Photonic crystal surface modes narrow-band filtering

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Abstract: Light transmission through a slab of two-dimensional photonic crystal is known to present forbidden gaps. By a particular choice of he surface cut of the slab, it is possible to introduce modes guided in the vicinity of the crystal surface, which can have propagation constants lying inside the forbidden gap. These modes can be excited using additional diffraction gratings positioned onto the surfaces. This resonant excitation introduces defects in the gap that can lead to a narrow-band transmission with a 100% maximum. By working near normal incidence, it is possible to use the flattening of the mode dispersion curve near the Bragg cell boundaries and to reduce the requirements for beam parallelism, while preserving the strong spectral selectivity.

OCIS codes: (240.6690) Surface waves ; (230.1950) Diffraction gratings ; (120.2440) Filters

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1. Introduction

Photonic crystals have been famous for being able to manipulate photons in a manner similar to the influence of common crystals on the electron behaviour [1]. The most discussed effect is the creation of forbidden zones leading to almost perfect reflection in a large band of angles on incidence [2]. Much less investigated are different properties of photonic crystals, well-known in other branches of optics, such as integrated optics and diffraction grating optics. Only in the beginning of the 2000s, it has been demonstrated [3,4] that photonic crystals can act as perfect diffraction gratings, having almost a 100% absolute diffraction efficiency in unpolarized light. Recently, it has been shown that in some conditions photonic crystals can guide light close to their surface [5,6]. The aim of this paper is to study the combination of two properties, light diffraction and guided wave propagation. The result can be a creation of narrow transmission line inside the band-gap, which can be used to narrow-band transmission filtering.

Such effect can be otherwise created by introducing different types of defects inside the volume of the crystal. However, this could be difficult to be achieved and controlled technologically. The resonant guided wave excitation in corrugated waveguides has been known since 20 years to lead to enhanced transmission and reflection [7-12], creating a domain of optics known under the name ‘subwavelength gratings’. However, due to the natural low reflection of dielectric waveguides, narrow-band filtering is obtained in reflection, while applications often require filtering in transmission. To achieve it, we propose to use a photonic crystal, which ensures almost zero transmission slab inside its forbidden gap. Under some conditions, the photonic crystal can support guided modes that are localized near its surface and guided in the outermost optical dense layer. If the surrounding media are identical, as well as the cuts of the two crystal faces, both interfaces can support identical modes which couple through tunnelling effect. This coupling can lead to resonant enhanced transmission, supposed one can excite the guided waves created by the crystal surfaces. To this aim, it is not possible to count on the periodicity of the crystal itself, because the wavelength-to-period (λ/d) ratio is too large to provide coupling between the incident and the guided wave(s). To overcome this difficulty, we introduce a kind of ‘defect’ on the surface, a grating having twice the period of the crystal, a period sufficiently large to couple the two wa

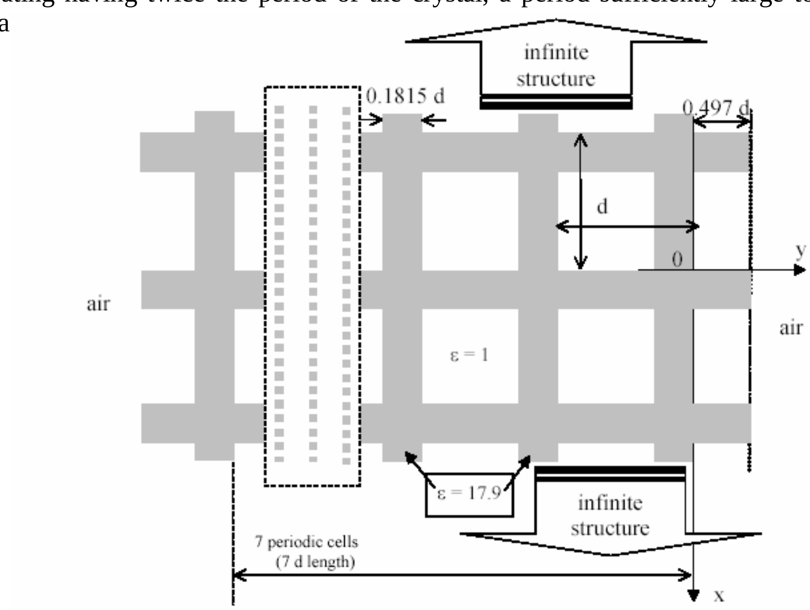

Fig. 1. Schematic representation of a two-dimensional photonic crystal slab and its optogeometrical parameters

2. Photonic crystal band-gap and surface-supported guided waves

The photonic crystal under investigation is chosen according to two conditions: (i) to have sufficiently large band-gap, and (ii) to support a guided wave along it interface with vacuum, such that its propagating constant lies inside the band-gap. Such is the case proposed in ref. 6 and is schematized in Fig. 1. It represents a cross-section of a two-dimensional crystal made of squares cells with linear filling factor of 0.1815. The symmetric crystal cell is repeated 7 times in the horizontal direction and infinitely times in the vertical direction. The slab is symmetrical with respect to both vertical and horizontal plane and invariant in the z-direction. Its Bloch diagram is plotted in Fig. 2 for the TM polarization, with the electric vector lying in the cross-section plane. One observes a relatively large forbidden band-gap. All the results presented in this work have been obtained using the differential method [13].

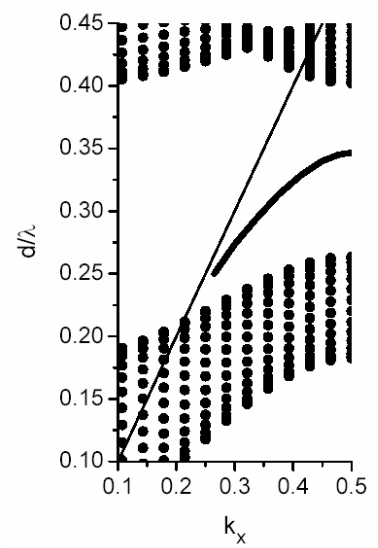

Fig. 2. The band-gap structure of the photonic crystal presented in Fig. 1 and the dispersion curve of the guided surface-induced TM mode. The parameter k_x is the normalized x-component of the wavevector $\vec{k}$: $k_x = \frac{2\pi}{d}\vec{k}.\vec{x} = \frac{\lambda}{d}\sin\theta$ (for θ, see Fig. 3). The thin ligh presents the light cone and the thick line, the mode dispersion curve

It is possible to create guided waves along the surface cut in the crystal, which largely depend on the cut position [6]. The outermost portions of the slab are cut at almost half-height to introduce TM-polarized mode guided in the adjacent to the surface portion of the crystal and having a propagation constant lying inside the band-gap, Fig. 2. In fact, there are two guided waves supported by each of the interfaces, but their coupling is very weak due to the band-gap which forbids transmission. However, these waves cannot be excited by incidence from outside, because they are lying outside of the light cone.

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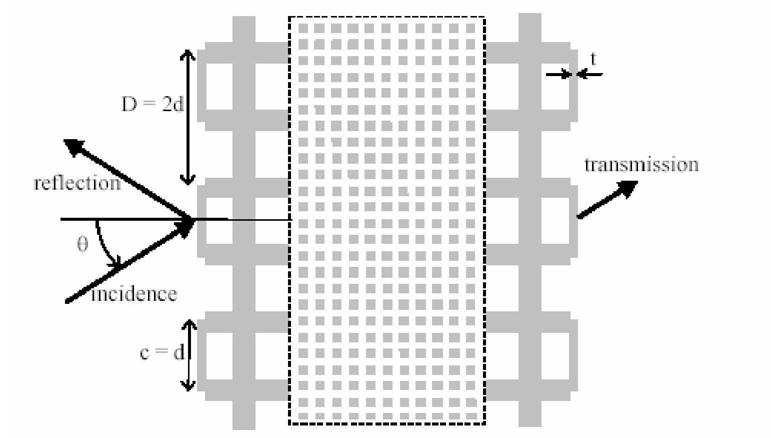

Fig. 3. Schematic representation of the in-coupling gratings having twice the period D = 2d and thickness t, made of the same dielectric material as the crystal. Incident wave comes from the left and generates a reflected and a transmitted waves

3. Guided wave excitation and transmission defection

There are several possibilities to excite guided waves lying outside the light cone: prism coupling, excitation by evanescent waves, or grating coupling. Physically, the principle is the same, but technically these are quite different solutions. Experience shows that the latter is preferable. To avoid creation of parasitic diffraction orders that will bring away energy, let us chose the period of the grating D to be twice the photonic crystal cell period d. This will keep the wavelength-to-grating ratio still high enough to avoid non-zeroth diffraction orders in the surrounding media, so that the only propagating waves there are the incident, the reflected and the transmitted orders, Fig. 3. The grating consist of thin lamellae made of the same material as the high-index constituent of the photonic crystal. The thinner the lamellae, the weaker the change of the guided mode characteristics and the weaker the coupling between the guided and the incident waves, with its phase-matching conditions given by the grating equation:

$$\sin\theta + n\frac{\lambda}{D} = \alpha_g \qquad (1)$$

where q is the incident angle, n is the diffraction order number, and α_g is the guided mode effective index given as the ratio between the mode propagation constant and the free space wavenumber:

$$\alpha_g = k_g / k_0 \,. \qquad (2)$$

A phenomenological approach to resonant grating anomalies has been well developed during the 1980s and know under the name of 'polology', coming from the terms pole and zero of diffraction efficiency [8,14]. It is outside the scope of this paper to detail the principles and consequences of the polology. Let us remind several important points, valid for whatever the type of the diffraction system and the character of resonance involved [8]:

(i) the excitation of a resonance (guided wave, plasmon-polariton wave, cavity resonance, Fabry-Perot resonance, etc.) lead to a pole α^p in all the diffraction amplitudes;

(ii) the existence of a pole requires a zero α_n^z in the propagating diffraction orders amplitudes, in general depending on the diffraction order number n. Thus, the phenomenological resonant formula for the n-th order amplitude A_n reads [15]:

$$A_n = c_n \frac{\alpha - \alpha_n^z}{\alpha - \alpha^p} \qquad (3)$$

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where $c_n \approx \text{const.}$ and $\alpha = \sin\theta$.

(iii) Depending on the number of propagating orders and the symmetry of the diffraction system, some of the zeros can be real while in general they are complex numbers. In particular, if the system is lossless and supports only two propagating orders (for example, one reflection and one transmission order, as in Fig. 3), their zeros are subjected to the following simple rules:

(1) For a diffraction system having a plane of symmetry, for example, an infinitely long corrugated waveguide with a symmetrical-profile corrugation or a photonic crystal with a symmetrical cell, the transmission zero is real, leading to a 100% reflectivity resonant maximum. This case is of great importance when searching for highly performing narrow-band reflection filters and has already find several practical applications.

(2) A diffraction system having an axis of symmetry will have a real reflection zero, i.e., the transmission at this point will reach 100%, whatever the non-resonant transmission would be. In particular, the system drawn in Fig. 3 has a higher symmetry (both vertical and horizontal symmetry and thus an axis of symmetry in the middle) and is supposed to have both reflection and transmission zeros real. In order to ensure a real reflection zero (and thus a 100% transmission maximum), we need to have identical interfaces and gratings on them at the two crystal phases.

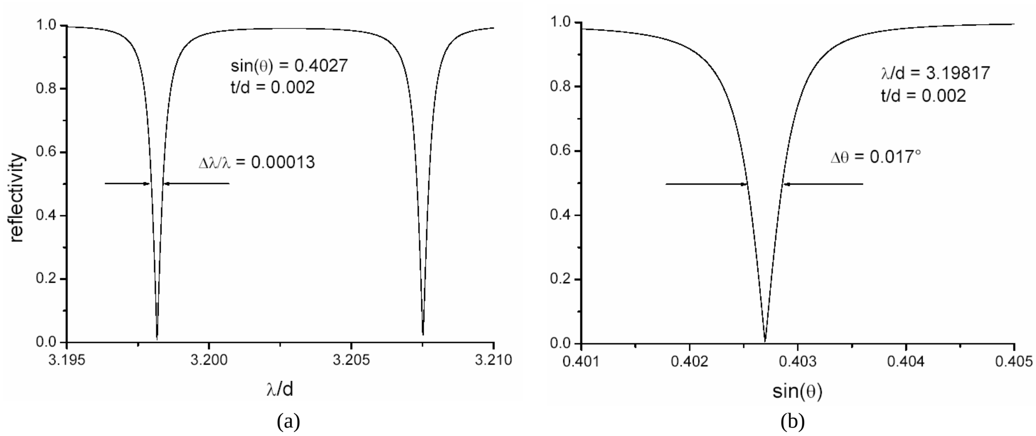

Fig. 4. Resonances in the spectral (a) and angular (b) responses of the system presented in Fig. 3 with t/d = 0.002 and working in non-normal incidence. The wavelength and angular parameters are indicated in the figure.

A particular application of these rules is illustrated in Fig. 4 which presents the spectral dependence of the reflectivity of the system given in Fig. 3, choosing a working point near the middle of the dispersion curve, plotted in Fig. 2, with $\alpha^p = 0.4027$. When the specific phase condition, Eq.(1), is satisfied to resonantly excite the guided mode inside the band-gap, the general polology rules require that a zero-reflectivity, i.e., 100% transmission is obtained. And indeed, one observes in Fig. 4(a) two well-defined minima in the spectral dependence, with the reflectivity coming rapidly down form 100% to 0. The appearance of a second minimum is due to the splitting of the single guided wave into two due to the strong resonant coupling between the otherwise identical weakly interacting modes propagating along the two crystal faces. The width of the maxima can be chosen quite small (it depends on the thickness t of the in-coupling additional gratings) and in this case (t/d = 0.002) is equal to $\Delta\lambda / \lambda = 0.00013 \Leftrightarrow \Delta\lambda / d = 0.04\%$. However, as already explained, the narrowness of the spectral response is displayed in the angular response, too, which has limited the use of corrugated waveguides as filtering elements for quite a long time [16]. And indeed, the angular dependence given in Fig. 4(b) presents a minimum with angular width of about 0.017°, which imposes quite strong requirements to the parallelism of the incident beam: a beam having larger divergence will be transmitted with less efficiency due to the convolution of the responses of its angular components [16].

4. Resonantly enhanced transmission in normal incidence

From the grating studies, it is well-known that for the resonant effects the medal has always two sides: narrow spectral response is accompanied by a narrow angular response, not welcome due to the natural divergence of the beams to be filtered. A solution has been found by using the direct interaction between modes propagating in opposite directions, which flattens the k-dependence of the dispersion curve [11,12]. This reduces the angular dependence by keeping the so-desired sharpness of the spectrum.

In our case, the direct mode coupling is ensured by two natural channels: the cellular periodicity of the photonic crystal structure and the tunneling between the two crystal faces. While the latter being quite weak, the former becomes very strong close to the Bragg cell boundaries, as is observed in the mode dispersion curve when $k_x \rightarrow 0.5$ in Fig. 2. The choice of the in-coupling grating having twice the period of the crystal cell brings us at exactly normal incidence when using the grating Eq.(1), a condition of great honor for transmission filter application. Using the same geometry of the system as in Fig. 4, but choosing another working point close to $k_x = 0.5$ in Fig. 2, it is possible to preserve the narrowness of the spectral resonance with sharply increasing the width of the angular resonance. Fig. 5(a) presents the spectral dependence at normal incidence (which requires changing the working wavelength) and its spectral width is only twice that in Fig. 4(a). Due to the symmetry of the incident wave in normal incidence, only one of the two coupled modes can be excited and a single minimum exists, contrary to Fig. 4(a). Fig. 5(b) presents the angular dependence for the wavelength corresponding to the minimum in the spectral dependence in Fig. 5(a) and one observers the widening of the angular response of about 100 times when compared to non-normal incidence (Fig. 4(b)). This makes it possible using the device with real beams.

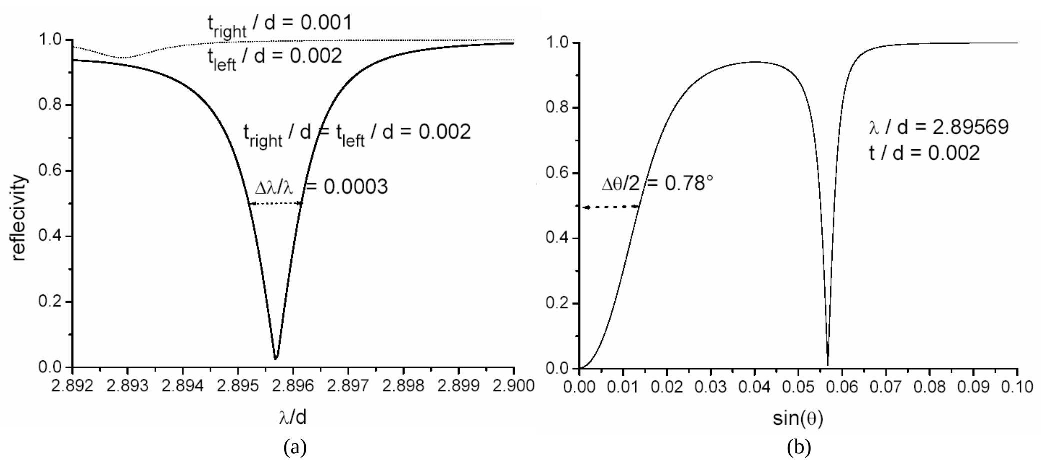

Fig. 5. As in Fig. 4 but working close to normal incidence. The thin curve in Fig. 5(a) corresponds to different thicknesses of the supplementary gratings in Fig. 3, the left grating is 0.002d thick, while the right grating is twice thinner.

A second minimum is observed due to the possibility to excite the second mode in non-normal incidence. As expected, its width is much smaller than in normal incidence.

The thin curve in Fig. 5(a) demonstrates the necessity to maintain the symmetry required by the phenomenological rules stated in the previous section. If the strength (thickness) of the two in-coupling gratings (the left and the right ones in Fig. 3) is different, this destroys the

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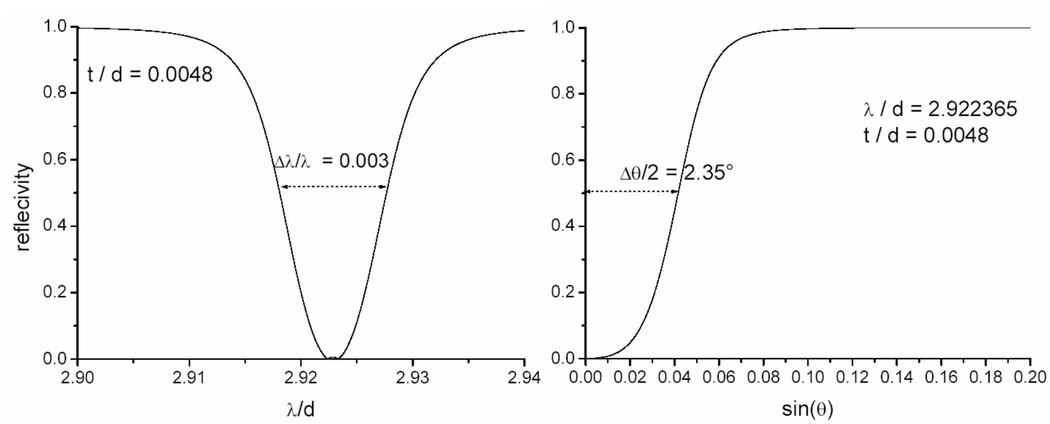
symmetry and the zero in the reflectivity is no more real, so that the minimum is quite far from reaching 0%.

As can be expected, the resonance anomaly properties depend strongly on the force of excitation, i.e., on the thickness t of the additional diffraction gratings. The stronger the coupling, the wider the resonances. Figures 6(a) and 6(b) present the spectral and the angular dependences of the reflectivity near normal incidence when the thickness of the additional gratings is increased 2.5 times. The spectral resonance is about 10 times larger, but still remains small enough to have practical meaning. As expected, the angular resonance is increased significantly and presents a portion with almost flat bottom wide about 1°.



(a) (b)

Fig. 6. As in Fig. 5 but with thicker supplementary gratings, t/d = 0.0048 instead of 0.002

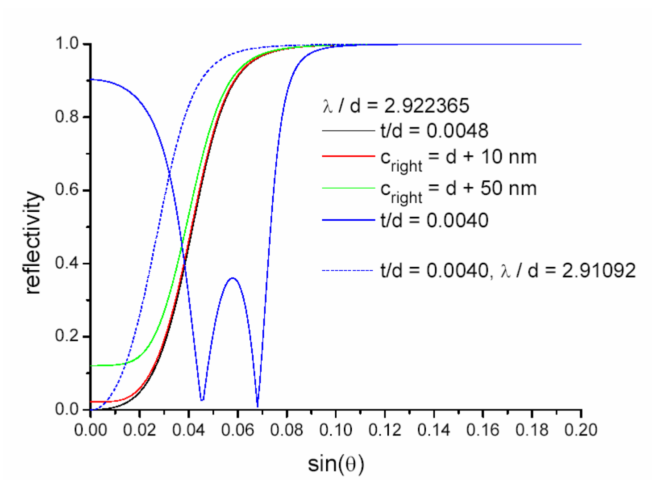


Fig. 7. As in Fig. 6(b), but for different in-coupling grating parameters

Finally, Fig. 7 presents a limited study of the tolerances. As can be observed, the precision in the width (filling factor) of the output grating is not quite important, as far as it is necessary to change it with more than 20 nm in order to obtain a visible reduction of performance. The same is valid for the influence of the width of the input grating. On the other hand, the tolerances are much tighter when considering the thickness of these additional gratings, as can be seen in Fig. 7. This can be easily explained taking into account that the surface mode is localized close to the surface so that the additional lamellae will strongly influence the mode propagation constant. However, even in that case it is possible to obtain filtering properties in normal incidence by slightly changing the working wavelength, as shown with a dashed line in Fig. 7.

5. Conclusion

Photonic crystal devices can demonstrate properties quite similar to the classical gratings and waveguides. The advantage of the former is the existence of relatively large bands forbidden for transmission, which can hardly be obtained by using classical waveguides. By using a combination of these properties, namely, a resonant excitation of guided waves propagating inside the forbidden band-gap, it is possible to obtain resonant filtering in transmission aiming to narrow-band filtering with vary narrow transmission spectral line. By staying close to normal incidence (i.e., choosing a working point close to the Bragg zone boundaries), the angular width of the resonances can stay sufficiently large to be used in practical applications.

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