Journal of Applied Physics

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Citation: J. Appl. Phys. **108**, 074304 (2010); doi: 10.1063/1.3486013
View online: http://dx.doi.org/10.1063/1.3486013
View Table of Contents: http://jap.aip.org/resource/1/JAPIAU/v108/i7
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Generation of enhanced evanescent Bessel beam using band-edge resonance

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(Received 17 June 2010; accepted 2 August 2010; published online 13 October 2010)

A method for generating enhanced evanescent Bessel beam is reported. When a radially polarized beam is strongly focused onto the last interface of one-dimensional photonic band gap structure, enhanced evanescent J_0 type Bessel beam can be generated via the band-edge resonance. Similarly, enhanced evanescent J_1 type Bessel beam can be created by reversing the multilayer structure under azimuthally polarized illumination. These enhanced evanescent Bessel fields may have important applications in optical manipulations of nanoparticles. © *2010 American Institute of Physics*. [doi:10.1063/1.3486013]

I. INTRODUCTION

Bessel beam is a nondiffracting beam solution of the free-space wave equation first introduced by Durnin *et al.*[1] The transverse distribution of this beam is nth-order Bessel function J_n of the first kind with field amplitude $\Phi(x,y,z;k)=\exp(ik_z z)J_n(k_r r)$, where $k_z^2+k_r^2=n^2k_0^2$ and $x^2+y^2=r^2$. When $k_r<nk_0$, this solution describes a propagating Bessel beam that maintains the transverse intensity distribution along the propagation z axis. It can be considered as the superposition of a set of plane waves with wave vectors along the surface of a cone, leading to the popular generation methods using an axicon or conical lens.[2] Evanescent Bessel beam solution can be obtained if one allows $k_r>nk_0$.[2–4] It can be realized by transmitting a Bessel beam across a dielectric interface beyond the critical angle.[2] Recently, highly focused cylindrical vector (CV) beams such as radial and azimuthal polarizations were explored to generate evanescent Bessel beams.[5,6] It is well known that when radially or azimuthally polarized beams are focused by high numerical aperture (NA) aplanatic lens, the electric field in the vicinity of the focus can be expressed as a set of integrals containing zeroth order or first order Bessel functions.[7] Thus any type resonance structure that gives rise to sharp angular transmittance could be used to mimic the function of an axicon and create Bessel beam near the focus. For example, it has been experimentally demonstrated[5] that J_0 type evanescent Bessel beams can be produced utilizing radial polarization as well as the angular selectivity of surface plasmon resonance (SPR). Both J_0 and J_1 type evanescent Bessel beams can be generated using the angular selectivity provided by the defect mode of a one-dimensional photonic band gap (1D PBG) structure along with highly focused radially or azimuthally polarized beams.[6]

For practical applications, high field strength, and flexibility are important metrics for different generation methods. The SPR based method can generate enhanced fields but only creates J_0 type evanescent Bessel beams with radial polarization. The defect mode method generates both J_0 and J_1 types of evanescent Bessel beams but the intensity throughout is low. In this paper, we demonstrate a new method using the gigantic transmission band-edge resonance in 1D PBG. By reversing the multilayer structure and switching the illuminate polarization between radial and azimuthal, both J_0 and J_1 type enhanced evanescent Bessel beams can be realized.

II. PRINCIPLES AND THEORETICAL DESCRIPTION

The proposed setup is shown in Fig. 1. A CV beam (radially or azimuthally polarized) illuminates the pupil plane of an oil-immersion aplanatic lens to produce a spherical wave converging toward the last dielectric-air interface of the 1D PBG located at the focal plane. For practical purposes, a circular blocking mask is placed in the pupil plane of the objective lens to eliminate potential imperfections of the CV beams and reduce the direct transmissions through the 1D PBG at angles near normal incidence. Owing to the use of this circular blocking mask, the illumination after the objective lens corresponds to a range of NA between $NA_{max}=1.43$ (given by the NA of the objective lens) and $NA_{min}=0.15$ (given by the radius of the blocking mask). The 1D PBG consists of 2N alternating high and low index of refraction dielectric layers. For practical reasons, we choose

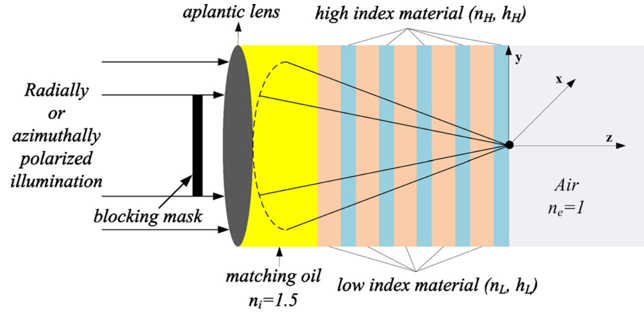

FIG. 1. (Color online) Diagram of the proposed setup for generate evanescent Bessel beam.

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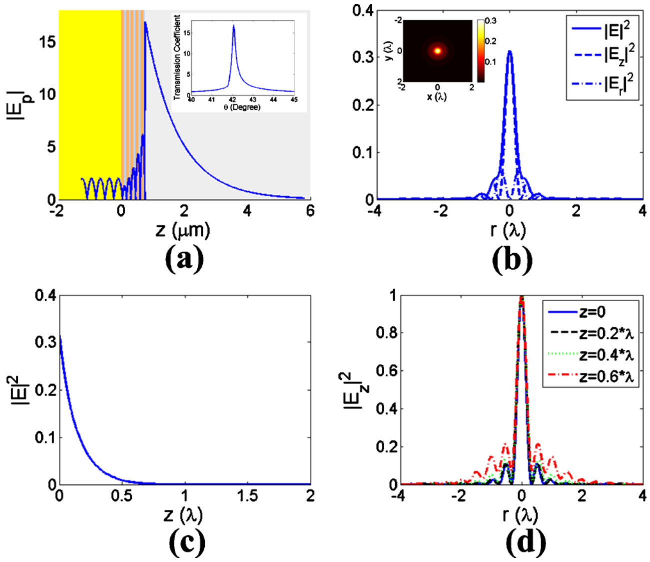

FIG. 2. (Color online) (a) Field distribution of p-polarization in the 1D PBG at resonance. Transmission coefficient is shown in the inset; (b) $|E_z|^2$ and $|E_r|^2$ at the bottom of the 1D PBG for a radially polarized illumination. The corresponding two-dimensional (2D) distribution of the total field strength $|E|^2$ is shown in the inset. (c) Total field strength $|E|^2$ along the z axis, showing the evanescent decay. (d) Normalized transverse profiles of $|E_z|^2$ at different distances from the bottom of the 1D PBG.

N=5 in this paper. Each period consists of two layers with index of refraction of $n_H=3.2$ (e.g., GaP) and $n_L=2.0$ (e.g., TiO_2), respectively, with thickness ratio of $n_L:n_H$. For an excitation wavelength of 633 nm, the period thickness is chosen to be 150 nm, whereas $h_H=57.7$ nm and $h_L=92.3$ nm. For radially polarized beam illumination, the stack order is shown in Fig. 1.

It is known that periodic structure can be designed as 1D PBG structure and the field amplitude transmission at the band edge will experience sharp peak resonance due to the high density of state.[8] Inset of Fig. 2(a) shows such a sharp and gigantic transmission coefficient for radial polarization (p-polarization). The transmission curve demonstrates the angular selectivity of the 1D PBG. Such a sharp angular resonance combined with the rotational symmetry of the setup mimics an axicon for the generation of Bessel beams. For the high index incident medium (oil, $n_i=1.5$) and exit medium (air, $n_e=1$) we use, the resonant angle $\theta_p=42.14°$ shown in inset of Fig. 2(a) indicates that the incident wave experiences total internal reflection from the 1D PBG. The field at the last interface is resonantly enhanced and confined, as shown in Fig. 2(a).

The field distributions just after the 1D PBG can be calculated with the method developed in Ref. 7. For radially polarized illumination, the field consists of a radial component and a strong longitudinal component

$$E_r(r,\varphi,z) = 2A\int_{\theta_{\min}}^{\theta_{\max}} \cos^{1/2}(\theta)P(\theta)t_p(\theta)\sin\,\theta\cos\,\theta \times J_1(k_1 r\sin\,\theta)\exp[iz(k_2^2-k_1^2\sin^2\,\theta)^{1/2}]d\theta, \tag{1}$$

$$E_z(r,\varphi,z) = i2A\int_{\theta_{\min}}^{\theta_{\max}} \cos^{1/2}(\theta)P(\theta)t_p(\theta)\sin^2\,\theta \times J_0(k_1 r\sin\,\theta)\exp[iz(k_2^2-k_1^2\sin^2\,\theta)^{1/2}]d\theta. \tag{2}$$

If the illumination is azimuthally polarized, only a donut shape azimuthal component exists

$$E_\phi(r,\varphi,z) = 2A\int_{\theta_{\min}}^{\theta_{\max}} \cos^{1/2}(\theta)P(\theta)t_s(\theta)\sin\,\theta \times J_1(k_1 r\sin\,\theta)\exp[iz(k_2^2-k_1^2\sin^2\,\theta)^{1/2}]d\theta, \tag{3}$$

where $t_p(\theta)$ is the transmission coefficient of the p-polarization and $t_s(\theta)$ is the transmission coefficient of the s-polarization at the incident angle of θ; A is a constant given by the incident power; $P(\theta)$ is the pupil apodization function; J_m is the mth-order Bessel function of the first kind; k_1 and k_2 are the wave vectors in the medium above and below the multilayer structure; $\theta_{\max}$ is determined by NA of the objective lens with $\theta_{\max}=\sin^{-1}(\mathrm{NA}_{\max}/n_i)$ and $\theta_{\min}=\sin^{-1}(\mathrm{NA}_{\min}/n_i)$. Inset of Fig. 2(a) shows that $t_p(\theta)$ has one delta-function like resonant peak, $t_p(\theta)\cong t_p(\theta_p)\delta(\theta-\theta_p)$. Thus Eqs. (1) and (2) can be reduced to $\exp[iz(k_2^2-k_1^2\sin^2\,\theta_p)^{1/2}]$ multiplied with Bessel functions. Since $k_2^2-k_1^2\sin^2\,\theta_p<0$, evanescent Bessel beam which evanescently decays away from the last interface into the exiting medium is resulted.

III. RESULTS AND APPLICATIONS

Numerical simulations based on Eqs. (1) and (2) are presented in Figs. 2(b)–2(d). The field strength $|E|^2$ of the evanescent Bessel beam generated at the last interface of the 1D PBG is shown in the inset of Fig. 2(b). The peak of the generated Bessel beam is stronger than the result using SPR.[5] The field transverse profiles are illustrated in Fig. 2(b). The full width half maximum (FWHM) of the central spot is 0.30λ. The decay length is estimated from Fig. 2(c) to be about 0.28λ defined by the $1/e^2$ point along the z axis. Normalized transverse profiles of field strength at different distances from the last interface are plotted in Fig. 2(d). The main lobes nearly overlap each other, indicating the nondiffracting property of Bessel beam. Consequently, an enhanced evanescent J_0 type Bessel beam can be obtained with the proposed setup under highly focused radially polarized illumination.

Similarly, highly focused azimuthal polarization can be used to realize enhanced evanescent J_1 type Bessel beams. Inside the 1D PBG, TE, and TM waves are localized in different index layers due to the different phases at the boundary. If we reverse the multilayer structure with the n_L dielectric being the ending layer and leave the other parameters unchanged, TE polarized waves will be enhanced instead [Fig. 3(a)]. The numerical results calculated with Eq. (3) are shown in Figs. 3(b)–3(d). An enhanced J_1 type Bessel beam

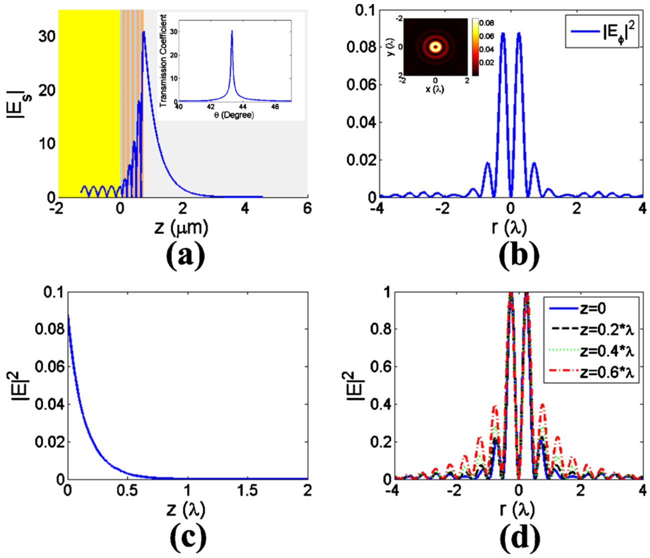

FIG. 3. (Color online) (a) Field distribution of s-polarization in the 1D PBG at resonant angle; (b) $|E_\varphi|^2$ at the bottom of the 1D PBG for an azimuthally polarized illumination. The corresponding 2D distribution of the total field strength $|E|^2$ is shown in the inset. (c) Total field strength $|E|^2$ along the z axis. (d) Normalized transverse profiles of $|E_\varphi|^2$ at different distances from the bottom of the 1D PBG.

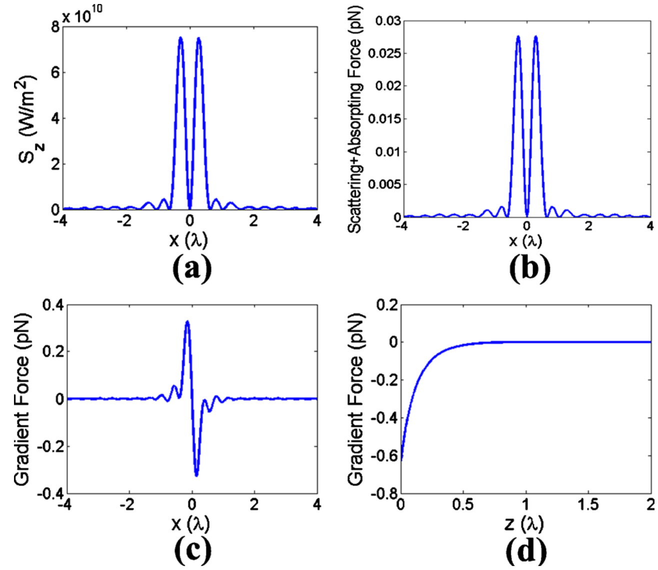

FIG. 4. (Color online) Radiation forces produced by highly focused radial polarization on a gold particle. (a) Calculated time averaged Poynting vector for a highly focused radial polarization at the focal plane; (b) sum of axial scattering and absorption forces in transverse plane; (c) transverse gradient force; and (d) axial gradient force.

with an annular shaped focal region is generated with azimuthal polarization. The FWHM spot size of the main lobe is 0.25λ and the decay length is 0.29λ.

In the above examples, we have chosen the number of period N=5 for practical reasons. In general, for smaller number of periods, the resonant transmission peak will be broadened and the transmission at lower incident angles will increase. Consequently, the quality of the generated evanescent Bessel beam will degrade and the normalized transverse profile will no longer maintain constant shape. For increased number of periods, the generated field total intensity will decrease due to a too narrow resonant peak. In addition, design with more periods demands more complexity on fabrication and becomes less practical.

Enhanced evanescent Bessel beams may find applications in optical tweezers.[9] Due to the strong scattering/absorption force, metallic particles are generally considered difficult to trap. Radial polarization has been shown to be advantageous for stable trapping of metal nanoparticle since the axial Poynting vector of highly focused radial polarization near optical axis is substantially zero, minimizing the scattering/absorption forces that destabilize the trap.[10] We perform a simulation with the enhanced evanescent J_0 Bessel beam under the same conditions as Ref. 10 for a gold Rayleigh particle with diameter of 38.2 nm ($\varepsilon=-10.98+1.33i$ at 633 nm) and 100 mW laser power (Fig. 4). It can be seen that extremely strong axial field only contributes to gradient force. There is one equilibrium point in the transversal plane where the particle can be stably trapped [Fig. 4(c)]. The gradient forces are 50% larger compared to the results of Ref. 10 owing to the band-edge enhancement. Due to the evanescent decay of the generated Bessel beam, the gradient force in the z direction pointing toward the 1D PBG [Fig. 4(d)] is ten times higher than that reported in Ref. 10. Similarly, enhanced J_1 evanescent Bessel beam is useful to trap magnetic nanoparticles, hollow particles, and particles with a refractive index lower than the ambient.[11]

This comparison for the applications in optical tweezers demonstrates the importance of the field enhancement at the band edge, which is one of the key advantages of this proposed method for the generation of evanescent Bessel beam. The 1D PBG structure reflects the majority of impinging focused wave and only a small fraction of the incident angular plane wave spectrum will be able to couple to the surface mode. However, the field enhancement factor is high enough to overcome this to achieve trapping performance better than the case for highly focused CV beams in free space. The generation efficiency can be further significantly improved if the incident CV beam amplitude distribution $P(\theta)$ can be shaped into a narrow annular distribution that better matches to the resonant coupling angle.

IV. CONCLUSION

In summary, we studied a novel setup to generate enhanced evanescent Bessel beams. When a radially polarized beam is highly focused onto the last interface of a 1D PBG, the band edge resonance mimics the function of an axicon and creates resonantly enhanced field at the last interface of the 1D PBG, creating an enhanced evanescent J_0 type Bessel beam. By reversing the 1D PBG and switching the polarization of incident beam to azimuthal, J_1 type enhanced evanescent Bessel beam can also be generated conveniently. These enhanced Bessel beams may have important applications in optical manipulations of dielectric, metallic, and magnetic Rayleigh particles near the surface.

ACKNOWLEDGMENTS

This work was supported by the National Basic Research Program of China under Grant No. 2011CB301802, National Natural Science Foundation of China (Grant Nos. 60736037 and 10704070), and "the Fundamental Research Funds for the Central Universities."

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