One channel tunable bandpass superconducting filter for wavelength selective switching applications in communications systems

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***Abstract*—We design and evaluate the performance of optical filters that are built from one-dimensional photonic crystals (PhCs) amenable for integration into optical networks based on wavelength division multiplexing (WDM). The photonic heterostructures comprise the integration of a ferroelectric $(\mathrm{BaTiO_3})$, a dielectric $(\mathrm{Y_2O_3})$, and a critical high-temperature superconductor material $(\mathrm{YBa_2Cu_3O_{7-x}})$ in between. Such nanosystems can allow for routing and switching optical signals at well defined wavelengths in the near-infrared spectral regions, as required in optical telecommunication channels. By tailoring the superconductor key parameters (e.g. layer thickness), temperature and the direction of the incident light, we provide a computational test-bed for the implementation of multiplexed PhC-optical filters that can be integrated into either photonic and optoelectronic circuits or in devices for the transmission of information that work in the 1300 - 1700 nm range. The proposed filters are expected to work at very low-temperature environments (e.g., outer space conditions).**

***Index Terms*—Optical Filters, Superconductors, Transfer matrix technique, Photonic Crystals**

I. Introduction

To keep up with the global optical data traffic demands, current generation of optical communication systems need to increase transmission capacity [1]. Wireless communication uses as a main transmission media the ratio frequency (RF) spectrum. However, Infrared (IR) and Visible Light Communication (VLC) systems became an alternative to RF due to their operation at high frequency regions with larger transmission bandwidth and an increment in the information-carrying capacity of the communication system [2], [3]. In this context, an important issue is the need to develop novel devices that allow full control of light propagation throughout the visible and near-infrared (NIR) regimes, while minimizing losses during such process [4]–[8].

Here, we design and computationally characterize a novel optical filter built from a one-dimensional (1D) PhC that

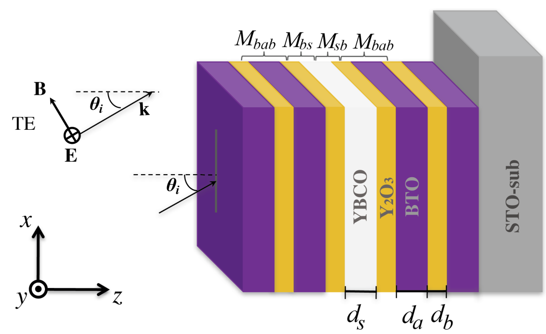

Fig. 1. Schematics of the $(\mathrm{BTO/Y_2O_3})_\mathrm{N}/\mathrm{YBCO}/(\mathrm{Y_2O_3/BTO})_\mathrm{N}$ 1D tunable photonic filter, composed of alternating layers of $\mathrm{BaTiO_3}$ and $\mathrm{Y_2O_3}$, with a $\mathrm{YBa_2Cu_3O_{7-x}}$ superconductor defect layer, with corresponding widths d_a, d_b and d_s, respectively. **k** is the incident wave vector that fixes the direction of $\mathbf{E} \times \mathbf{B}$, and **E** and **B** denote the electric and magnetic fields, respectively. The light propagation is defined by θ_i, the angle with the z-axis, and xz is the plane of light incidence. M_{bab}, M_{bs}, M_{sb} indicate the transfer matrices in the intermediate layers ($\mathrm{Y_2O_3}$, $\mathrm{BaTiO_3}$, or $\mathrm{YBa_2Cu_3O_7 - x}$).

can be integrated into optical networks based on wavelength-division multiplexing (WDM), with a high-Q factor in the telecom region. These filters route and switch optical signals at a given wavelength in the NIR range, following the spectral grids for WDM applications as per the ITU-T G.694.2 recommendation from the International Telecommunication Union (ITU) [9]. The photonic heterostructures are built from the integration of ferroelectric and ceramic materials, and superconductors, and we report on their performance above and below the superconductor critical temperature. We show that such a nanosystem can allow the implementation of optical filters based on PhCs that are amenable for integration into photonic and/or optoelectronic circuits, or in devices for the transmission of information in the visible and NIR

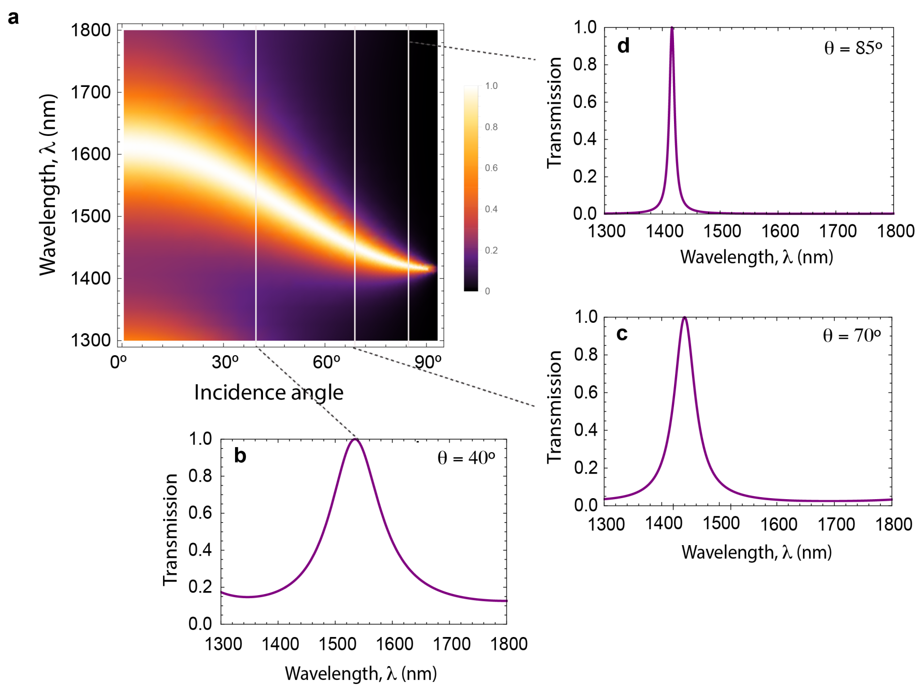

Fig. 2. **(a)** Photonic crystal optical filter response for TE polarization in the whole range of incident angles at $T = 80$ K, in the NIR range. The dark areas correspond to the high-reflectance ranges and yellow regions indicate high transmission bands. White vertical lines in the figure are a guide to the eye, and correspond to the results for 40º, 70º and 85º, respectively. Panels **(b)**, **(c)** and **(d)** display the calculated transmittance of a $(BTO/Y_2O_3)_2/YBCO/(Y_2O_3/BTO)_2$ nanostructure, at $T = 80$ K and incidence angles of 40º, 70º and 85º, for TE polarization, respectively.

ranges, at very low temperature environments (as in outer space conditions, to cite just one example).

II. Results and Discussion

In order to produce the optical filter here presented, the strategy is to model a waveguide with a core of low refractive index surrounded by a periodic multilayer reflector. We start with the design of an efficient periodic reflector such as a quarter-wave stack [10] built up of a number of quarter-wave layers of Y_2O_3 and $BaTiO_3$ materials. In particular, the quarter-wave reflector has been designed, although not restricted to, for a normal angle of light incidence, that is $\theta_i = 0$, and for a given operating wavelength in the infrared region centered at 1550 nm. To complete the optical filter, an ultrathin superconducting film was surrounded on each side by a periodic reflector containing N bilayers of $BaTiO_3$ and Y_2O_3.

Figure 2 plots the filter optical response for $N = 2$, in the wavelength region from 1300 nm to 1800 nm as a function of the whole range of incident angles for TE polarization at $T = 80$ K and $d_s = 10$ nm. In Fig. 2**(a)**, the dark areas correspond to the high-reflectance ranges, while yellow areas, indicate high transmission ranges where radiation passes through the structure. An interesting feature that arises is related to the light transmission through the structure: it has quite a sensitive response to the light incidence angle as it can be observed in the continuous displacement of the band to shorter wavelengths as the incident angle increases. In fact, one transmission band arises in the near-infrared region at 1600 nm at 0º, which continuously decreases to 1418 nm near 90º. We remark the importance of such a band, since it lies within several spectral bands used in optical fiber communications (i.e., the E, S, C, and L bands) [11].

In Figures 2**(b)**, **(c)** and **(d)**, we plot the transmittance behavior for spectra computed at incident angles of 40º, 70º and 85º, respectively. The sharp peaks in these figures mean that the $(BTO/Y_2O_3)_2/YBCO/(Y_2O_3/BTO)_2$ nanostructure can indeed be configured as a narrow-band filter [12]. These results show noticeable changes in the transmission band width with the incident angle, which narrows as the angle of incidence approaches 90º. In such a way, for angles closer to 90º, the shape of the transmission peak changes, allowing for a bandpass filter over a narrower range. Then, if the light incidence angle is varied by a small amount, it is possible to tune the bandpass over a narrow range of wavelengths. For example, Fig. 2**(d)** shows that the optical nanostructure allows the passage of a very narrow wavelength width and attenuates frequencies outside the transmission peak, resulting in a transmission coefficient that goes to zero. This result is in agreement with the fact that when a wave impinges at a right angle, it moves parallel to the separation surface of the two media, and therefore, its energy is not transmitted through the surface [10].

References

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