. Dispositif selon l'une quelconque des revendications précédentes, dans lequel le milieu de collecte (300) s'étend dans la direction s'éloignant de l'habillage supérieur de drain (310).
8. Dispositif selon l'une quelconque des revendications précédentes, dans lequel l'un quelconque desdits noyaux ou habillages de guide d'ondes est une couche unique ou est multi-couche.
- 15
9. Dispositif selon la revendication 1, dans lequel l'indice de réfraction effectif de l'habillage supérieur de drain (310) est identique à ou différent de l'indice de réfraction du milieu de collecte (300).
- 20
10. Dispositif selon l'une des revendications précédentes, dans lequel le milieu de collecte (300) est un espace libre avec un indice de réfraction égal à l'indice de réfraction de l'air ou est un milieu avec un indice de réfraction supérieur à l'indice de réfraction de l'air.
- 25
11. Dispositif selon l'une quelconque des revendications précédentes, dans lequel les indices de réfraction effectifs de l'habillage inférieur de source (302) et de l'habillage supérieur de source (304) sont identiques ou différents de l'indice de réfraction effectif du noyau de source (303).
- 30
12. Dispositif selon l'une quelconque des revendications précédentes, dans lequel les indices de réfraction effectifs de l'habillage supérieur de source (302) et de l'habillage inférieur de grille (305) sont identiques ou différents ou les indices de réfraction effectifs de l'habillage supérieur de grille (307) et de l'habillage inférieur de drain (308) sont identiques ou différents.
- 35

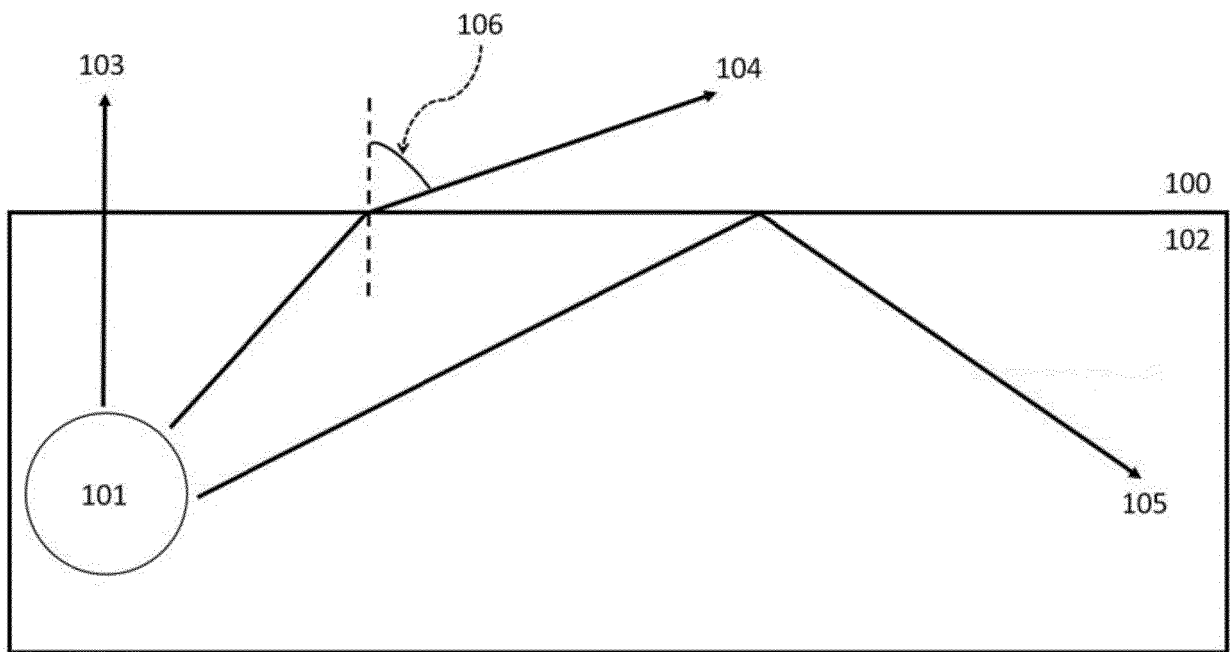


Fig. 1

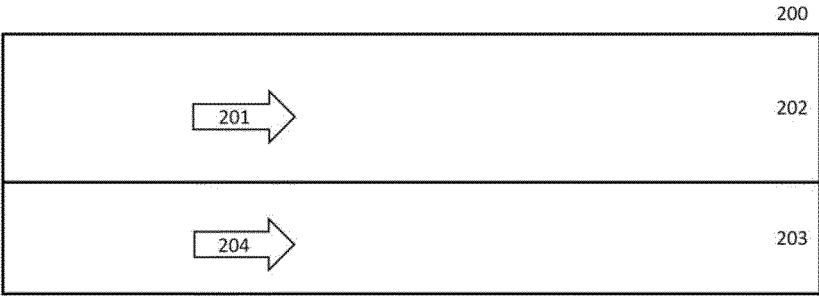


Fig. 2a

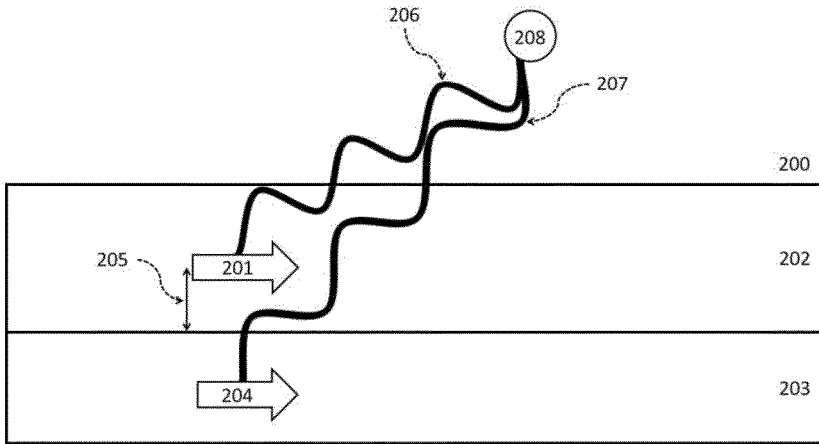


Fig. 2b

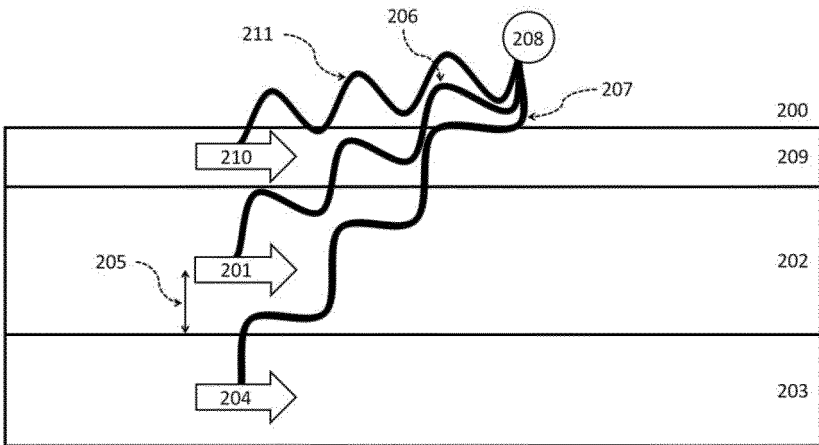


Fig. 2c

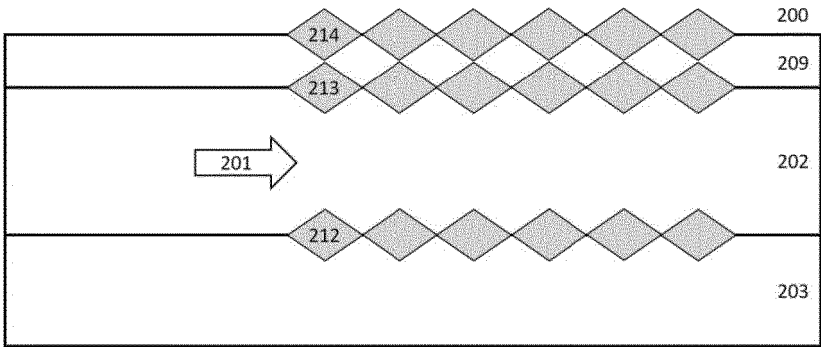


Fig. 3a

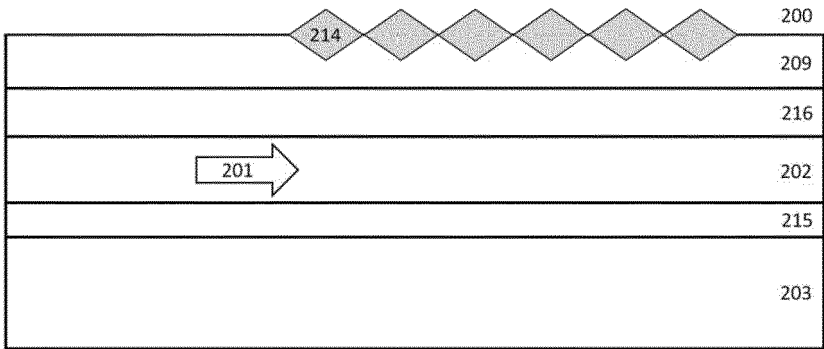


Fig. 3b

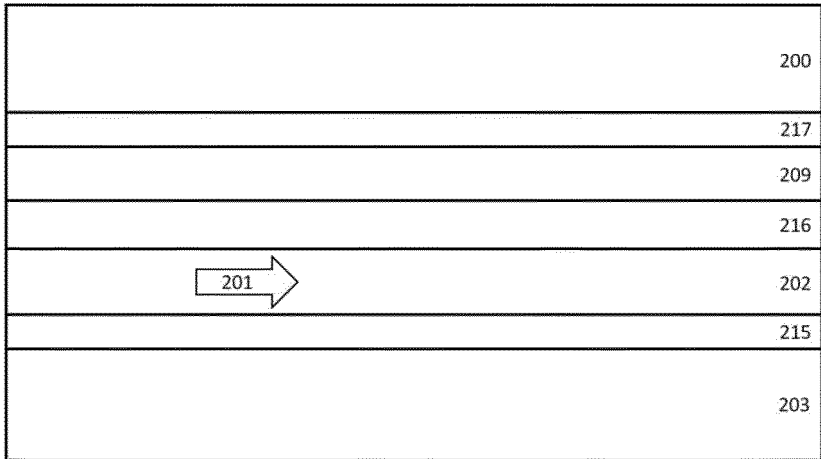


Fig. 3c

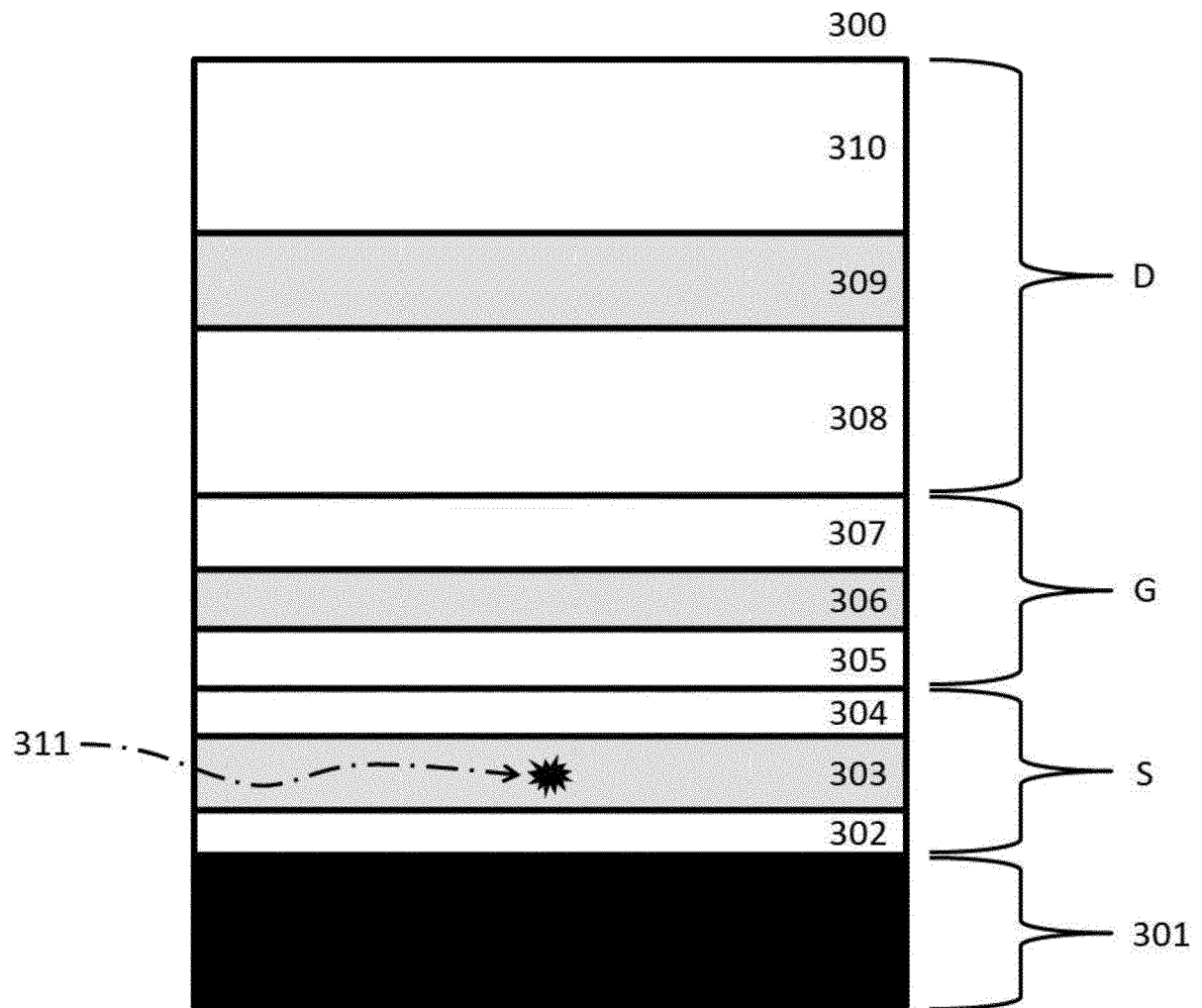


Fig. 4

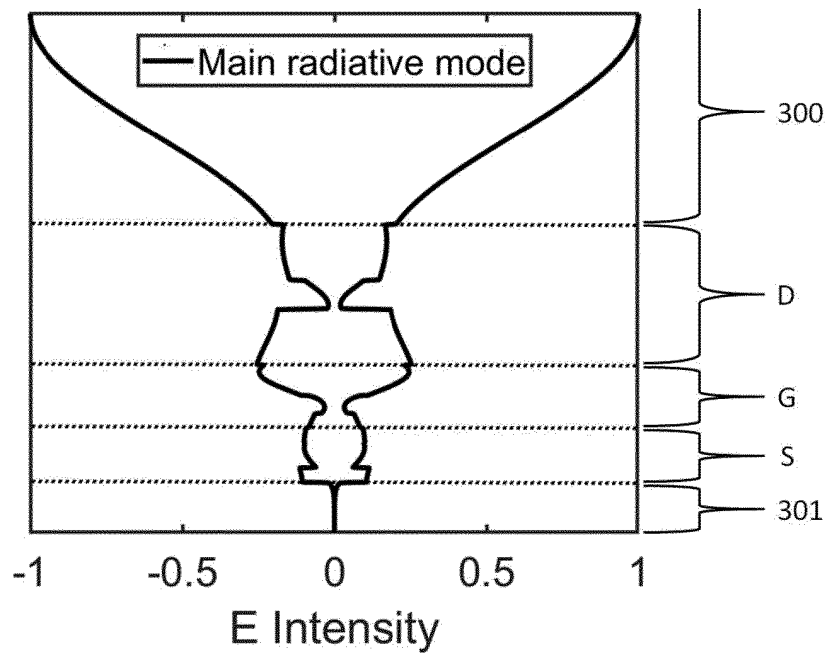


Fig. 5a

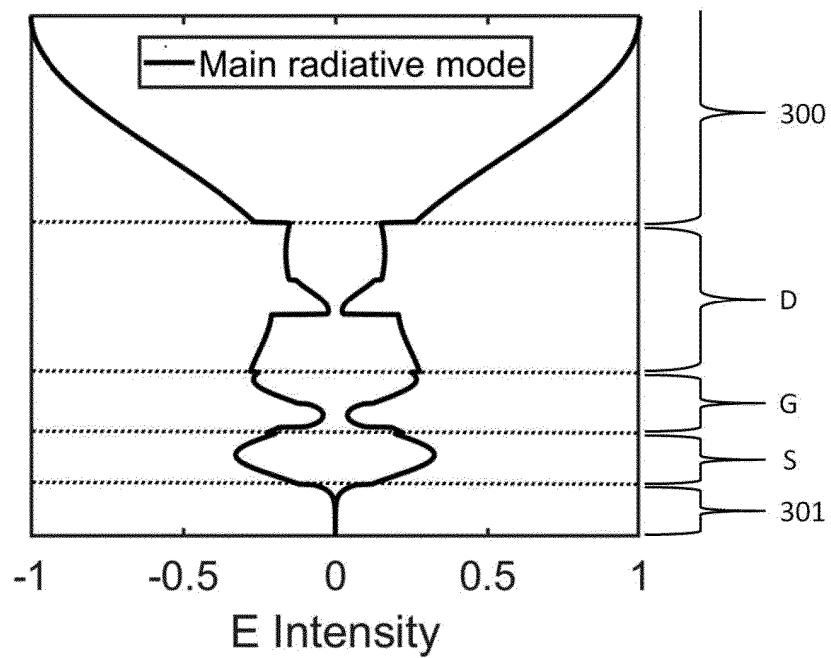


Fig. 5b

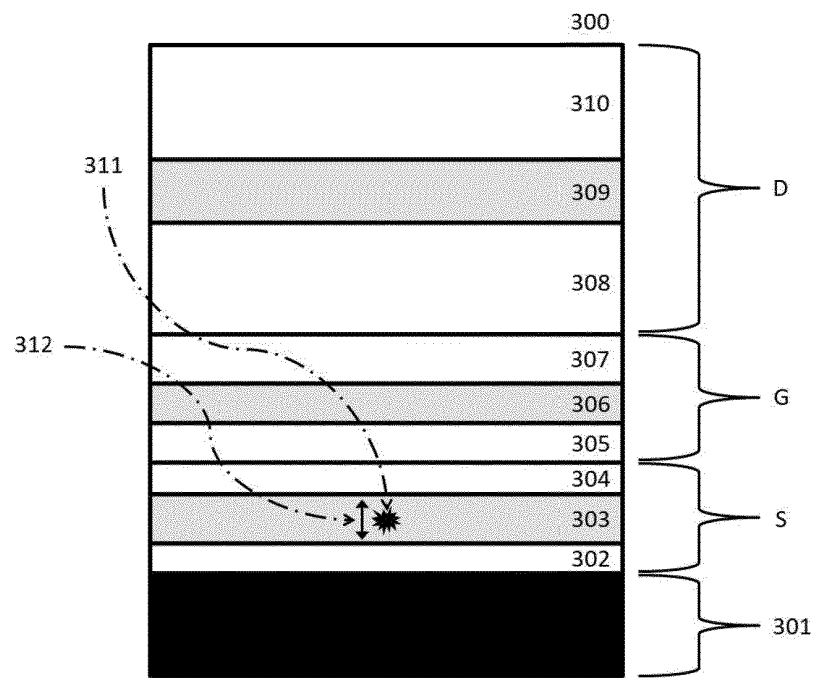


Fig. 6a

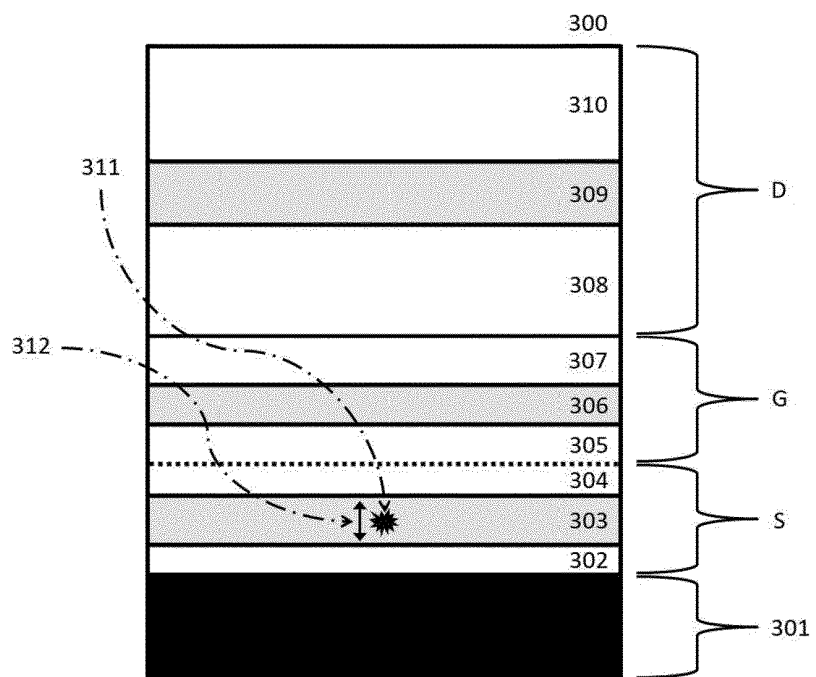


Fig. 6b

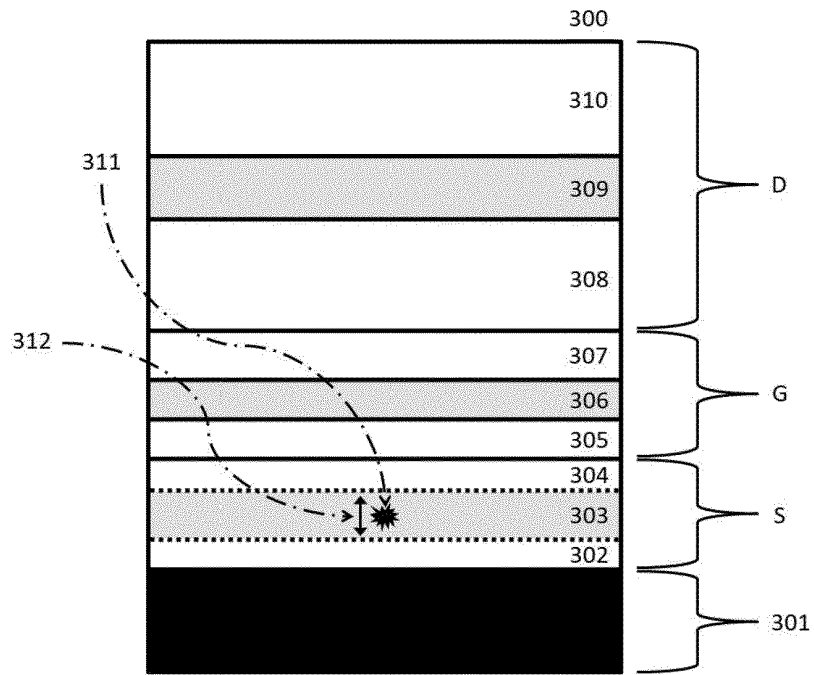


Fig. 7a

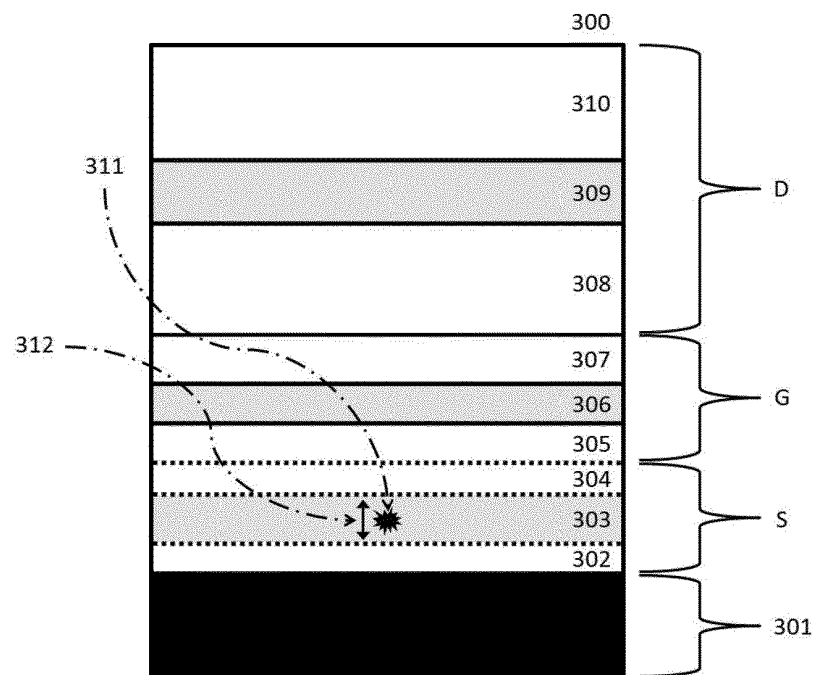
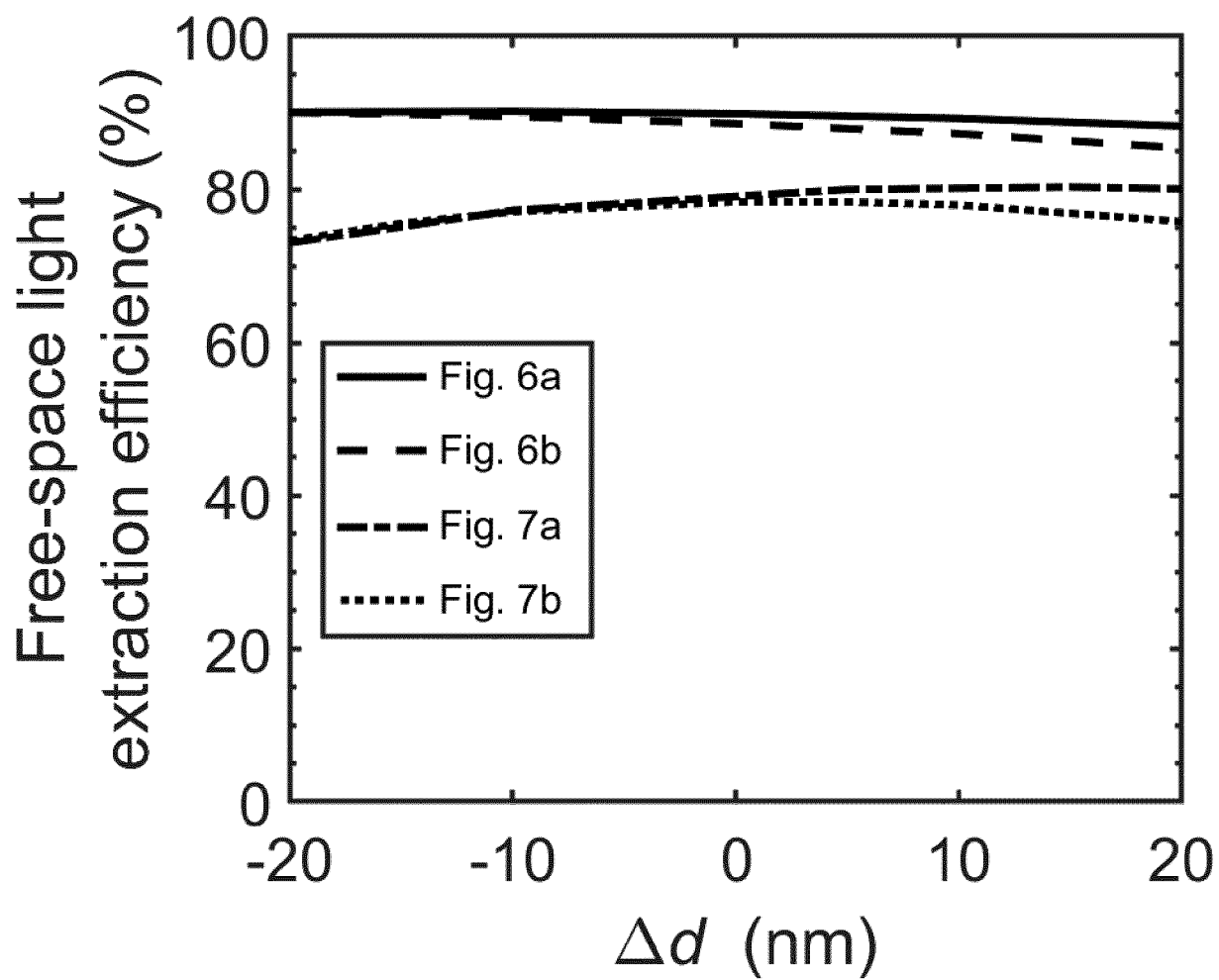
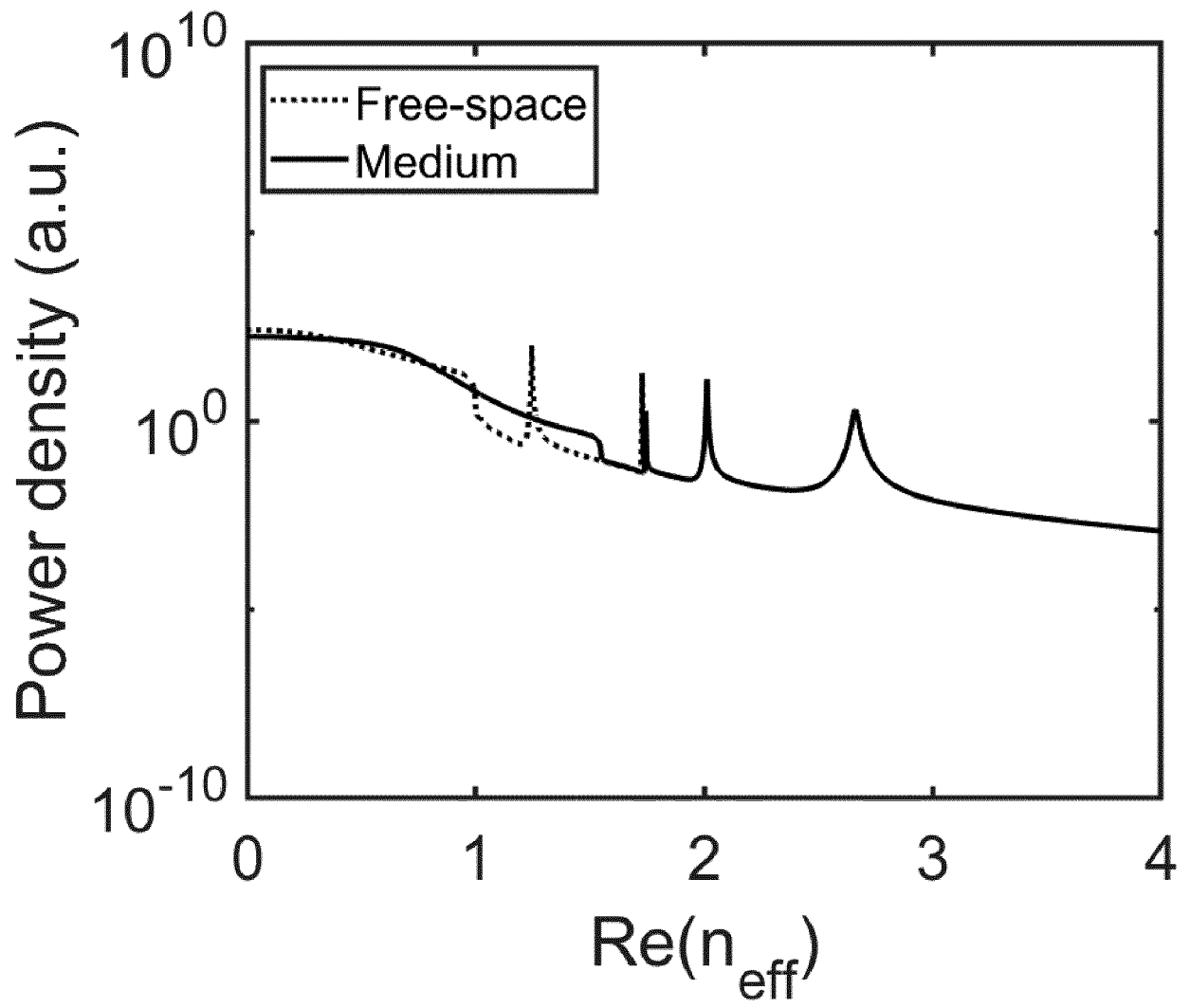


Fig. 7b

**Fig. 8**

**Fig. 9**

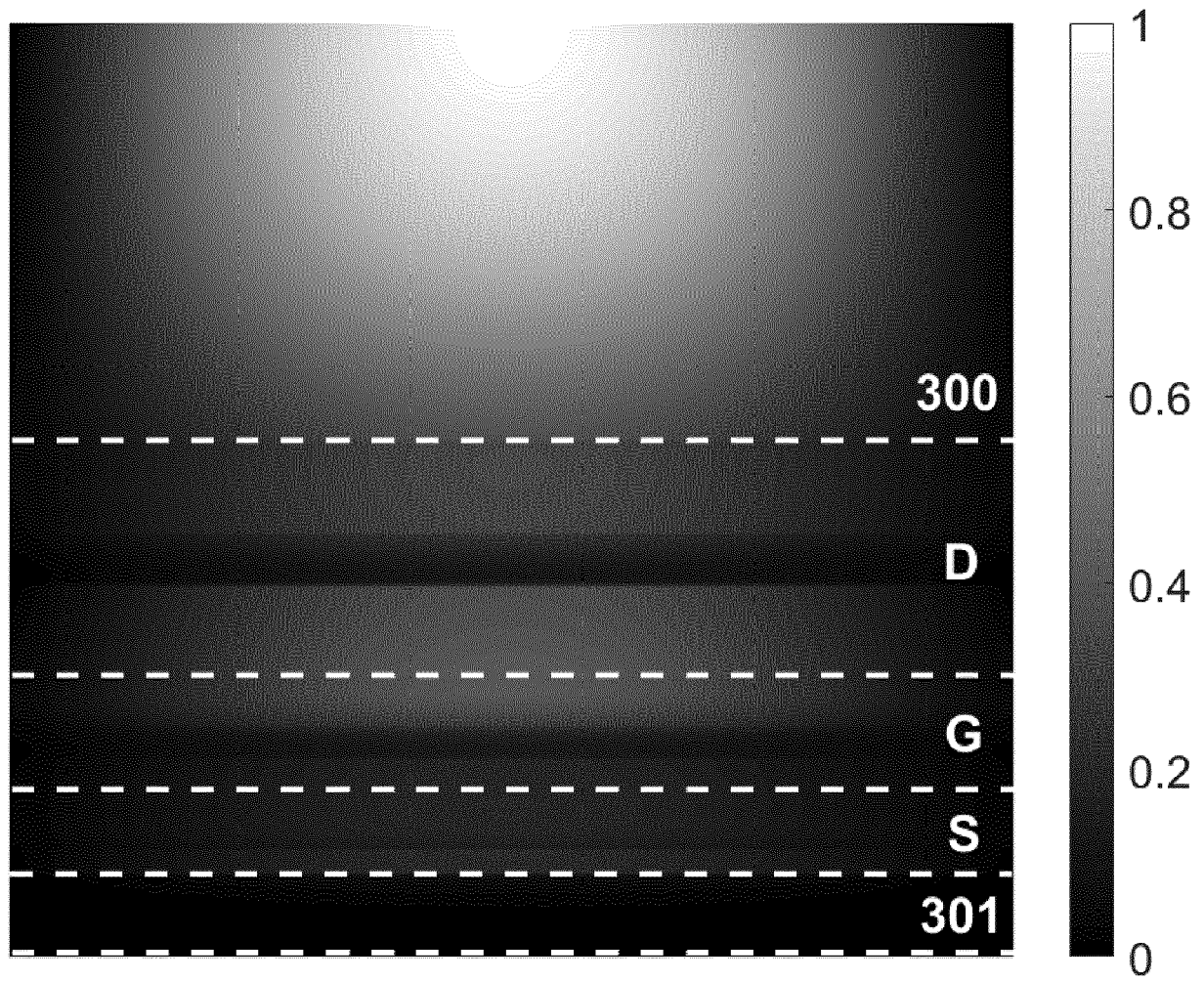


Fig. 10

REFERENCES CITED IN THE DESCRIPTION

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