Paper

A Photonic-Crystal Selective Filter

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Abstract—A highly selective filter is designed, working at 1.55 μm and having a 3-dB bandwidth narrower than 0.4 nm, as is required in Dense Wavelength Division Multiplexed systems. Different solutions are proposed, involving photonic crystals made rectangular- or circular-section dielectric rods, or else of holes drilled in a dielectric bulk. The polarization and frequency selective properties are achieved by introducing a defect in the periodic structure. The device is studied by using in-house codes implementing the full-wave Fourier Modal Method. Practical guidelines about advantages and limits of the investigated solutions are given.

Keywords—filter, Fourier Modal Method, periodic structures, photonic bandgap materials, photonic crystals.

1. Introduction

Photonic crystals are artificial media, constituted by periodic implants of a material with a specific dielectric permittivity embedded in a homogeneous background of different permittivity [1], [2]. The main feature of a photonic crystal is the presence of frequency bands within which the waves are highly attenuated and do not propagate (bandgaps or stopbands). This property is exploited in a lot of applications, in the microwave region, as well as in the infrared and optical range; new ideas are under continuous research and novel components are designed [3]–[17].

The study of photonic crystals with defects is a topic of great interest. Defects may obviously be present in a structure due to fabrication errors [18], [19]. Very often, though, defects are on purpose introduced in photonic crystals to design resonant cavities, filters or switches [20]–[24]. In fact, the occurrence of a sharp transmission peak inside a bandgap may result from defect creation. By suitably choosing the configuration of the structure, it is possible to shape its transmission properties in a versatile way [25], [26].

In this work, we focus on the design of a photonic-crystal filter for fiber optic applications. The design specifications are that radiation at 1.55 μm has to be transmitted, with a 3-dB selectivity smaller than 0.4 nm, as is required in Dense Wavelength Division Multiplexed (DWDM) systems. The required filtering properties are obtained by using a dielectric photonic crystal and by properly interrupting its periodicity. In particular, some implants are removed in the middle of the synthesized structure, so that a homogeneous layer of anomalous thickness is present between two adjacent layers of rods.

The proposed device is studied by using in-house codes implementing the Fourier Modal Method (FMM) [27], as briefly resumed in Section 2. The FMM is a fast, accurate and versatile spectral-domain technique for the solution of plane-wave scattering problems by dielectric diffractive optical elements and photonic crystals.

Numerical results for the synthesized filter are presented in Section 3. Different solutions are proposed and compared, with photonic crystals made of rectangular- or circular-section dielectric rods, or else of holes drilled in a dielectric bulk. The transmission properties of the proposed components are investigated as a function of the polarization and the wavelength of the incident radiation.

Practical comments about advantages and limits of the different investigated solutions are given in Section 4, where conclusions are drawn.

2. FMM Modeling of Photonic Crystals

The structures proposed in this paper are designed and characterized by using an in-house code implementing the Fourier Modal Method (FMM), a full-wave spectral-domain technique that solves the monochromatic plane-wave diffraction problem by dielectric photonic crystals. The formulation of the method proposed in [27] is adopted. This approach was originally developed for the characterization of two-dimensional diffraction gratings [28]–[30]. Subsequently, it was demonstrated that the FMM can be successfully employed for the accurate modeling of two-dimensional photonic crystals [27], [31], [32]. More recently, the method has been extended and applied to the characterization of three-dimensional photonic crystals and crossed gratings [7], [8], [33].

The photonic crystal is considered as a finite stack of periodic grids of implants in a hosting medium (e.g., dielectric rods arranged in the air, or air holes drilled in a dielectric bulk). Adjacent grids may be separated by homogeneous layers. The general approach for exactly solving the electromagnetic problem associated to this kind of structure involves the solution of Maxwell's equations inside each periodic layer of the crystal, in the homogeneous regions between different periodic layers and outside the crystal. Boundary conditions have to be imposed between different regions.

A fundamental step in the FMM is the expansion in a Fourier series of the dielectric permittivity of each layer constituting the photonic crystal. Plane-wave expansions of the electromagnetic field are used (Rayleigh expansions outside the crystal, modal expansions in the crystal layers). This approach leads to a set of eigenvalue problems, which have to be solved. Then, the tangential electric and magnetic field components are matched at all the boundary surfaces. The resulting linear equation system is solved for the reflected and transmitted field amplitudes, so that the reflection and transmission efficiencies of the photonic crystal can be determined.

The total transmission efficiency of a photonic crystal is defined as the sum of the efficiencies of all the transmitted diffracted orders. The efficiency of the n-th transmitted order is equal to the Poynting-vector component, along the transmission direction, of the n-th order transmitted wave, divided by the Poynting-vector component, along the same direction, of the incident wave.

The FMM treatment of photonic crystals is accurate and versatile, it allows studying structures with arbitrary-shape implants forming whatever kind of lattice. The effects of interruptions in the photonic-crystal periodicity can be investigated by this method [25], [26].

3. Numerical Results

3.1. Rectangular-Section Rods

The first solution that we propose uses a two-dimensional photonic crystal with rectangular-section silicon rods arranged in a rectangular lattice. The host material is the air. The geometry of the filter is sketched in Fig. 1. The refractive index of rods is assumed to be $n_d = 3.4$ in the considered frequency range, the lattice periods along the two orthogonal periodicity directions are d_1 and d_2, and the size of the cross-section of the rods is $b_1 d_1 \times b_2 d_2$. The required frequency-selective behavior of the structure is obtained by suitably interrupting its periodicity. In particular, the introduced defect consists of some rods missing in the middle of the structure: an air gap with length L is present between the two central layers of rods. ND is the number of rod layers located on each side of the defect. The structure can also be viewed as a Fabry-Perot resonator, with two mirrors consisting of identical photonic crystals separated by an air region.

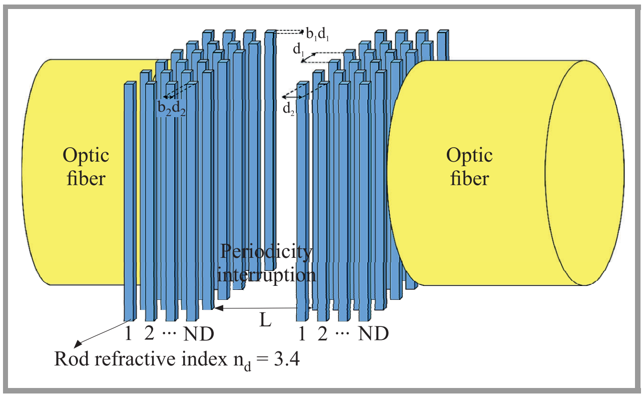

Fig. 1. Geometry of the photonic-crystal filter made of square-section rods.

Calculation results for this filtering structure are presented in Fig. 2, for different values of ND. It is chosen to design a square-lattice ($d_1 = d_2 = d$) square-section rod ($b_1 = b_2 = b$) structure, because it is easier and cheaper to fabricate with respect to a rectangular-lattice rectangular-section solution. The electromagnetic behavior of the synthesized filter is illustrated by plotting its total transmission efficiency as a function of the free-space wavelength λ normalized to d. Curves for both the fundamental TE (full line) and TM (dashed line) polarization states are reported. In TE polarization, the electric field propagating through the filter is parallel to the photonic-crystal rods. In TM polarization, instead, the electric field is orthogonal to the rods. With $b = 0.4$ and $L = 1.6d$, a TE transmission peak centered on $\frac{\lambda}{d} \cong 2.75$ is present while propagation is prohibited for TM polarization.

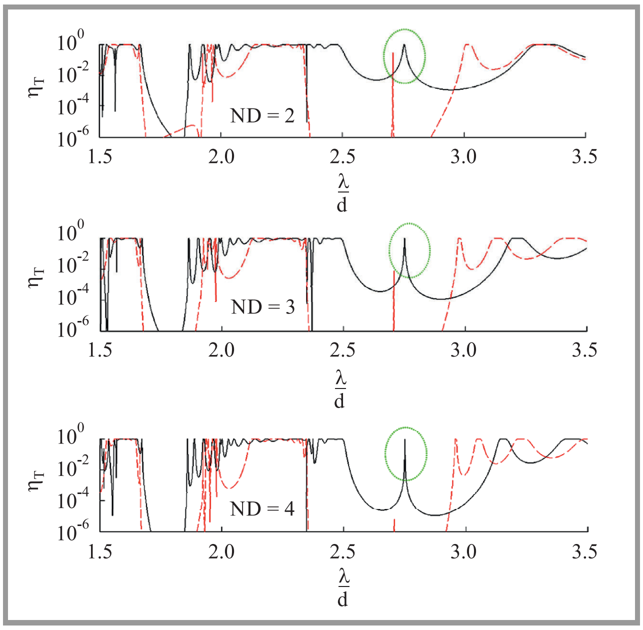

Fig. 2. FMM results for the photonic-crystal filter made of square-section rods.

It can be appreciated that the selectivity of the structure becomes higher as ND increases. In particular, if $ND = 2$ the transmission peak is centered on $\frac{\lambda}{d} = 2.758$: with a period $d = 0.562$ μm, transmission of radiation at $\lambda = 1.55$ μm occurs and the 3-dB width of the transmission peak turns out to be 4.5 nm. If $ND = 3$ the peak is centered on $\frac{\lambda}{d} = 2.753$: with $d = 0.563$ μm, radiation at $\lambda = 1.55$ μm is transmitted and the 3-dB width of the peak is 1.1 nm. Finally, if $ND = 4$ the peak is centered on $\frac{\lambda}{d} = 2.748$: with $d = 0.564$ μm, the transmission of radiation at $\lambda = 1.55$ μm is obtained and the 3-dB width of the peak is 0.28 nm (less than 0.4 nm, that is the design specification).

3.2. Rectangular-Section Holes

The second structure that we consider is a two-dimensional photonic crystal with rectangular-section holes arranged in a rectangular lattice and drilled in a dielectric bulk, as sketched in Fig. 3. The geometrical parameters are denoted as for the first structure, the refractive index of the dielectric material is again $n_d = 3.4$.

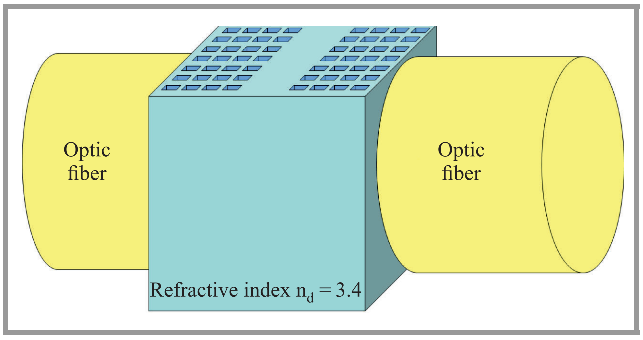

Fig. 3. Geometry of the photonic-crystal filter made of square-section holes drilled in a dielectric bulk.

Numerical results are given in Fig. 4 for different values of ND, being $d_1 = d_2 = d$, $b_1 = b_2 = 0.75$ and $L = 1.25d$; the full-line curves correspond to TE polarization and the dashed-line curves correspond to TM polarization.

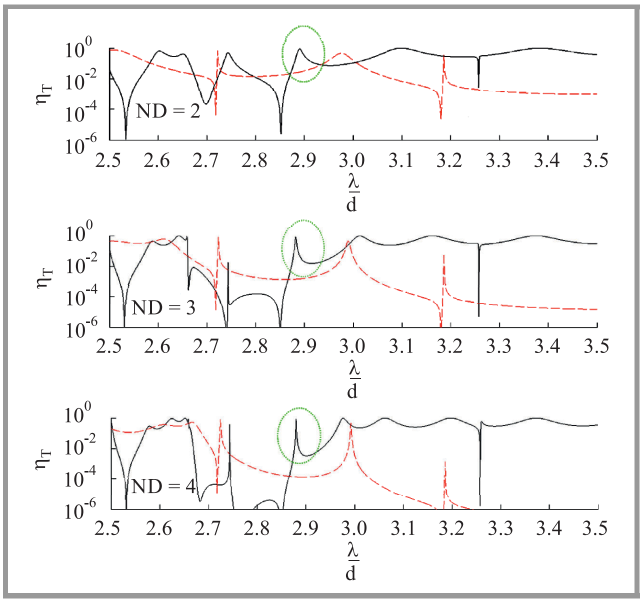

Fig. 4. FMM results for the photonic-crystal filter made of square-section holes drilled in a dielectric bulk.

If $ND = 2$, a TE transmission peak in $\frac{\lambda}{d} = 2.892$ is obtained: with a period $d = 0.536$ μm this peak is centered on $\lambda = 1.55$ μm and its 3-dB width is 6.4 nm. If $ND = 3$, the TE transmission peak is in $\frac{\lambda}{d} = 2.881$. If a period $d = 0.538$ μm is chosen, this peak is centered on $\lambda = 1.55$ μm and its 3-dB width is 1.4 nm. Moreover, if $ND = 4$, the TE transmission peak is in $\frac{\lambda}{d} = 2.876$. With a period $d = 0.539$ μm this peak is centered on $\lambda = 1.55$ μm and its 3-dB width is 0.47 nm.

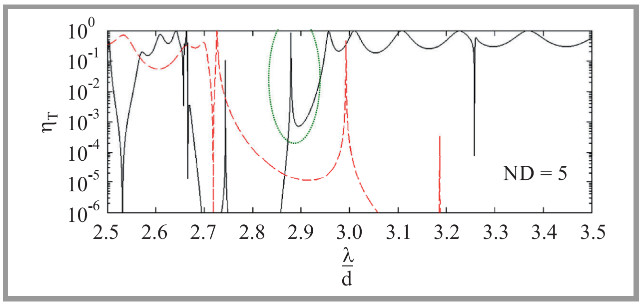

Fig. 5. FMM results for the photonic-crystal filter made of square-section holes drilled in a dielectric bulk: $ND = 5$.

This filter is easier to fabricate but slightly less selective than the solution with square-section rods proposed in the previous subsection, if the same number of inclusions ND is considered. It is necessary to drill $ND = 5$ rows of holes in the dielectric bulk, to satisfy the design specification. Relevant centered results are reported in Fig. 5. In this case, the transmission peak is centered on $\frac{\lambda}{d} = 2.870$. By choosing a period $d = 0.540$ μm, the transmission of radiation having wavelength $\lambda = 1.55$ μm is achieved, and the 3-dB width of the transmission peak turns out to be 0.16 nm.

3.3. Circular-Section Rods

The third structure that we propose is shown in Fig. 6. It uses a two-dimensional photonic crystal with circular-section rods arranged in a rectangular lattice, with periods d_1 and d_2. The radius of the rod section is called R and the refractive index of the dielectric material is again $n_d = 3.4$. The length of the periodicity interruption (the central air gap) is called L.

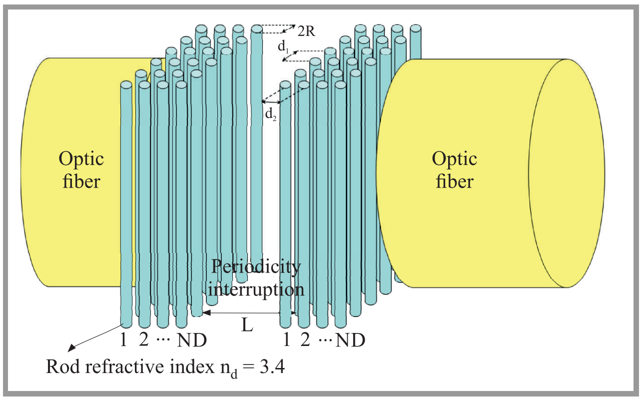

Fig. 6. Geometry of the photonic-crystal filter made of circular-section rods.

The results presented in Fig. 7 are obtained for a structure with $d_1 = d_2 = d$, $R = 0.226d$, $L = 1.55d$ and $ND = 5$. The total transmission efficiency of the filter is plotted

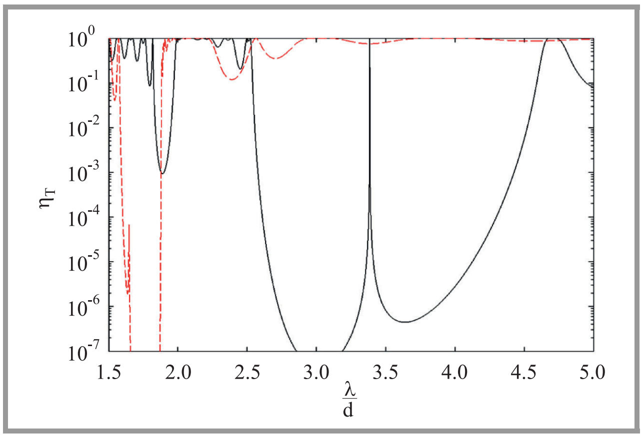

Fig. 7. FMM results for the photonic-crystal filter made of circular-section rods.

as a function of the normalized wavelength $\frac{\lambda}{d}$. The presence of a sharp TE transmission peak is observed, centered on $\frac{\lambda}{d} = 3.385$. By choosing a period $d = 0.458$ μm, the transmission of waves propagating at $\lambda = 1.55$ μm is achieved; the 3-dB width of the transmission peak turns out to be 0.14 nm.

3.4. Circular-Section Holes

The fourth structure that we consider is sketched in Fig. 8. It consists of a two-dimensional photonic crystal with circular-section holes arranged in a rectangular lattice and drilled in a dielectric bulk. The geometrical parameters are denoted as for the third structure and the refractive index of the dielectric material is $n_d = 3.4$.

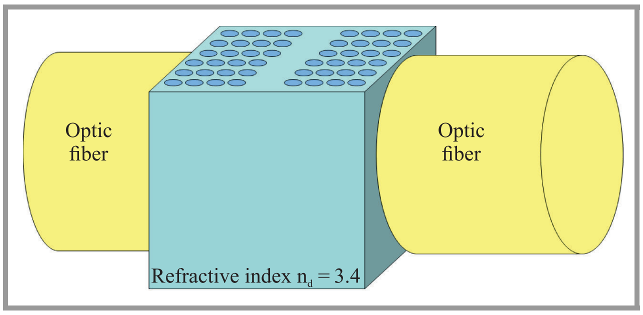

Fig. 8. Geometry of the photonic-crystal filter made of circular-section holes drilled in a dielectric bulk.

In Fig. 9 results obtained with $d_1 = d_2 = d$, $R = 0.432d$, $L = 1.136d$ and $ND = 5$ are presented. Even in this case, a transmission peak for TE polarization is present. This peak is centered on $\frac{\lambda}{d} = 4.627$. With a period $d = 0.335$ μm, the transmission of $\lambda = 1.55$ μm is guaranteed and the 3-dB width of the peak is 3 nm.

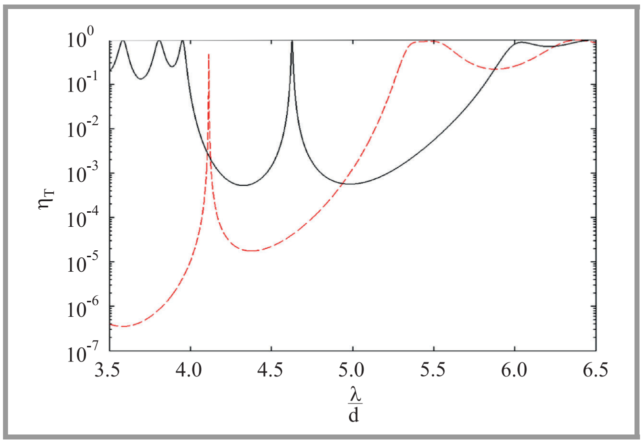

Fig. 9. FMM results for the photonic-crystal filter made of circular-section holes drilled in a dielectric bulk.

4. Conclusions

In this work, the design of a photonic-crystal filter is presented. The filter transmits radiation at 1.55 μm, with a 3-dB selectivity smaller than 0.4 nm. Four different solutions are proposed and examined, involving photonic crystals made of square or circular cross-section dielectric rods, or holes drilled in a dielectric bulk. The required selective behavior is obtained by suitably introducing a defect in the adopted photonic crystal. The structures are simulated by using in-house codes implementing the rigorous Fourier Modal Method.

Solutions with holes are easier to fabricate, with respect to solutions involving rods, moreover they are less fragile; however, they are less selective than solutions involving rods, thus requiring a slightly higher number of periodic layers to satisfy the 0.4 nm specification. Thus, a filter made of holes turns out to be larger than a filter made of rods and stronger scattering losses occur during the propagation of the radiation through the filter. An advantage of the filter made of rods, is that its transmission peak can be easily tuned to 1.55 μm by adjusting the defect length L. To deal with imperfections and non-idealities in the fabricated photonic-crystal structure, which may be present and influence the optical properties of the filter.

The calculation results show that strong and narrow dips are present in the transmission-efficiency curves (e.g., in Fig. 2 at $\frac{\lambda}{d} \cong 2.4$ and in Fig. 4 at $\frac{\lambda}{d} \cong 3,27$). This suggests that the studied structures may be designed and sized to act as highly-reflective narrow-band filters, which also are of interest in fiber optics communication.

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