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Subdiffraction confinement in dielectric waveguide with extreme anisotropy

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ABSTRACT

All-dielectric slab waveguide filling the core with metamaterials of extreme anisotropy realizes the light transport being confined in a subdiffraction region with substantial energy concentration. The extreme anisotropy makes the evanescent waves in the claddings decay faster and the guided mode tightly localized in the core. Furthermore, the cutoff width can be decoupled from the group velocity of the mode, it can reach zero in the limit of extreme anisotropy but still sustain considerable group velocity. We analyze technically realizable cases and conclude that our work can contribute to improvements of various electromagnetic devices, from visible to microwave frequency regions.

1. Introduction

In the last decade, massive effects have been devoted to the miniaturization and integration of electronics and photonics on the same platform [1]. However, the diffraction limit of light is a fundamental barrier to combine optical functionalities with electronics at nanoscale [2], which hampers the localization of electromagnetic wave into regions with dimensions much smaller than the wavelength in the material.

The use of metal is one of the most elementary and feasible ways in the visible range to overcome the diffraction limit due to the collective oscillations of the surface plasmon-polariton (SPP) at interface [3], which forms a kind of evanescent waves containing high spatial-frequency information [4,5]. However, the absorption in metal limits light to propagate only within a few micrometers and subsequent thermal issues hinder dense photonic integration. Hence, all dielectric components are desirable to realize efficient light transport and confinement in deep subwavelength space.

Dielectric approaches to confine light in subwavelength regions are generally based on the control and manipulation of guided modes, including large refractive index contrast [6–8] and Bragg reflection of waves in the bandgap of photonic crystals [9,10]. However, it is the evanescent wave that limits the extent of subwavelength confinement. All dielectric metamaterials with extreme anisotropy offer an extra dimension of flexibility with their capability of efficiently controlling the optical momentum of evanescent waves. A glass waveguide surrounded with all-dielectric metamaterial claddings has been demonstrated to confine light below the diffraction limit in the context of relaxed total internal reflection (TIR), which demands the dielectric constant of the core to be larger than the component of that of the metamateral claddings in the direction perpendicular to the interface. In addition, the penetration depth of evanescent waves into the claddings is governed by the ratio of the components of the dielectric tensor [11]. However, this kind of waveguide has several drawbacks. Firstly there is a tradeoff between the group velocity and the extent of transverse light confinement. This is because the core material in Ref. [11] is ordinary dielectric. It is well known that the larger the refractive index of the core is, the energy is more concentrated. But this will be simultaneously accompanied by the decrease in group velocity. As a consequence, the cutoff width which exists for the asymmetric geometry will also increase. Secondly, from the practical point of view, the realization of dielectric metamaterials with extreme anisotropy mostly relies on a multilayer structure consisting of two materials with high index contrast and the layer thicknesses far below the wavelength of light [12]. The dielectric response of periodic multilayer structures can be accounted for by a uniaxial dielectric tensor with two distinct elements in the Effective Medium Theory (EMT) approximation [13]. If one component of the dielectric tensor satisfies the relaxed-TIR condition, i.e., being smaller than the dielectric constant of the core, the other cannot be extremely large according to EMT, which restricts the realization of extreme anisotropy. Using a high index core may solve the problem but will again lead to the decrease in group velocity. Moreover, two claddings of dielectric metamaterial involving two multilayer structures will occupy much space, which prevent the compactness of integration.

In this paper, a new class of all-dielectric slab waveguides comprising artificial materials is proposed which surpasses the diffraction limit and realizes subdiffraction confinement. In addition, a considerable group velocity of the mode can still be sustained and the cutoff frequency is removed in the limit of extreme anisotropy. Finally, the

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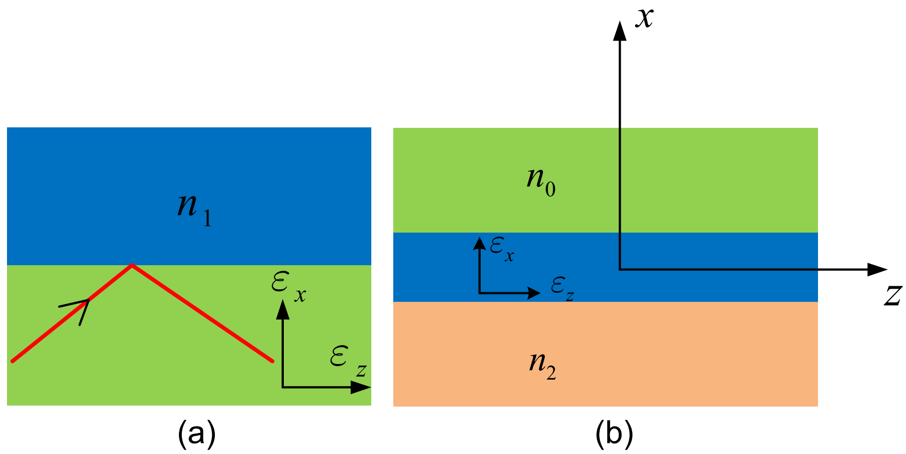

Fig. 1. (a) Relaxed-TIR: the condition for TIR is relaxed to $\sqrt{\varepsilon_x} > n_1$ when light moves from anisotropic medium (ε_x,ε_z) to dielectric n_1; (b) slab waveguide based on Relaxed-TIR: $\sqrt{\varepsilon_x} > n_0$ and $\sqrt{\varepsilon_x} > n_2$ preserve the conventional waveguiding mechanism, the wave can be confined inside the core using anisotropy ($\varepsilon_z \gg 1$).

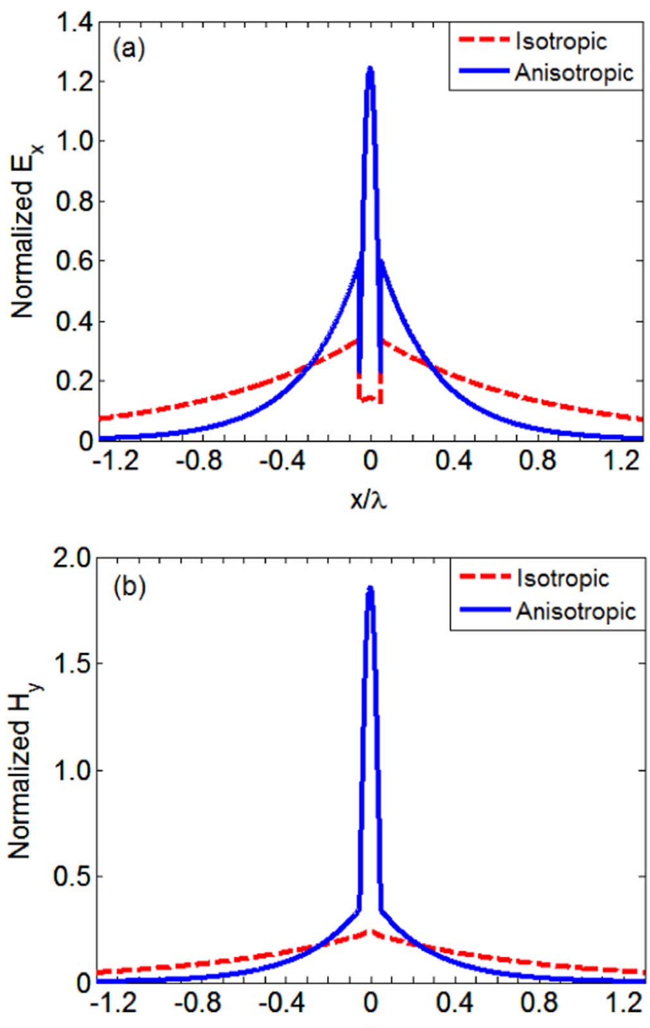

Fig. 2. Normalized (a) E_x and (b)H_y profiles of TM mode for a slab waveguide with all-dielectric metamaterial core ($\varepsilon_x = 2.6$, $\varepsilon_z = 40$) surrounded by air (solid line) on comparison to the case of a conventional waveguide ($\varepsilon_x = \varepsilon_z = 2.6$) (dashed line). The core size is 0.1 λ. Inset: the mode length achieves subdiffraction deeply as ε_z increases.

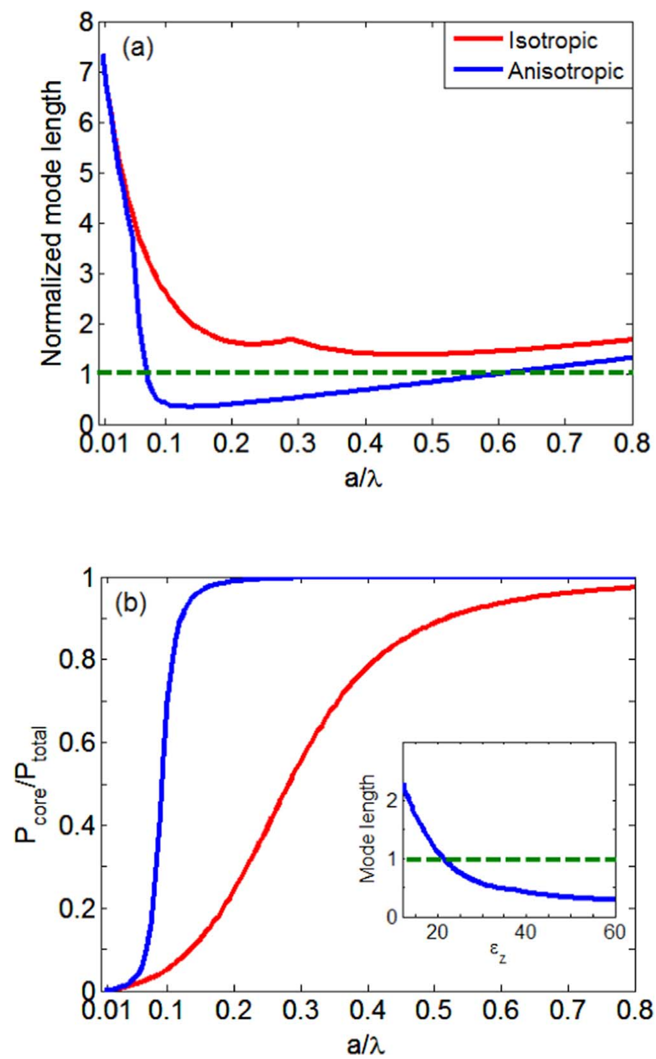

Fig. 3. Mode length comparison of slab waveguides with the core size. It shows that the anisotropic core ($\varepsilon_x = 2.6$, $\varepsilon_z = 40$) can grasp TM mode to subdiffraction values. Inset: the total power completely concentrates in the core across a large range of the core size as compared to the case in conventional waveguide.