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Hybrid Confinement of Visible Light in a Nanophotonic Resonator

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Abstract. We report on the design of a novel nanoresonator operating at visible wavelengths, in which light confinement is achieved by a hybrid mechanism based on total internal reflection and photonic band gap. We show that this structure can support resonant nanophotonic modes with mode volumes on the order of one cubic wavelength, and Q factors exceeding several tens of thousands. Its properties make it ideal for controlling and enhancing the light-matter interaction at sub-wavelength scales.

1 Introduction

Nanoresonators are extremely powerful in increasing the light-matter interaction in dielectric systems, as they can provide high quality factors (Q) and small mode volumes (V). In this respect, structures based on photonic crystals (PhCs) are known to support resonant modes characterized by small V, even smaller than a cubic wavelength of light [1]. However, such structures are usually quite challenging to fabricate, because they require a sufficient refractive index contrast of the constituent materials and are typically realized in suspended membranes, which limits their mechanical stability. Finally, the large field enhancement achievable in these systems is often obtained inside the structure, reducing their utility in those applications that require the enhancement of the light-matter interaction near the surface.

Bloch surface waves (BSWs) propagating at the truncation interface of a periodic multilayer are a valuable approach for surface optics, with surface field enhancements larger than those achievable in dielectric slabs [2]. BSWs provide large freedom in terms of constituent materials, from organic compounds to semiconductors, and operate in a wide spectral range, remarkably at visible wavelengths, for which there is paucity of transparent materials having a strong refractive index contrast. The possibility of guiding BSWs by simply realizing a polymeric ridge waveguide makes them appealing for the development of an etchless, all-dielectric integrated photonic platform [3]. A full 3D confinement of BSWs can be readily achieved, e.g., by bending the ridge on itself to obtain high-Q ring resonators [4].

However, so far, the development of BSW-based ridges has been hampered by relatively high propagation loss (of the order of dB/mm or higher) that cannot be explained in terms of surface scattering or material absorption. Plus, 3D confinement via ring resonators or other whispering-gallery-mode solutions [5] usually comes at the price of relatively large V, due to the large bending radii allowed by the gentle in-plane confinement of light.

Here, we demonstrate a photonic crystal nanobeam cavity (PhCNC) in a PhC ridge supporting BSWs [6], thus combining the small V and footprint size of a PhC cavity with the surface field enhancement typical of BSWs. We also track down the origin of the disappointing performance of PhC ridge waveguides in terms of propagation loss, and suggest a general design principle to reduce it.

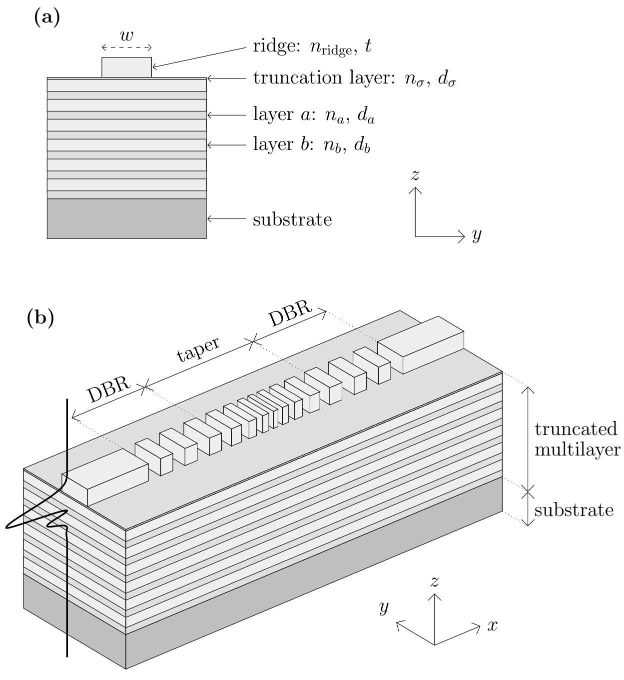

Figure 1. (a) Cross section of the PhC ridge. (b) Sketch of the BSW-based PhCNC.

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2 Results

The structure under investigation is a truncated $TiO_2(a)/SiO_2(b)$ periodic multilayer having a unit cell composed of two layers of thickness $d_a = 100\,\text{nm}$ and $d_b = 182\,\text{nm}$, and refractive index $n_a = 2.67$ and $n_b = 1.46$, respectively. The multilayer has $N = 15$ periods and is truncated with a TiO_2 layer of thickness $d_\sigma = 11\,\text{nm}$. The planar structure is loaded with a PMMA ($n_{\text{ridge}} = 1.49$) ridge of width $w = 1.0\,\mu\text{m}$ and thickness $t = 0.4\,\mu\text{m}$ in air ($n_{\text{clad}} = 1$), as illustrated in Fig. 1(a). We operate at a target wavelength $\lambda_0 = 532\,\text{nm}$. Here, light confinement relies on the hybrid combination of total internal reflection (TIR) from the homogeneous cladding and reflection within a (polarization-dependent) photonic band gap (PBG) from the multilayer. The geometry above guarantees the existence of a TE-like guided BSW that propagates along the ridge with estimated propagation loss of about 5.4 dB/m.

The PhCNC is obtained by patterning two Bragg mirrors (DBRs) along the PMMA ridge, each including $N_{\text{Bragg}} = 30$ repetitions of a PMMA rectangular stack/air slit unit cell having lattice constant $\Lambda_{\text{Bragg}} = 189\,\text{nm}$ and PMMA filling fraction $f = 0.476$, as sketched in Fig. 1(b). This geometry greatly simplifies the fabrication procedure, which can be done by standard lithography. In addition, the system can be modeled within an effective index (EI) framework to limit the computational cost of its optimization, which usually requires to investigate a large parameter space.

Here, the EI method is applied twice. First, we determine the effective refractive index of the guided mode supported by the ridge (n_{eff}) by modeling its cross section as an effective slab waveguide, where the cladding and core refractive indices are those of the modes supported by the 1D bare (n_{bare}) and PMMA-loaded (n_{load}) multilayers, respectively. Second, the in-plane cavity is treated as an effective 1D multilayer of alternating layers of indices n_{eff} and n_{bare} for each PMMA stack and air slit, respectively. All these tasks are easily solved, e.g., via the transfer matrix method, which can take only minutes, if not seconds, on a standard personal computer.

In our design, the Bragg mirrors are adiabatically tapered by quadratically resizing a number $N_{\text{taper}} = 30$ of unit cells in both directions away from the center of the cavity [7], with the lattice constant Λ_i of the i-th cell of the taper given by $\Lambda_i = \Lambda_0 + (\Lambda_{\text{Bragg}} - \Lambda_0)(i/N_{\text{taper}})^2$, where $\Lambda_0 = 181\,\text{nm}$ is the minimum lattice constant.

Tapering the Bragg mirrors is crucial to mitigate the effect of diffraction loss [8], which is expected to be the leading loss mechanism when one neglects scattering loss from fabrication imperfections and finite size effects of the multilayer. This can be understood by looking at the mode field distribution in Fourier space. The field Fourier components that fall inside the air light cone or outside the multilayer PBG are not guided and can couple to the continuum of radiation modes. A smooth modification of the nanobeam geometry gives rise to a gentle variation of the electric field, and therefore, to a narrower distribution of its Fourier components, which can be piloted away from the leaky region. We notice that, as compared to free-standing or on-insulator nanobeams, here the leaky region extends not only to the air light cone, but also to the photonic bands associated with the underlying periodic multilayer.

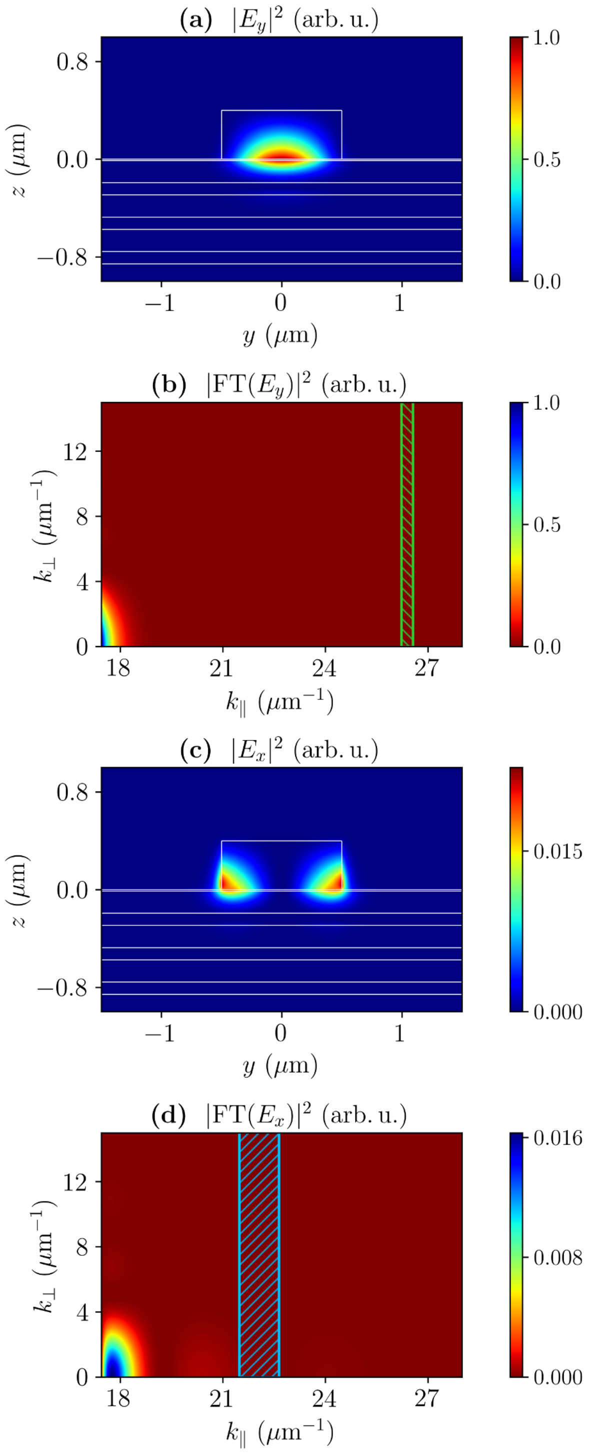

Figure 2. Intensity profiles (normalized to the maximum value) of (a) E_y and (c) E_x for the unpatterned ridge waveguide, along with the Fourier transform (FT) of (b) E_y and (d) E_x. The dashed areas correspond to regions where the (b) (green) TE and (d) (cyan) TM PBGs are closed.

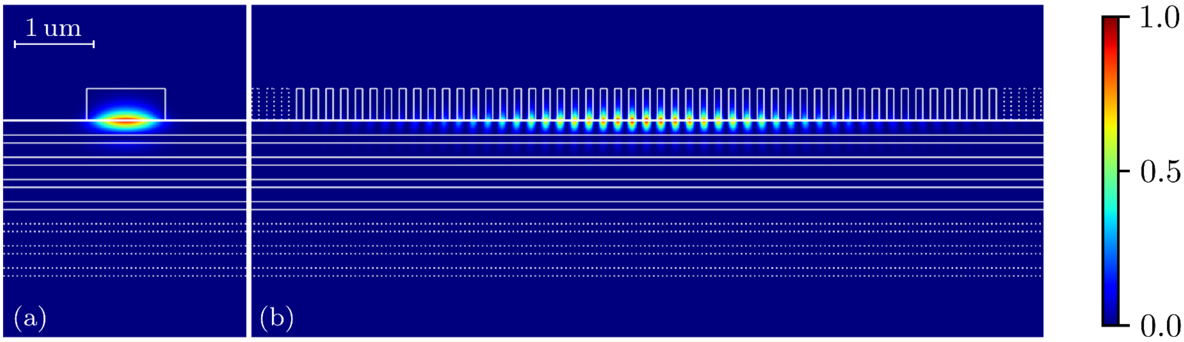

Figure 3. Intensity profile (normalized to the maximum value) of the electric field of the fundamental mode as obtained from FDTD simulations. (a) PhC-ridge cross section. (b) Nanobeam cross section.

In this respect, light polarization plays an essential role. We remark that, due to the confinement in the lateral direction, the mode supported by the PhC ridge is not purely TE polarized, but TE-like polarized, in that it exhibits all six nonvanishing field components, with E_y being the dominant one and E_x, E_z being weak but nonzero. Hence, the simultaneous presence of both TE and TM PBGs is always required to have each field component's Fourier distribution well-located within the appropriate PBG. A careful choice of the PhC ridge geometry can ensure wide and well-overlapping TE and TM PBGs in the spectral region of interest.

An analogous polarization-wise strategy also allows one to obtain low-loss guided modes in the unpatterned ridge without resorting to ultra-wide ridges, thus ensuring small mode areas in a single-mode regime [9]. Low-loss waveguide modes are particularly desirable for the realization of more complex devices, e.g., PhCNC arrays. In Figs. 2(a) and 2(c) we show the intensity profiles for the electric field components E_y (TE component) and E_x (TM component), respectively, of the TE-like mode guided by the unpatterned ridge (E_z is not shown because negligible). Figs. 2(b) and 2(d) show the corresponding Fourier transforms (FTs) as a function of the in-plane wavevector $k_\parallel = \sqrt{k_x^2 + k_y^2}$ and the out-of-plane wavevector $k_\perp = k_z$. The dashed areas denote the leaky regions in which either TE or TM PBG is closed. We observe that both E_y and E_x FTs are distributed almost entirely within the respective guiding regions, which results in reasonably low propagation loss $\alpha = 5.4\,\mathrm{dB/m}$. One can show that even a slight variation of the multilayer composition (e.g., changing its filling fraction or its period or both) can determine a considerable modification in the spectral position and extension of the TE/TM PBGs, which can result in a dramatic increase in propagation loss.

In Fig. 3 we show the results of a full 3D FDTD simulation for the PhCNC with the geometry parameters reported above, which are obtained from an EI-based optimization. 3D confinement of the BSW mode is associated with a Q factor of about 5×10^4 and $V \sim \lambda_0^3$. This demonstrates the existence of the confined mode and also assesses the efficacy of our EI framework, which proves to be robust to some variation of the model parameter that accounts for the variability of the actual fabrication process.

3 Conclusion

We demonstrated a new PhC resonator based on BSWs. This structure, characterized by a high Q/V and a field enhancement near the structure surface, has a small footprint size, is mechanically stable, is flexible in terms of constituent materials, and can be fabricated with etching-free technologies, e.g., from low-index polymeric ridges on commercially available multilayers. It can be implemented in a wide spectral range, from infrared to visible wavelengths.

All these properties, which are not easily obtained at once in other conventional photonic cavities, make this platform appealing for a number of applications that require large enhancement of surface light-matter interaction, from optical sensing to quantum nanophotonics.

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