Grazing beaming in metallodielectric nanostructures

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Abstract

We identified a family of nanostructured devices that can sustain subwavelength diffraction-free beams with grazing propagation. The basic configuration consists of a planar multilayered metal-dielectric arrangement deposited on a solid transparent substrate. Potential application in optical trapping and submicrochannel machining are outlined.

1. Introduction

An emerging area of interest in applied physics is the development of optical devices based on surface plasmon polaritons (SPPs). Potential applications of plasmonics are widespread, including waveguiding and ultrafast nanocircuitry, biosensing, and imaging. Due to the spatial confinement of energy on the subwavelength scale, the idea of exploiting plasmons as signal carriers has become of high importance, and experiments on a variety of metallic structures have been carried out [1]. Here we put special emphasis on stratified metal-dielectric (MD) media and attend to resolve one of the principal problems that arise in using SPPs, that is, the poor capacity of nondiffracting beams (NDB) to be spatially confined over a given MD flat interface in spite of its high localization perpendicularly.

2. Localized waves under zero diffraction in finite multilayered MD structures

The device consists of a planar MD multilayer with a finite number N of Ag films alternating with silica, deposited over a solid substrate, as shown in Fig. 1(a). In principle, we consider dielectric ending layers of width $d_d/2$, which results in a higher performance as discussed elsewhere [2]. The NDB is launched from the substrate where we elude evanescent propagation and dissipative effects ($\epsilon_s \gg 1$). It consists of a set of TM-polarized monochromatic plane waves (PWs), whose wave vector $\vec{k} = (k_x, k_y, k_z)$ projected onto the propagation z-axis gives the characteristic propagation constant, $k_z = \beta$,

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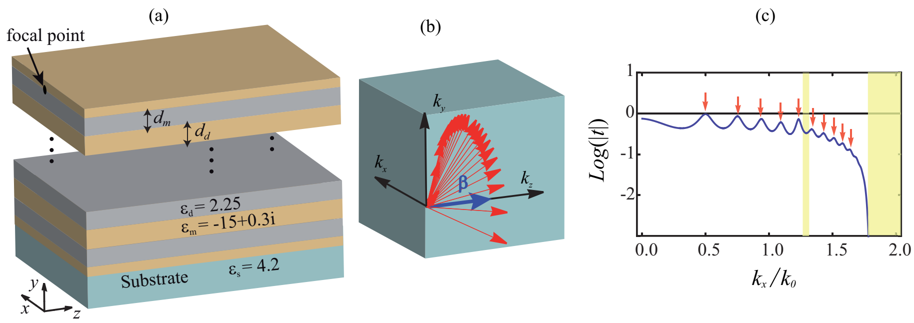

Figure 1: (a) The multilayered structure composed of thin films of Ag and fused silica. (b) Wave-vector distribution of the NDB launched on the MD lattice. This construction guarantees the nondiffractive character of the beam. (c) Transmission coefficient for the optimized MD structure. Red arrows point resonance peaks associated with values of k_x used in the generation of the NDB.

as illustrated in Fig. 1(b). In the substrate the dispersion equation reads $k_x^2 + k_y^2 = k_0^2\epsilon_s - \beta^2$, where $k_0 = 2\pi/\lambda_0$. In the numerical simulations a wavelength $\lambda_0 = 550$ nm is assumed, and we also fix the propagation constant $\beta = k_0$ and the number $N = 10$.

In previous studies we showed that an infinite periodic structure can sustain nondiffracting wavefields with a transverse beamsize clearly surpassing the diffraction limit [3, 4]. Such a subwavelength effect is due to the combination of two different mechanisms: (1) the formation of surface resonances in the MD interfaces and (2) the existence of transparency bands associated with high spatial frequency of the wave field. 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. As shown in Fig. 1(c), high transmission peaks emerge from these spectral bands which are attributed to optical resonant tunneling. Importantly we construct the NDB using those PWs demonstrating high-efficiency transmission across the multilayered MD structure.

The superposition of a set of PWs as proposed cannot in general generate a localized wave field inside the MD device. Therefore some favorable requisites must be established in order to form a *line focus* parallel to the z-axis around a given transverse point $P_0 = (x_0, y_0)$. For that purpose we manipulate their relative phases in order to achieve a phase matching at P_0. 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 pointed in Fig. 1(a).

3. Results

Following our previous studies we consider two optical attributes that the MD structure should exhibit in order to optimize the formation of a tightly-confined NDB. 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. In the pursuit of an optical response following the above criteria we arrived to the optimal values $d_m = 25$ nm and $d_d = 160$ nm. The resulting transmission coefficient is also depicted in Fig. 1(c).

In Fig. 2(a) we represent the transverse distribution of intensity computed for the succeeding NDB. The numerical procedure is followed from Ref. [4], which is based on the transfer-matrix method. The anamorphic focal spot has a subwavelength beamsize of FWHMs $\Delta_x = 116$ nm and $\Delta_y = 39.9$ nm. Importantly the intensity reached at focus is 2.7 times higher than that encountered by the in-phase interference of PWs as encountered in the substrate. Therefore light confinement and wave amplification occur simultaneously. Moreover, let us remind that the focal placement is fully arbitrary, which suggests

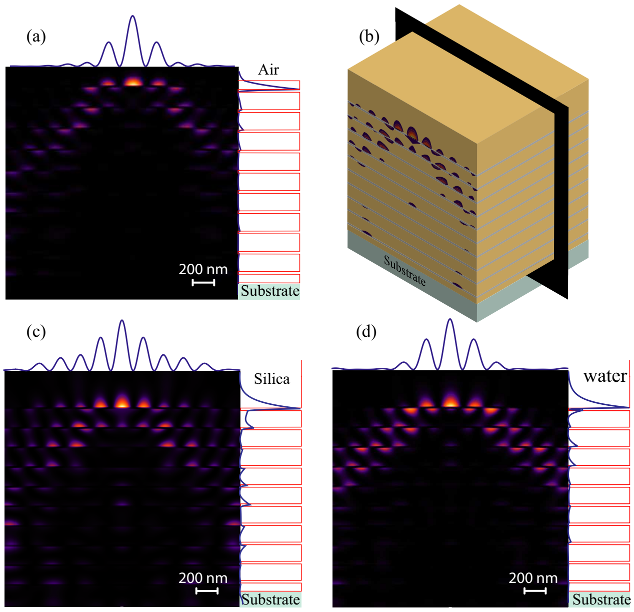

Figure 2: (a) Intensity pattern of the NDB in the xy-plane for the optimized device. (b) 3D view when the silica ending layer is enlarged to become an infinite superstrate. (c) The same as in (b) shown in the xy-plane. (d) The same as in (a) using a water superstrate.

potential applications in the generation of surface nanochannels in fused silica. For that purpose, and from a practical point of view, we would employ an overlaying stratum of silica, leading to a light distribution shown in Figs. 2(b) and (c). In this case it yields $\Delta_x = 103$ nm and $\Delta_y = 52$ nm. If we substitute the solid superstrate by a given aqueous solution, the setup might be used to manipulate and guide nanosized particles. The resultant NDB is shown in Fig. 2(d), which focal spot has FWHMs given by $\Delta_x = 116$ nm and $\Delta_y = 48$ nm. For the numerical simulations shown in Figs. 2(a)-(d) we employed a solid substrate characterized by $\epsilon_s = 4.2$.

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