Generation of nondiffracting subwavelength-beams in finite metal-dielectric structures

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ABSTRACT

We identified nanostructured devices sustaining subwavelength diffraction-free beams with grazing propagation. The components of the optical assembly are a metal-dielectric multilayer stack deposited on a solid transparent substrate. Launched from the substrate, the nondiffracting beam is resonantly transmitted though the stratiform medium leading to light confinement and wave amplification around the beam axis near the top end. Potential applications include optical trapping, biosensing, and nonlinear optics.

Keywords: plasmonics, diffraction

1. INTRODUCTION

The control of light propagation and localization on a subwavelength scale is one of the key challenges in applied physics. Concerning this issue, surface plasmon polaritons (SPPs)[1] in metallic nanostructures are especially versatile optical excitations. The latter are hybrid modes consisting of collective electron oscillations in a metal with propagating electromagnetic surface waves on nanometer length scales.[2,3] Moreover, localized surface plasmons and the associated field enhancements can lead to the spatially selective generation of near-field photonic forces[4] and nonlinear optical signals.[5] An efficient transformation of traveling delocalized SPPs into highly localized excitations is therefore of central importance to achieve bright illumination of confined volumes.

We are particularly interested in focus wave modes, i.e. localized wave fields whose transverse distribution of intensity is conserved is spite of diffraction. This will be crucial in various applications ranging from nanocircuitry and optical-electronic interconnects to near-field optical microscopy and biosensing. Here we put special emphasis on stratified metal-dielectric (MD) media. Two main problems arise in the generation of SPPs-assisted diffraction-free beams. One problem relies on dissipative effects that exhibit even good metals leading to a short propagation distance. From a fundamental point of view we may provide an infinite wave course by using self-healing electromagnetic fields, which are induced by means of an optical feeding mechanism. It can be found for example in prism coupling using attenuated total internal reflection in the Kretschmann and Otto configuration.[3] The second problem has to do with poor capacity of wave modes to be spatially confined on a MD interface. An ultrathin, low-index, dielectric waveguide set on the multilayer would lead to localize the resonant surface waves.[6]

In previous studies we demonstrated that bulk 1D photonic lattices can sustain nondiffracting wave fields,[7] including a transverse beamsize clearly surpassing the diffraction limit.[8] This subwavelength effect resides not only in the formation of surface resonances but also in the existence of transparency bands associated with high spatial frequencies of the wave field. We go deep into these concepts encompassing realistic nanostructured devices that include a finite number of layers and losses inside the metallic medium. After a manipulation of the angular spectrum characterizing the wave field we are able to generate a diffraction-free beam with transverse focus near the flat end surface of the structure. We also discuss some potential applications in electron acceleration, biosensing, and optical trapping.

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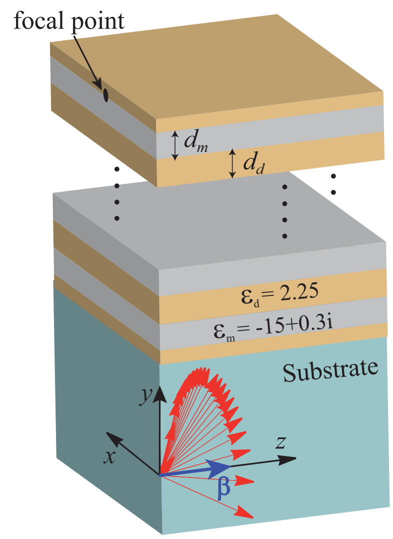

Figure 1. The multilayered structure composed of thin films of Ag and fused silica. In the substrate we plot the wave-vector distribution of the NDB launched. This construction guarantees the nondiffractive character of the beam.

2. DIFFRACTION-FREE BEAMS IN FINITE PLANAR MULTILAYERED METAL DIELECTRIC STRUCTURES

Let us consider a monochromatic vector beam propagating in a planar 1D metal-dielectric (MD) multilayer structure consisting of a finite number N of alternating layers of metallic and dielectric materials deposited over a solid substrate, as shown in Fig. 1. The y axis is set such that it is perpendicular to the MD interfaces. The stratified medium is characterized by a relative dielectric constant $\epsilon(y)$ in the form of a discrete function. Particularly it takes a value ϵ_s in the substrate, ϵ_m in the metallic films, and ϵ_d in the dielectric layers. Also d_m and d_d refers to the width corresponding to each metallic slab and each dielectric slab, respectively. Finally we consider dielectric ending layers of width $d_d/2$, which results in a higher performance as discussed elsewhere.[9,10] We also assume that the beam propagation is directed along the z axis, so that we may cast the electromagnetic field as

$$\vec{E}(x,y,z,t) = \vec{e}(x,y)\exp(i\beta z - i\omega t) \quad (1)$$

$$\vec{H}(x,y,z,t) = \vec{h}(x,y)\exp(i\beta z - i\omega t) \quad (2)$$

being ω the frequency of the monochromatic radiation. The homogeneity of the wave field in the coordinate z is explicitly parametrized in terms of the propagation constant β.

In order to excite surface resonances in the MD interfaces of our device, p-polarized waves should be employed. Therefore we consider TM waves whose magnetic field is confined in the xz-plane, that is $\vec{h} = (h_x, 0, h_z)$. We point out that the electric field is obtained from $\vec{h}$ by using the Maxwell equations, $\vec{E} = (i/\omega\epsilon\epsilon_0)\nabla\times\vec{H}$, and that the magnetic field is solenoidal leading to the equation $h_z = i\beta^{-1}\partial_x h_x$. We conclude that our problem may be fully established in terms of the scalar wavefield h_x, from which all the other electromagnetic components may be derived.

From a practical point of view it is reasonable to assume that the nondiffracting beam (NDB) is launched from the substrate where we elude evanescent propagation ($\mathrm{Re}(\epsilon_s) \gg 1$) and dissipative effects ($\mathrm{Im}(\epsilon_s) = 0$). By using the plane-wave expansion of the field h_x, the light beam in the substrate may be understood as the superposition of infinite plane waves which wave vector $\vec{k} = (k_x, k_y, k_z)$ projected onto the propagation axis z

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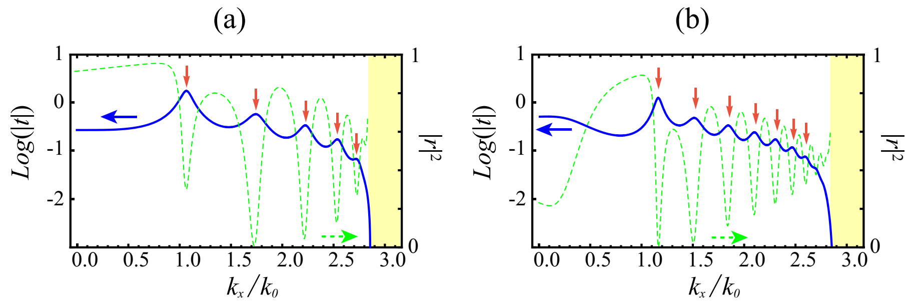

Figure 2. (a) Transmission coefficient (solid curve) and reflectance (dashed curve) for a MD structure as will be shown in Fig. 1 with $N = 5$ silver layers of width $d_m = 12.5$ nm immersed in fused silica ($d_d = 80$ nm). The high-index substrate is transparent ($\epsilon_s = 9.2$) and the covering medium is air. Shaded yellow region correspond to the forbidden band of the infinite MD structure. The red arrows marks the positive values of the spatial frequencies k_x used in the focal construction developed in Eq. (3). (b) The same as in (a) using $N = 10$.

gives the characteristic propagation constant, $k_z = \beta$. This is illustrated in Fig. 1. In mathematical terms, the wave field directed toward the MD nano-structure may be written as

$$[h_x]_{inc} = \sum_{k_x} w\left(k_x\right) \exp\left(ik_x x + ik_y y\right), \tag{3}$$

where the transverse spatial frequency $k_y > 0$ is given by the dispersion equation $k_y^2 = k_0^2 \epsilon_s - \beta^2 - k_x^2$. In Eq. (3) we assume a superposition of a discrete number of plane waves for convenience, however it may be generalized straightforwardly to a continuous distribution.[11] Finally $w\left(k_x\right)$ represents the strength of the spectral component with spatial frequency k_x in the plane-wave expansion (3).

In order to obtain the field distribution inside the MD structure we may consider each plane wave corresponding to a given spectral component shown in Eq. (3) individually. Next, using a standard matrix formulation for isotropic layered media[12] we can describe unambiguously the amplitude distribution generated inside our device by a plane waves of a given strength $w(k_x)$ launched from the substrate. The general procedure may be followed from Ref. 8. Finally, linearity let a construction of h_x characterizing the NDB in terms of a summation $\sum_{k_x} w\left(k_x\right) \exp(ik_x x)\tilde{h}(k_x, \beta, y)$ involving solutions $\tilde{h}$ of the scalar 1D wave equation.

The superposition of plane waves proposed in Eq. (3) by itself is not enough to generate a localized wave field inside the MD device. We need to establish some favorable conditions for the formation of a *line focus* parallel to the z-axis around a given transverse point $P_0 = (x_0, y_0)$. For that purpose we manipulate the relative phases among different plane-wave components in order to reach the same argument of the spectral field at the geometric focus P_0. Thus the oscillatory superposition yields the highest intensity achievable. Moreover, under ordinary conditions it cannot be found a point other than P_0 of the xy-plane where such a phase matching holds. As a consequence, a strong confinement of the NDB is expected to occur around P_0. In this paper we impose phase matching at a point P_0 placed on the uppermost MD interface as shown in Fig. 1(a). Also, for simplicity, we consider a uniform source distribution of plane waves leading to the condition $|w\left(k_x\right)| = 1$.

3. NUMERICAL RESULTS

In previous studies we showed that the contribution of all non-evanescent Block modes, that is included in allowed bands of an infinite periodic structure, in a superposition alike Eq. (3) together with the phase matching condition generates a transverse focus of a full width that might surpass the diffraction limit.[7,8] Such a subwavelength effect is due to the combination of two different mechanisms. In the direction of the periodicity, superresolution is carried out by the formation of surface resonances in the MD interfaces concurring fast decays out of these planes. On other hand the control over its FWHM in the x direction, Δ_x, is exercised by the spectral distribution of spatial frequencies k_x. The higher value of k_x participating in the coherent superposition (3) the lower Δ_x.

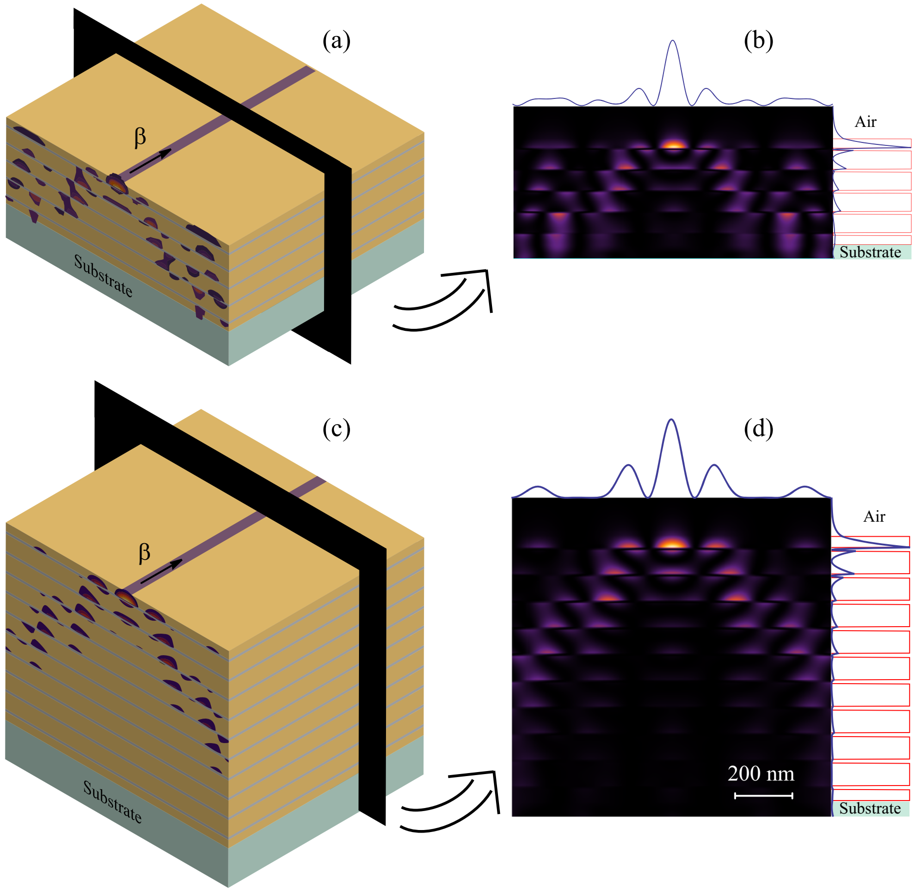

Figure 3. (a) 3D view of the optimized device and the NDB generated for $N = 5$. (b) Intensity pattern of the NDB in the xy-plane. Intensity distributions along $y = 0$ and $x = 0$ are shown at the top and left sides. (c) and (d) the same as in (a) and (b) respectively, but using $N = 10$.

In realistic finite-sized devices the transmittance from the front end joining the substrate up to the back-end surface keeps on showing the existence of transparency bands. Moreover, as shown in Fig. 2, high transmission peaks emerge from these spectral bands which are attributed to optical resonances of different nature. At the same time, we can also see as the reflectance is practically minimal at those same spatial frequencies k_x, and, furthermore, it grows sharply when we got away from these points. It is evidently that this behavior limits the contribution of all k_x thus stimulating those related with optical resonances. For this reason we choose a discrete superposition (3) of plane waves demonstrating high-efficiency transmission and low reflection across the multilayered MD structure.

In order to optimize the formation of a tightly-confined NDB, and following our previous studies, we consider two optical attributes that the MD structure should exhibit. Firstly large allowed bands leading to high transmittance of the PWs launched from the substrate. Secondly a high cutoff spatial frequency k_x that admits spatial distributions with extremely narrow peaks along the x-axis. Let us remind that our MD device consists of silver ($\epsilon_m = -15 + 0.3i$) and fused silica ($\epsilon_d = 2.25$) layers deposited onto a solid transparent substrate whose relative dielectric constant we fix to $\epsilon_s = 9.2$. Monochromatic plane waves of wavelength $\lambda_0 = 550$ nm are also assumed. In the search of a response following the above criteria we finally obtained $d_m = 12.5$ nm and $d_d = 80$ nm. This procedure ensures a suitable behavior for a moderate and high number N of metallic layers.

In Fig. 2(a) we represent the response in transmission and reflection of a MD device composed of $N = 5$ metallic layers. Here the propagation constant $\beta = k_0$ lead to inhomogeneous waves in air for $k_x \neq 0$. Red arrows point resonance peaks associated with values of k_x used in the generation of the NDB. The transverse

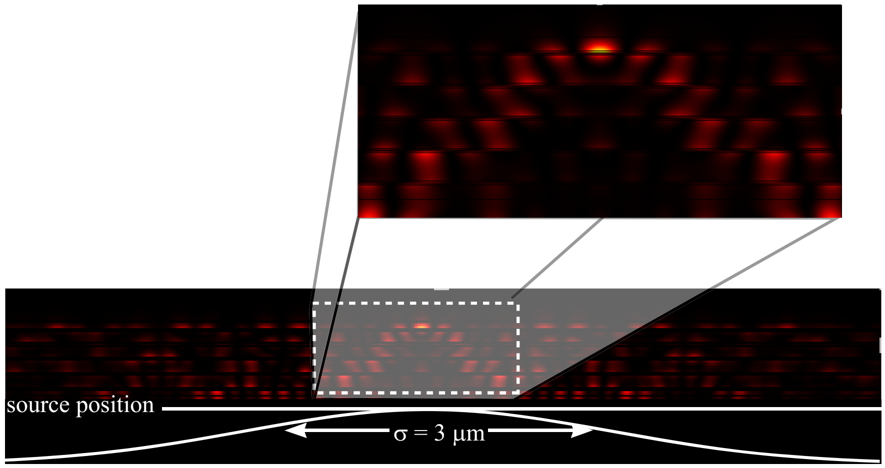

Figure 4. Numerical experiment performed with COMSOL Multiphysics.

distribution of intensity computed for a NDB with focus located on the center of the uppermost MD interface is plotted in Fig. 3(b). A NDB with anamorphic focal spot of subwavelength beamsize given by (FWHMs) $\Delta_x = 81$ nm and $\Delta_y = 19.4$ nm is obtained. We point out that the value of Δ_y is approximately one half of that encountered in the SPP generated by a single silver-fused silica interface at our wavelength ($\Delta_y = 40$ nm). This effect is related with the generation of high-order plasmonic modes.[13] Importantly the intensity reached at focus is 2.17 times higher than that encountered by the in-phase interference of plane waves given in Eq. (3) performed in the substrate. Therefore light confinement and wave amplification occurs simultaneously, which may have potential applications in nonlinear optics.

Increasing the number N of metallic layers leads also to an increment in the number of transmittance peaks. In principle, it is expected that high values of k_x participate in the NDB generation, lowering the values of Δ_x. Considering $N = 10$, the number of peaks only pass form 5 to 7 and the NDB achieves a hot spot with $\Delta_x = 78.8$ nm and $\Delta_y = 18.7$ nm. In comparison with the previous case a moderate enhancement of the resolution is observed along the x and y direction. Unfortunately dissipative effects become severe and the peak intensity is only 1.14 times of that encountered in an isotropic medium. Apparently taking greater values of N will not be, from a practical point of view, useful due to dissipative effects.

In practice, finite size of plane waves may impose further restrictions for an adequate formation of a transverse focus. It is well documented that beam truncation also circumscribes the effective propagation distance along which the NDB is maintained unaltered.[14,15] The latter effect however is not discussed in this paper. In Fig. 4 we plot the spatial distribution of the NDB sustained by the MD multilayered structure obtained from a numerical experiment performed with a commercial finite-element package (COMSOL Multiphysics). In this experiment we have considered a MD device of $N = 5$ silver films and the same opto-geometric characteristics used for Figs. 3(a) and (b). Following a realistic model, the infinite plane wave is here substituted by a gaussian wave of intensity distribution $\propto \exp(-x^2/\sigma^2)$, being the gaussian width $\sigma = 3$ μm. The gaussian source is placed beside the front-end surface of the MD photonic device. We confirm the validity of our previous results given in Fig. 3(b). In spite of using a considerably narrow gaussian source including high-angle spectral components, we form a subwavelength NDB propagating over the uppermost MD interface. Spurious light out of the boxed region decreases in intensity due to the finite extent of the gaussian source along the x direction, which might become a beneficial effect for most potential applications.

4. CONCLUSIONS

We have identified a nanostructured device that can sustain nondiffracting wave fields with grazing propagation and exhibiting transverse beamsizes clearly surpassing the diffraction limit of half a wavelength. This device consists of a planar multilayered MD structure with a finite number of layers deposited on a solid substrate. We illuminate from the substrate with a set of p-polarized monochromatic plane waves all having a wavevector that projected onto the z-axis gives the characteristic propagation constant of the beam. The spectral components are chosen attending on criteria of transmission efficiency as they pass through the MD structure. In the numerical simulations we also consider intrinsic material losses. Finally the relative phases of every incident wave are conformed to achieve a perfect phase matching at a given focal point. A strong localization of the NDB is demonstrated to occur around the focus accordingly. Since light confinement and wave amplification occur simultaneously, NDBs have potential applications in nonlinear optics. In waveguide-based biosensing, these structures might provide new opportunities for applications in which the waveguide is made out of functionalized molecular layers of nanometric thicknesses. Other applications include microlithography, optical micromanipulation, and electron acceleration.

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REFERENCES

1. H. Raether, *Surface plasmons on smooth and rough surfaces and on gratings*, Springer-Verlag, Berlin, 1988.
2. S. A. Maier and H. A. Atwater, "Plasmonics: Localization and guiding of electromagnetic energy in metal/dielectric structures," *Journal of Applied Physics* **98**(1), p. 011101, 2005.
3. S. A. Maier, *Plasmonics: Fundamentals and applications*, Springer, New York, 2007.
4. G. Volpe, R. Quidant, G. Badenes, and D. Petrov, "Surface plasmon radiation forces," *Phys. Rev. Lett.* **96**, p. 238101, 2006.
5. C. Ropers, D. R. Solli, C. P. Schulz, C. Lienau, and T. Elsaesser, "Localized multiphoton emission of femtosecond electron pulses from metal nanotips," *Phys. Rev. Lett.* **98**, p. 043907, 2007.
6. T. Sfez, E. Descrovi, L. Yu, D. Brunazzo, M. Quaglio, L. Dominici, W. Nakagawa, F. Michelotti, F. Giorgis, O. J. F. Martin, and H. P. Herzig, "Bloch surface waves in ultrathin waveguides: near-field investigation of mode polarization and propagation," *J. Opt. Soc. Am. B* **27**, pp. 1617–1625, 2010.
7. J. J. Miret and C. J. Zapata-Rodríguez, "Diffraction-free beams with elliptic Bessel envelope in periodic media," *J. Opt. Soc. Am. B* **25**, pp. 1–6, 2008.
8. J. J. Miret and C. J. Zapata-Rodríguez, "Diffraction-free propagation of subwavelength light beams in layered media," *J. Opt. Soc. Am. B* **27**(7), pp. 1435–1445, 2010.
9. M. Scalora, M. J. Bloemer, A. S. Pethel, J. P. Dowling, C. M. Bowden, and A. S. Manka, "Transparent, metallo-dielectric, one-dimensional, photonic band-gap structures," *J. Appl. Phys.* **83**, pp. 2377–2383, 1998.
10. S. Feng, M. Elson, and P. Overfelt, "Transparent photonic band in metallodielectric nanostructures," *Phys. Rev. B* **72**, p. 085117, 2005.
11. C. J. Zapata-Rodríguez and J. J. Miret, "Diffraction-free beams in thin films," *J. Opt. Soc. Am. A* **27**, pp. 663–670, 2010.
12. P. Yeh, *Optical Waves in Layered Media*, Wiley, New York, 1988.
13. S. M. Vukovic, Z. Jaksic, and J. Matovic, "Plasmon modes on laminated nanomembrane-based waveguides," *J. Nanophoton.* **4**, p. 041770, 2010.
14. J. Durnin, J. J. Miceli, and J. H. Eberly, "Diffraction-free beams," *Phys. Rev. Lett.* **58**, pp. 1499–1501, 1987.
15. G. Indebetouw, "Nondiffracting optical fields: some remarks on their analysis and synthesis," *J. Opt. Soc. Am. A* **6**, pp. 150–152, 1989.