Multiple wavelengths filtering of light through inner resonances

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We show that by using the internal resonances of a grating, it is possible to design a filter working for multiple wavelengths. We study the characteristics of the device with respect to the constituting parameters and we propose a realization process.

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During the past decade, photonic band gap (PBG) structures, which are artificial structures that range from multilayer stacks in one dimension to much more complicated topologies in three-dimensional space, have been the subject of extraordinary interest due to their unusual linear and nonlinear optical properties [1]. From the point of view of nonlinear optics, the most important property of PBGs is perhaps the possibility of enhancement of the field intensity by several orders of magnitude near the band edge, thanks to light localization effects [2,3]. The simultaneous availability of exact phase matching conditions and field confinement, at certain frequencies, leads to interesting applications such as the generation of a second-harmonic signal with high efficiency [4], and the processes of multiple wave mixing and down conversion [5], to name a few. In addition to the large number of possible applications in nonlinear optics, PBGs also prove to be useful for classical applications, such as interference filters [6], ordinary Bragg mirrors, and omnidirectional reflectors [7].

With the increasing use of lasers, the problem of laser shielding with both active and passive devices is becoming more and more important, as the range of wavelengths of available sources covers nearly the entire visible range. Many efforts are directed at studying solutions to the so-called optical limiting problem, i.e., active laser shielding. An ideal optical limiter transmits light linearly up to a certain input threshold, after which the transmission is fixed to a nearly constant value, thus providing sensor protection and eye protection from laser radiation over a wide range of wavelengths [8]. Nevertheless, a passive multiwavelength filter for different laser wavelengths without reduction of the overall filter transparency is still an open task. Designing an interference filter for more than a wavelength is a typical problem that can be solved with a PBG device. The ideal transmission versus wavelength function should present as low a transmission as possible at those wavelengths that are to be shielded, and as a high transmission for the remaining visible range, thus ensuring color neutrality of the overall structure. Nowadays conventional filters are realized by dispersion of semiconductor powders in a solid-polymeric or glassy-polymeric matrix. Shielding comes about via semiconductor absorption [8].

In this paper, we propose the design of a structure for simultaneous shielding of 532 nm [second harmonic of a Nd yttrium-aluminum-garnet (Nd:YAG) laser], 632.8 nm (He-Ne laser) and 800 nm (Ti-sapphire laser), that is, the wavelengths of the most common laser devices. The physics that underlies our design is that of resonant gratings [9–13]. That is, the filter works by using some particular resonant properties of a PBG. The structure that we propose is basically a lamellar grating deposited on a homogeneous slab (cf. Fig. 1). The slab is made of SiO_2, the grating is made of square rods of TiO_2 between which another material is deposited. The point is to design the structure in such a way that the wavelengths to be shielded are inner resonances of the device: the presence of such resonances will be signaled by sharp dips in the transmission spectrum, just like absorption lines in the spectrum of natural materials. Internal resonances can be analyzed in two different ways: (i) a less conventional Mie scattering approach and (ii) a more usual leaky guided mode approach. The Mie resonances of the fiber correspond to frequencies, for which the energy is strongly localized inside the rod. When there are many rods, the rods behave as a set of strongly coupled oscillators, resulting in the shifting and, possibly, the split-

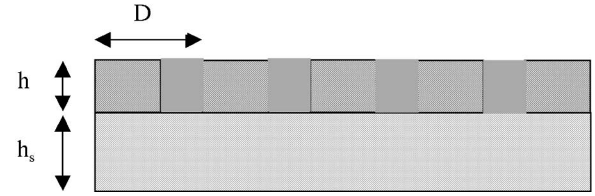

FIG. 1. Schematics of the filter.

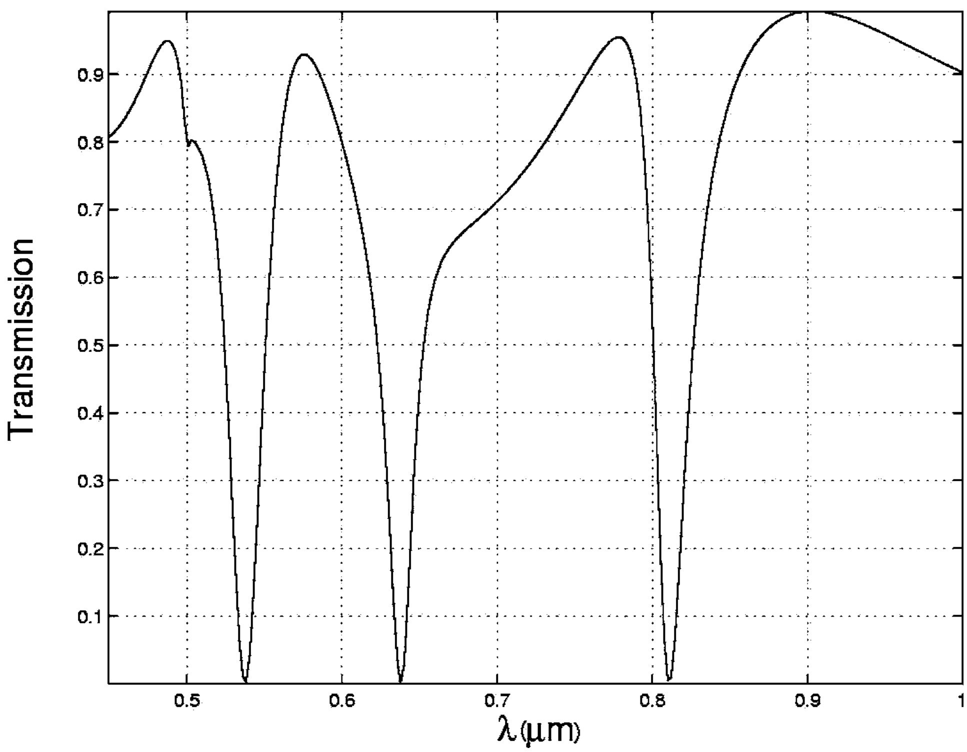

FIG. 2. Transmission through filter in normal incidence.

ting of the resonances [14–16]. In practice, the higher the index of refraction of the rods is, the stronger the confinement of the field and the smaller the shifting of the resonances will be.

The second, more conventional approach is to associate the internal resonances of the structure with leaky guided modes. For instance, by weakly modulating a homogeneous slab, it is possible to excite guided modes because of the folding of the bands above the light cone. Both approaches have their domain of validity: Mie scattering works well for high contrast rods, while the second approach describes more accurately the physics of weakly modulated structures. Although the resonance is always due to the excitation of a guided mode, it is the physical origin of this mode that changes according to the different point of view. For practical applications in the optical range, we do not expect to

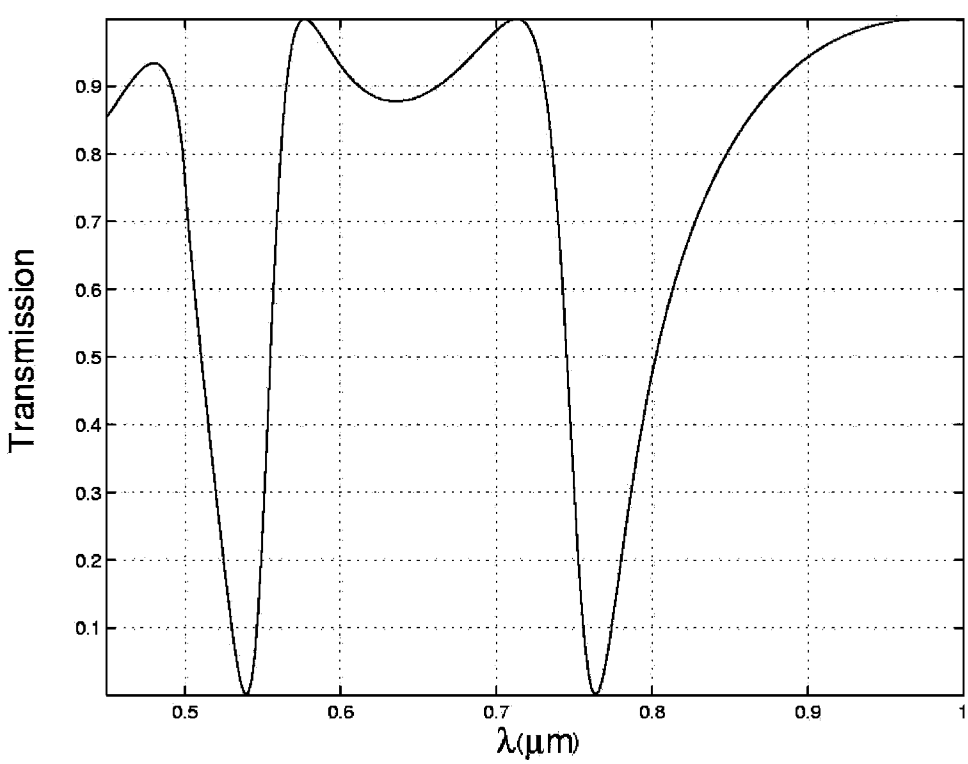

FIG. 3. Transmission through the grating alone in normal incidence.

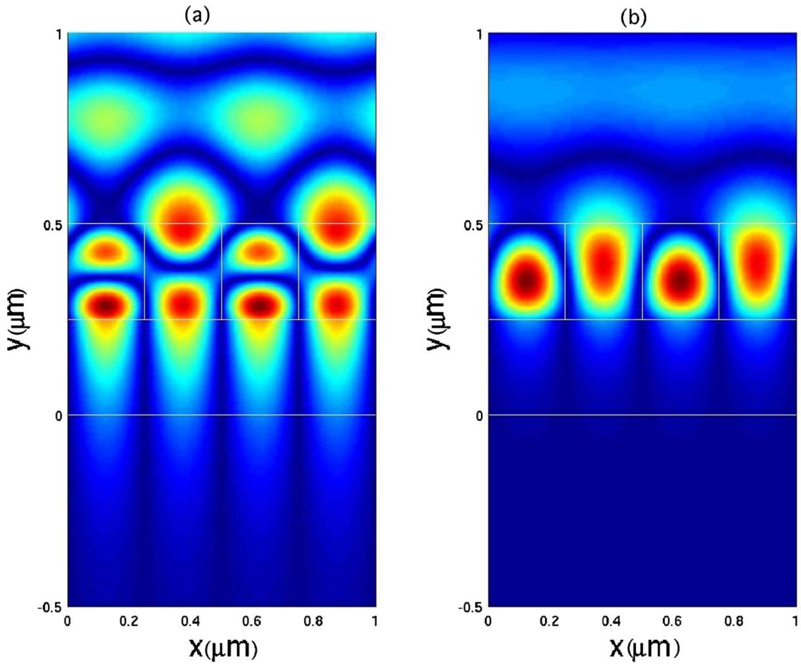

FIG. 4. (Color online) Maps of the field for the resonances of the grating. (a) $\lambda=0.53$ μm, (b) $\lambda=0.74$ μm.

have very high indexes at our disposal. Neither can we use weakly modulated structure, due to the constraints on the selectivity of the filter.

The reasoning above thus suggests a hybrid approach, and so we use a rigorous numerical code in order to find the position of the resonances. For the numerical results that follow, we use an algorithm that allows the rigorous resolution of the Maxwell system, by means of the rigorous coupled waves method [17]. The geometrical parameters for our filter are the following (see Fig. 1): $D=0.5$ μm, $h=0.25$ μm, $hs=0.25$ μm. The spatial frequency is denoted $K=2\pi/D$. In Fig. 2, we have plotted the transmission spectrum for an incident plane wave at normal incidence. The filling material has an index of 1.5 (i.e., that of SiO_2). There are sharp dips near the expected wavelengths and a good transmission outside these particular values, showing that the device complies with the above cited constraints for the design of an efficient filter. Let us now elaborate on the physi-

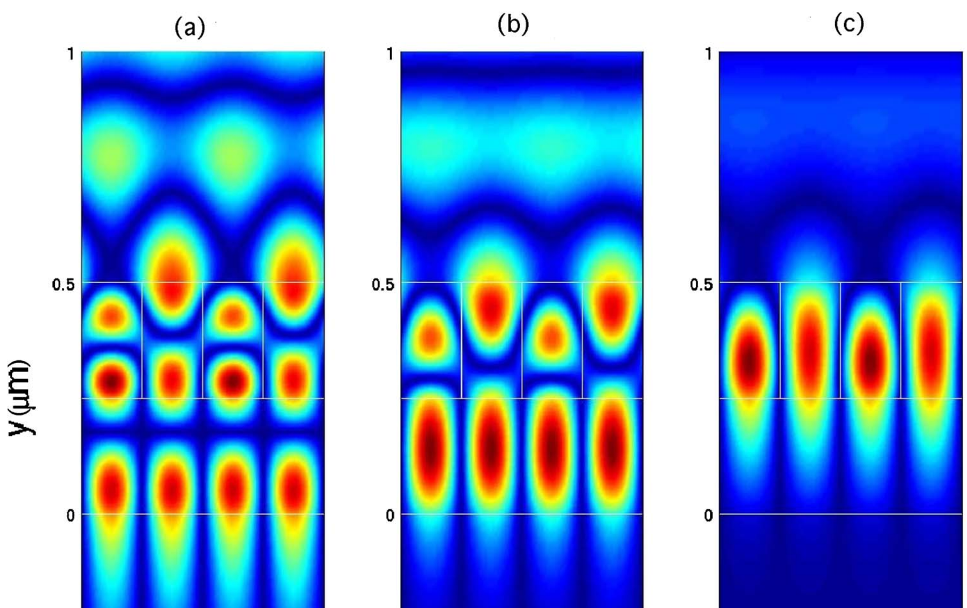

FIG. 5. (Color online) Maps of the field for the three resonances of the filter. (a) $\lambda=0.53$ μm, (b) $\lambda=0.63$ μm, (c) $\lambda=0.8$ μm.

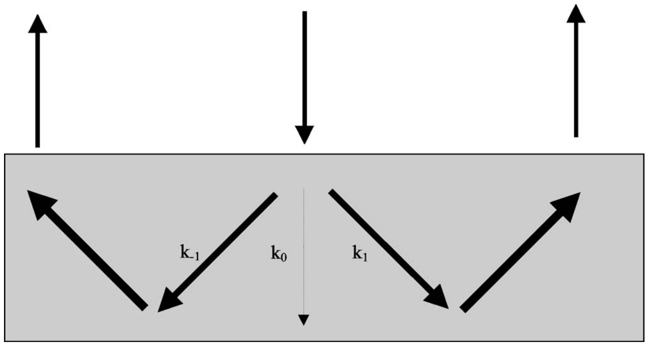

FIG. 6. Ray interpretation of the resonance.

cal origin of this behavior. To do so, we consider first the grating alone, that is, with the index of the slab set equal to 1. The transmission curve is given in Fig. 3. There are only two dips instead of three as in Fig. 2. These dips correspond to internal resonances of the grating alone. This is clearly seen in Fig. 4, where we have plotted the map of the magnetic field for these particular wavelengths. The field is clearly concentrated in the higher index zones of the grating. Now, when a slab of index 1.5 is added to the structure, a third resonance appears: it corresponds to the coupling that occurs between the grating and the slab. The maps of the field for the resonances of the filter are given in Fig. 5. It can be seen that the higher resonance is very much like that of the grating alone: it is mainly concentrated in the high index zone of the grating. This is due to the high concentration of the field inside the dielectric material, implying a higher quality factor, and hence a lower coupling to the outside. On the contrary, the middle resonance is strongly modified by the presence of the slab, which indicates strong coupling, hence a lower quality factor and, therefore, a less sharpened resonance. Finally, the resonance for the lower wavelength is clearly a resonance as a whole: the field spreads throughout the device.

We shall not elaborate further on the notion of resonance, which is linked to the profound phenomenon of Wood anomalies [18]. However, it is possible to form a simple picture of the physics of the field inside the photonic crystal that leads to a zero transmission coefficient (for lossless materials). In the range of wavelengths that we use here, there are three propagating modes inside the grating: that of orders −1, 0, and 1 (see Fig. 6): $\beta_0, \beta_{-1}, \beta_1$. The three main Bloch vectors are $k_0=(0,\beta_0)$, $k_1=(K,\beta_1)$, and $k_{-1}=(-K,\beta_{-1})$. It can be shown that at the resonant frequencies, the field corresponds to the Bloch modes with wave vector $k_{\pm 1}$. This wave vector is totally reflected at the lower interface, and hence, the transmission is zero.

Let us now look at the sensitivity of the filter to the various parameters. In Fig. 7, we study the evolution of the resonances with respect to the index of the slab. We have noted above that some resonances of the grating alone might couple strongly with the slab. Therefore, it is of primary importance to specify the influence of the slab. When the index of the slab is increased from 1 to 2.25, new resonances appear, and the redshift is much more pronounced compared to just varying the index of the filling material, as we will see below. This shows that the physics of these resonances is quite sensitive to the coupling mechanism and is in large part due to the small optical indexes at play. In fact, for higher indexes, the resonances would have a much higher quality factor, and would be less susceptible to coupling with other parts of the device. Nevertheless, the two chosen materials are well known and commonly used in optical applications. Next, we look at the evolution of the transmission as the index of the filling material is varied. Indeed, for practical purposes, the value of the index might vary due the fabrication process. Therefore, we would like the filter not to be too sensitive to variations of the index of the interstitial material. In Fig. 8, we have plotted the transmission with respect to the index of the interstitial material, as it varies between 1 and

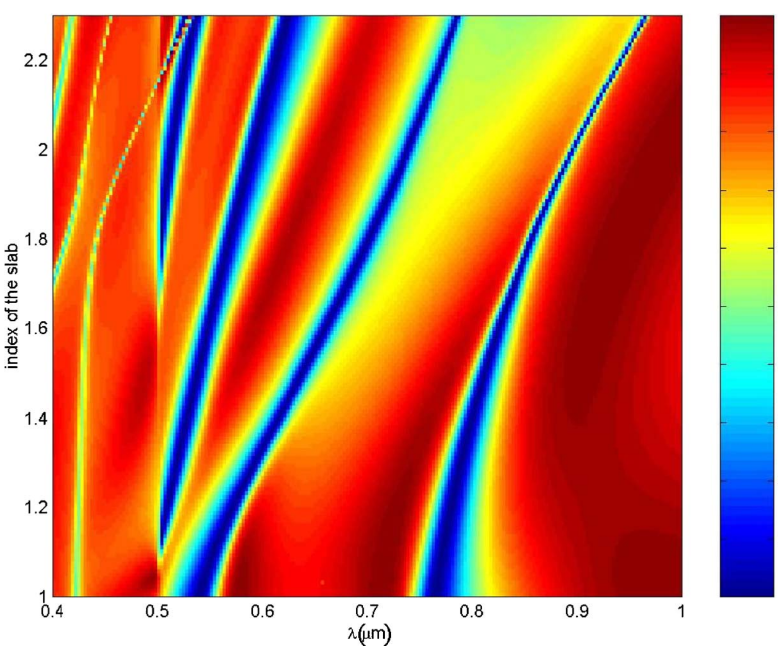

FIG. 7. (Color online) Transmission as a function of the slab index.

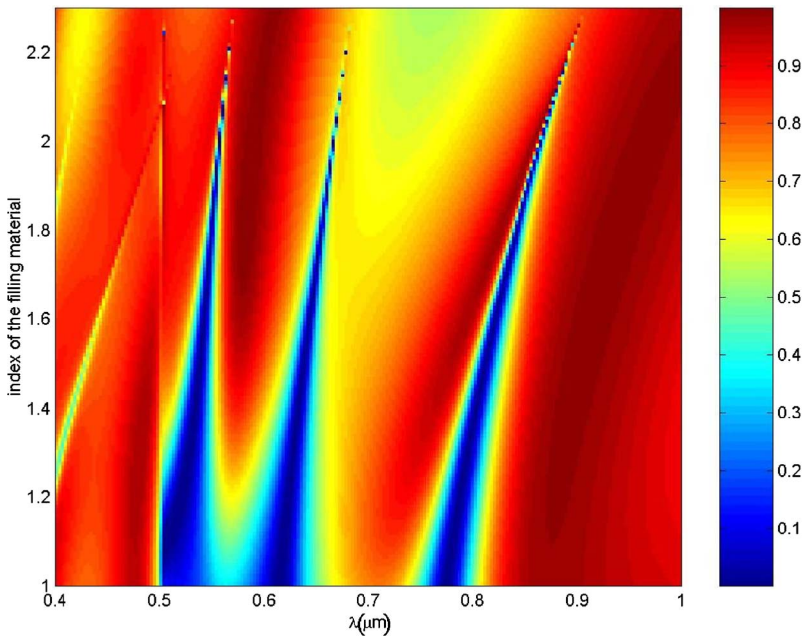

FIG. 8. (Color online) Transmission as a function of the index of the filling material.

2.3 (that is, that of TiO_2). The index of the slab is kept constant and equal to 1.5. The figure suggests that the resonances sharpen and are redshifted as the index increases. This is to be expected, as the resonances disappear when the index contrast is zero. We observe that the shift is only of a few percent, so that the filter is not very sensitive to the contrast. Finally, in Fig. 9, we plot the transmission as a function of the angle of incidence. We see that the positions of resonances are rather sensitive to the angle of incidence, which once again is due to the low index values. In fact, there is a splitting of the resonances resulting in the filtering of more than three wavelengths. However, the filter works sufficiently well for a variation of ±5° around normal incidence.

A few words should be said in regard to the practical realization of such a device. As described, the device could be fabricated using a multistep process, schematically represented in Fig. 10. First, SiO_2 and TiO_2 layers are deposited, one after the other, over a glass substrate by a conventional film deposition technique such as as sputtering or thermal evaporation. The TiO_2 layer is then patterned by electron beam lithography in order to obtain the

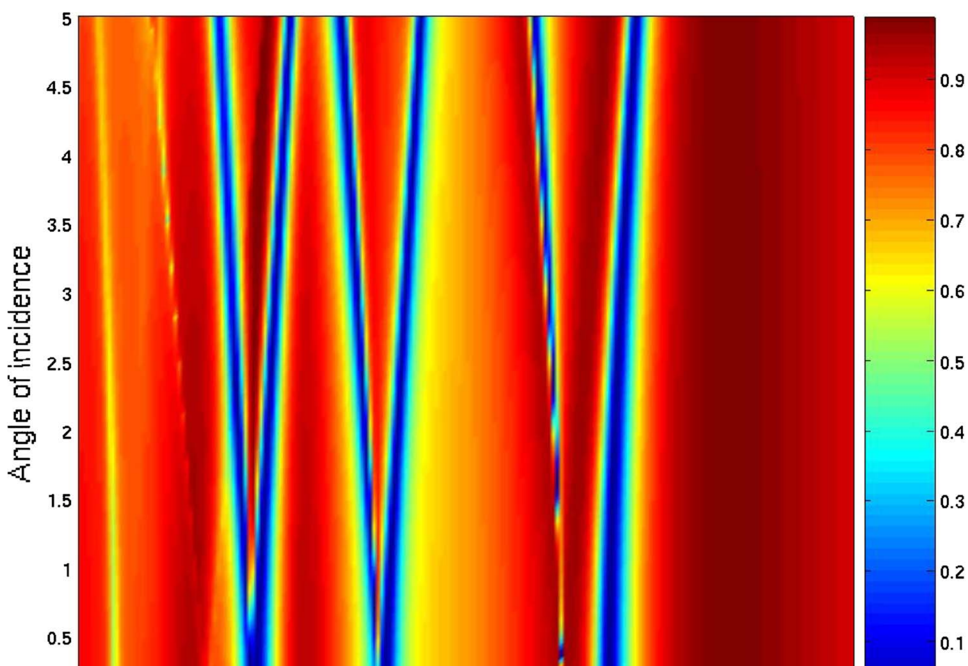

FIG. 9. (Color online) Transmission as a function of the angle of incidence.

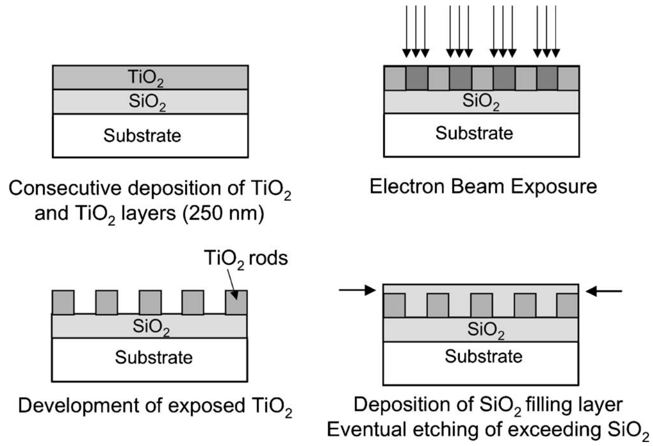

FIG. 10. Schematics of the realization process.

desired width and lateral distance for the resulting rods. Concerning this process, a crucial task will be to assess the surface roughness after the beam exposure. The obtained pattern will be developed by reactive ion etching (RIE) to remove with a solvent the area of TiO_2 exposed to the electron beam. As a result, only the TiO_2 rods will be left. Finally, the empty spaces in between two successive rods will be filled with SiO_2. This can be achieved by another deposition of a SiO_2 layer. Due to the required low depth to be filled ($\sim$250 nm), this last part of the fabrication process is expected to be the most difficult one. Specifically, we expect to get some SiO_2 deposited also outside the channels. This residual SiO_2 material can eventually be removed via an ion etching process.

In conclusion, we have proposed a multiwavelength filter based on resonances. By modifying the geometric parameters, the resonances can be tuned. The filter shows good stability with respect to the principal parameters (i.e., the index of the substrate and that of the filling material) which is a fundamental property for the design of a working device.

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