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2 × 1D crossed strongly modulated gratings for polarization independent tunable narrowband transmission filters

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We design a narrowband polarization independent transmission guided mode resonance filter whose center wavelength is tunable with respect to the angle of incidence. The device is composed of two identical structures assembled back to back. Each half structure is a dielectric multilayer stack in which a grating is engraved. This so-called 2 × 1D crossed gratings component has already been demonstrated for reflection filtering [Opt. Lett. 36, 1662 (2011); Opt. Lett. 39, 6038 (2014)]. The functioning in transmission requires the use of a high index material for the grating bumps. For the design, we resort to a clustering global optimization algorithm, used for the first time to our knowledge for grating structures. We demonstrated two filters with a quality factor of about 4000, tunable over more than 15 nm when the angle of incidence varies over a range of 4°, and with a transmittivity at resonance greater than 95% whatever the incident polarization.

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1. INTRODUCTION

Guided mode resonance gratings are potentially interesting for narrowband spectral free space filtering. They are composed of a dielectric multilayer stack in which a subwavelength grating is engraved. The period of the grating and the refractive index of the substrate and superstrate are chosen in such a way that only the zeroth diffraction order is propagative. The coupling in and out of one eigenmode of the structure through one (evanescent) diffraction order generates a resonance peak in their reflectivity or transmittivity spectrum. The peak is very narrow for shallow gratings and lossless materials [1]. Moreover, the reflectivity at resonance theoretically reaches 100% provided that the structure is symmetrical with respect to the normal to the interfaces of the layers. Conversely, the transmittivity at resonance reaches 100% provided that the structure is symmetrical with respect to a plane parallel to the interfaces of the layers [2]. Hence, efficient reflection or transmission filters can be obtained if the stack behaves, respectively, as an antireflective coating or as a mirror out of resonance. Note that the symmetry properties are sufficient but not necessary conditions, and 100% transmission can be obtained without the aforementioned symmetry [3].

Another interesting property of a guided mode resonance filter is that its center wavelength depends quasi linearly on the angle of incidence [4]. This particularity is attractive for instance for spectroscopic applications. Yet, most of the time, the incident light is nonpolarized or of unknown polarization, thus requiring polarization independent components. Guided mode resonance filters are strongly dependent on the incident polarization if only one mode is excited. But their polarization independence is ensured if two modes can be excited simultaneously (for the same angle of incidence and same wavelength) with orthogonal incident polarizations [5]. Hence, polarization independent filters have been reported relying either on the simultaneous excitation of a TE (transverse electric, electric field orthogonal to the direction of propagation) and a TM (transverse magnetic, magnetic field orthogonal to the direction of propagation) [6] mode, or on the simultaneous excitation of a symmetric and an antisymmetric mode (with respect to the plane of incidence) [7–10]. Yet, for these configurations, the resonance wavelength for the two orthogonal polarizations moves away when changing the angle of incidence, which is not acceptable for very narrowband (below 0.5 nm) filtering.

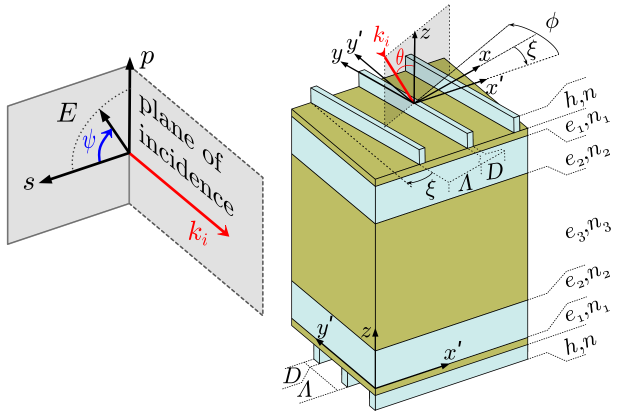

Fig. 1. $2 \times 1D$ crossed gratings configuration. See Table 1 for the numerical values.

In a previous paper [11], we proposed a polarization independent reflection guided mode resonance filter (band-stop filter) whose central wavelength was tuned by varying the angle of incidence. Its Q factor equaled 13,000, and its reflectivity remained greater than 99% whatever the incident polarization; the filter wavelength was tuned over 90 nm as the incidence angle changed from 11° to 22°. The device was composed of two identical half structures (same dielectric stack and same grating parameters) assembled back to back such that the directions of periodicity of the two gratings were not exactly mutually orthogonal (see Fig. 1), a configuration that we called $2 \times 1D$ crossed gratings. In a more recent paper [12], using this $2 \times 1D$ crossed gratings configuration, we experimentally demonstrated a polarization independent reflection filter tunable with the angle of incidence. The aim of the present paper is to adapt the $2 \times 1D$ crossed gratings configuration for transmission filtering (bandpass filter). Indeed, angularly tunable transmission filters are easier to use in practice than reflection ones. Yet the $2 \times 1D$ crossed gratings configuration is not straightforwardly adaptable to the filtering in transmission, especially because the background (nonresonant contribution) has to work as a mirror instead of as an antireflection coating. The high reflectivity can be achieved thanks to a stack of high and low index dielectric quarter-wavelength layers, but one loses the advantage of guided mode resonance filters as compared to Fabry–Perot filters in terms of number of layers. Engraving the grating in a layer of high index lossless material is a more promising solution, at least in the mid-infrared range where silicon can be used. In these strongly modulated gratings, multimode resonances [13–16] provide wideband mirrors and polarizers that can be used as a background for narrow-band transmission filters [17,18].

In what follows, we first recall the basic principles used for the design of the polarization independent reflection filter tunable with the angle of incidence [11,12] (the $2 \times 1D$ crossed gratings configuration). Then we explain how it can be adapted to become a transmission filter. Last, we show and discuss the calculated performances of two designed polarization independent transmission filters tunable with the angle of incidence.

2. BASIC PRINCIPLE OF $2 \times 1D$ CROSSED GRATINGS FILTERS

The $2 \times 1D$ crossed gratings configuration is represented in detail in Fig. 1. The two half structures have the same parameters for the stack and the grating, the period of which is denoted Λ. The directions of periodicity of the gratings (x for the upper grating and y' for the lower grating, both being orthogonal to z, the normal to the plane of the layers) form an angle $90° - \xi$. A thick, low-index substrate (thickness e_3, index n_3) separates the two structures. Basically, the functioning of this polarization independent reflection filter tunable with the angle of incidence relies on two principles. First, for any angle of incidence, the mode in the upper structure and the mode in the lower structure must be excited simultaneously (e.g., for the same angle of incidence and the same wavelength). The upper mode (respectively the lower one) is excited by the incident wave through the top (respectively bottom) diffraction grating. Second, at the design angle of incidence, the incident polarization allowing the excitation of one mode must be orthogonal to the incident polarization allowing the excitation of the other mode, thus ensuring polarization independence.

To understand how the structure represented in Fig. 1 can achieve this, we make two assumptions. First, we suppose that the modes of the entire structure are the modes that exist in the two half structures when they are taken separately. In other words, we suppose that there is no coupling between the modes of the upper structure and that of the lower structure when assembled. The evanescent coupling between the modes is negligible as long as the modes do not leak into the substrate and the substrate is thick enough. Second, we suppose that the modification induced by the gratings on the guided modes of the multilayer stack is weak: the modes of each half structure have an almost real propagation constant, being the same for both structures (the imaginary part is related to the width of the resonance), and their field is either TE or TM. This supposition is valid if the grating depth and refractive index contrast are small enough. This corresponds to the narrowband filters we considered in [11,12]. In the following, for the sake of simplicity, we will consider TE modes only.

The excitation of a guided mode though one diffraction order of a grating occurs when the modulus of the in-plane wavevector of the diffraction order matches the modulus of the propagation constant of the mode (coupling condition). In Fig. 2(a), a top view of the $2 \times 1D$ crossed gratings structure is represented. The gray circle has a radius equal to the real part $k_g(\lambda)$ of the propagation constant of the guided mode at a fixed wavelength λ, identical in the upper and the lower structures. Let us consider that the plane of incidence is the bisecting plane of the directions of periodicity, as represented in Fig. 2(a), where the in-plane component of the incident wavevector is denoted as κ_i. In the case sketched in the figure, the mode in the upper half structure (with wavevector $\mathbf{k_u}$) is coupled through the −1 diffraction order of the top grating ($\mathbf{K_t} = -\frac{2\pi}{\Lambda}\hat{\mathbf{x}}$), while the mode in the lower half structure (with wavevector $\mathbf{k_l}$) is coupled through the −1 diffraction order of the bottom grating ($\mathbf{K_b} = -\frac{2\pi}{\Lambda}\hat{\mathbf{y}}'$). Hence, when the plane of incidence is a bisecting plane of the directions of periodicity of the gratings, the guided mode in the upper grating and

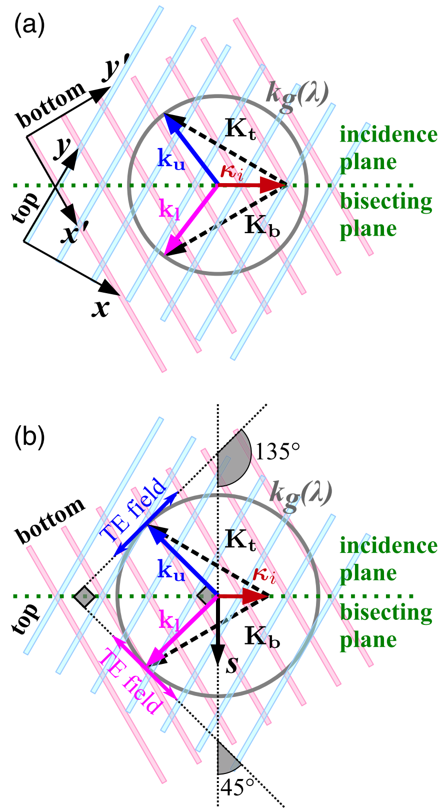

Fig. 2. (a) Simultaneous modes coupling with the 2 × 1D crossed gratings configuration. (b) Coupling of modes in orthogonal direction with the 2 × 1D crossed gratings configuration.

the guided mode in the lower grating can be excited for the same wavelength, whatever the polar angle of incidence θ. When the incident wavevector is not in a bisecting plane of the directions of periodicity, the coupling condition is not fulfilled for the same wavelength for the two gratings. Note that the simultaneous excitation can be performed through any other diffraction order, provided that the order used is the same for the two gratings.

To obtain the polarization independence, the two modes have to be excited with two orthogonal incident polarizations. We must emphasize that this condition concerns the incident field rather than the field of the excited modes inside the structure. On the other hand, as we are considering here TE excited modes, the direction of the field is perpendicular to its direction of propagation, which can be easily determined, using the coupling condition, as a function of the structure parameters and the angles of incidence. Hence, for the design, it can be practical to derive a condition concerning the field of the excited modes rather than the incident field.

As the field of a TE mode lies in the plane of the layers ((x, y) plane), the coupling between the field of an incident plane wave and the field of the mode involves the projection of the incident field on the (x, y) plane only. To characterize the field of the incident plane wave, we will refer to the two canonical s and p polarizations. We thus introduce the s and p vectors (see Fig. 1, left) and the angle ψ between the s vector and the direction of the incident electric field E. The s vector is perpendicular to the plane of incidence (defined by the axis z and the incident wavevector k_i), and p is the unitary vector colinear to $s \times k_i$.

At normal incidence, both s and p are in the (x, y) plane, and the projected electric field forms an angle ψ with respect to the s vector. Near normal incidence, by definition s is still contained in the (x, y) plane, but not p. The projected electric field now forms an angle ψ_p with respect to the s vector. ψ_p is no longer stricly equal to ψ but remains extremely close for small angles of incidence (the difference between their directions is below 5° up to $\theta = 30°$). For the design, we are interested in small values of the angle of incidence to provide a small incident beam spot on the grating surface and compact size of the final setup. As a consequence, at a first stage, we can consider that the two modes will be excited with orthogonal incident polarizations if their field are mutually orthogonal.

As represented in Fig. 2(b), this is possible for a particular angle of incidence. It can be seen that the field of the mode of the upper structure makes an angle of 135° with the s-direction (represented with a black arrow), while that of the lower structure makes an angle of 45° with the s-direction. Equivalently, we can say that their directions of propagation have to make an angle of 45° with respect to the plane of incidence. The configuration represented in Fig. 2(b) can serve as a first step for the optimization of a structure in which the TE guided modes of the upper and lower structures are excited with linear incident polarizations making an angle $\psi = 135°$ and $\psi = 45°$ with s, respectively.

To sum up, for TE modes, the condition of orthogonality between the directions of propagation of the modes (or equivalently, between their field) is a good approximation of the condition of orthogonality of the incident polarizations exciting the modes for small values of the incidence angle. Note that the configuration represented in Fig. 2(b) is not possible for positive diffraction orders, which leads necessarily to an angle smaller than 90° between the two directions of propagation (for positive values of ξ). Yet, if the modification induced on the guided modes by the gratings and the assembling of the half structures is such that the modes are no longer TE but have more complex fields, they can be excited with orthogonal incident polarizations without requiring the orthogonality between their directions of propagation, which may be possible even for positive diffraction orders.

Staying within the limit of validity of the first hypothesis (no coupling between the modes of the two half structures), the design can be performed on one half structure only rather than on the whole structure. This point is important since the calculations, performed with the Fourier modal method (FMM) [19], are much less time consuming for gratings periodic along one direction than for gratings periodic along two directions. Our homemade numerical code includes the S-matrix propagation algorithm [20], the correct rules of factorization of products of Fourier series, and the formulation in the covariant and contravariant basis, allowing the modeling of gratings with slanted directions of periodicity [19]. To perform the design of the structure, an optimization algorithm was combined with our homemade FMM code. Several parameters, including layer thicknesses and grating parameters, need to be optimized in order to fit a specific spectral target. A simple local nonlinear least-squares optimization technique is inefficient, and a global optimization procedure is required. Our laboratory has considerable experience in the use of the clustering global optimization (CGO) method [21–23], especially for thin films design problems where for a targeted reflectance and/or transmittance spectrum and a given alternation of thin film materials, one wants to find the optimal thin film layer thicknesses. CGO methods can be viewed as a modified form of the standard multistart procedure, in which a local search is performed from several starting points distributed over the entire multiparametric search domain. A drawback of the multistart technique is that when a large number of starting points is used, the same local minimum may be identified several times, thereby leading to an inefficient global search. Clustering methods are designed to avoid this inefficiency through careful selection of the points from which the local search is initiated. Other optimization algorithms such as particle swarm optimization (PSO) have been proved to be efficient for the design of guided mode resonance filters [24]. An advantage of CGO with respect to the PSO is that all the local minimum in the multiparametric search domain are found, provided that the number of starting configurations is enough as compared to the size of the search domain. Hence, it usually provides several interesting solutions. Moreover, the CGO does not need crucial initialization parameters.

3. DESIGN OF TRANSMISSION FILTERS

The polarization independent 2 × 1D crossed grating reflection filter tunable with the angle of incidence presented in [11,12] uses a TE guided mode excited with the −1 diffraction order. The half structure was designed to behave as a reflection filter for one polarization and as an antireflection coating for the orthogonal polarization. Our aim here is to adapt the idea described in the previous paragraph to the design of a transmission filter. The main difficulty is that the half structure must behave as a transmission filter for one polarization (e.g., the linear polarization making an angle $\psi = 135°$ with the s polarization) and as an antireflection coating for the orthogonal polarization ($\psi = 45°$). Hence, out of resonance, the half structure must behave as a polarizer. To achieve this, we propose to use high index dielectric material gratings in which multimode resonances can create wideband mirrors, polarizers, or transmission filters [13–18]. We consider a grating made of a high index lossless material such as crystalline silicon (index 3.48 in the near infrared range). To design one half structure, we used the optimization algorithm with two targets. The first target was used for the transmission filter for the polarization at $\psi = 135°$. Our target spectrum was a Lorentzian curve with full width at half maximum (FWHM) 0.15 nm, centered at 1.575 μm and with sidebands (ranges from 1.565 to 1.574 μm and from 1.576 to 1.585 μm) below 10^{-4}. The second target was used for the antireflection coating for the polarization at $\psi = 45°$, and it aimed at reflection values smaller than 0.01 over the range from 1.565 to 1.585 μm. We tried several values for ξ between 0° and 6°. The angle of incidence θ chosen for the design was 7°. Among the solutions given by the optimization algorithm, we chose two solutions, denoted S_1 and S_2. The corresponding parameters are reported in Table 1. For both structures, the substrate is glass with index 1.45 and the superstrate is air. We used 3.48 and 1.45 for the indexes of the silicon and the silica layers, respectively.

Table 1. Parameters of the Structures S_1 and S_2[a]

	S_1	S_2
e_2 [nm]	1635.3	1574.5
e_1 [nm]	646.3	652.3
h [nm]	132.5	186.75
Λ [nm]	933.7	918.9
D [nm]	336.2	662.1
ξ [deg]	5.4	3.6
ϕ [deg]	47.7	46.8

[a] See Fig. 1 for the notations. The refractive indexes are $n_1 = 1.45$, $n_2 = 3.48$, and $n = 3.48$. For the half structure, the substrate is infinite; for the double structure $e_3 = 1$ mm and $n_3 = 1.45$. The dimensions are in nanometers, and the angles in degrees.

We plot in Fig. 3 for structure S_1, and in Fig. 4 for S_2, the transmittivity spectrum for $\psi = 135°$ and the reflectivity spectrum for $\psi = 45°$ for the incidence angle $\theta = 7°$ (logarithm scale). First of all, let us emphasize that the optical function we try to obtain is quite complicated: a transmission filter (including a mirror) for one polarization and an antireflection coating for the orthogonal polarization. Hence, the performances of the antireflection coating and the mirror of the solutions shown here do not reach that of the defined target. However, these performances are enough to prove that 2 × 1D high index crossed gratings can be used to create polarization independent narrowband transmission filters tunable with the angle of incidence. The peak of transmittivity reaches 98.5%, and its FWHM is 0.4 nm for the structure S_1, and 95% with a 0.35 nm FWHM for the structure S_2. Second, a dent at 1.575 μm can be observed in the curve of the reflectivity for $\psi = 45°$ for both structures, which means that the mode can be slightly excited with this polarization. This is linked to the fact that the field diffracted in the zero order of the structure

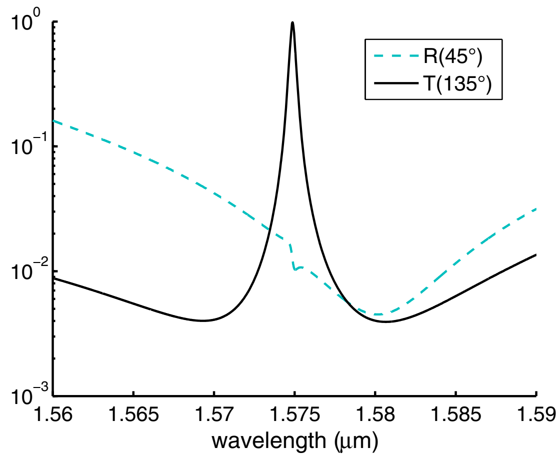

Fig. 3. Spectra for the structure S_1 at $\theta = 7°$: reflectivity for a linear polarization with an angle $\psi = 45°$ with respect to the s polarization (blue dashed line) and transmittivity for a linear polarization with an angle $\psi = 135°$ (black straight line).

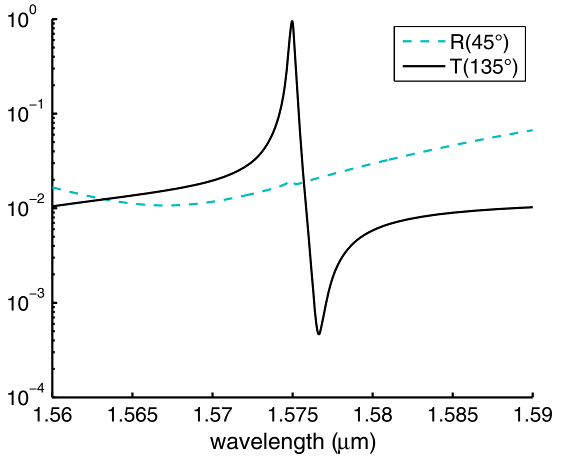

Fig. 4. Same as in Fig. 3, but for structure S_2.

does not have the same polarization as the incident field. We have indeed numerically calculated that the field transmitted by the structures S_1 and S_2 when illuminated with a linear polarization with a direction $\psi = 45°$ or $\psi = 135°$ with respect to s are slightly elliptically polarized with an axis at $\psi = 45°$ or $\psi = 135°$ with respect to s, and moreover the two elliptical polarizations are not orthogonal to each others. This phenomenon may be due to the fact that the grating is engraved in a high index material, and it will lead to a slight coupling between the modes of the two half structures when assembled.

4. PERFORMANCES OF THE DESIGNED TRANSMISSION FILTERS

So far, we have only considered half structures. In this section, we now consider two 2 × 1D complete structures named D_1 and D_2 that are obtained by combining two S_1, respectively two S_2, half structures in a 2 × 1D crossed configuration as shown in Fig. 1. The thickness of the middle layer (thick substrate in silica) is 1 mm for the two structures, and the angle ξ between the gratings is given in Table 1. We study the behavior of D_1 and D_2 with respect to the angle of incidence θ. For each θ between 0° and 9° with a step of 0.05°, we calculated the transmittivity spectrum of the structure, which presents a resonance peak in the range of wavelengths expected from the calculations on the half structures (see Figs. 3 and 4). We plot the resonance wavelength with respect to θ in Figs. 5 and 6 (right axis, in red) for D_1 and D_2, respectively. There is a difference between D_1 and D_2 in the angular dependence of the resonance wavelength: it is decreasing for D_1 and increasing for D_2. This comes from the fact that the mode in D_1 is excited through the +1 diffraction order of the grating, while it is through the −1 order for D_2. Indeed, an analysis of the amplitude of the diffraction orders at resonance shows that the +1 diffraction order is dominant for S_1 and the −1 diffraction order for S_2, from which we deduce that the mode is excited through the +1 diffraction order for S_1 and the −1 diffraction order for S_2. The tunability is −3.6 nm per degree for D_1 and 3.3 nm per degree for D_2.

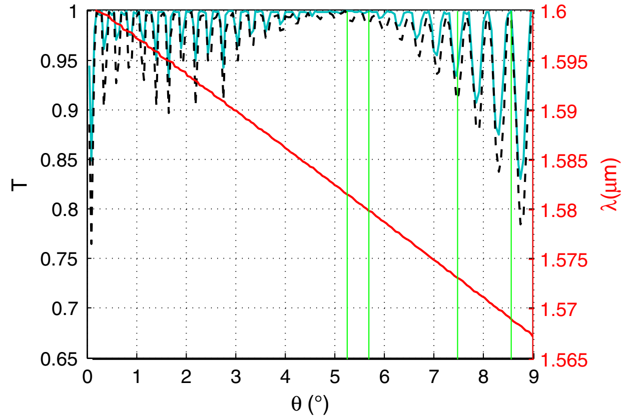

Fig. 5. Behavior with respect to θ for the structure D_1. Left axis: upper (straight cyan line) and lower (dashed black line) bounds of the transmittivity when the incident plane wave takes any polarization state at the resonance wavelength; right axis (red line) resonance wavelength with respect to the polar angle of incidence for the lower bounds of transmittivity. The spectra for the θ marked with the straight vertical green lines are represented in Fig. 7.

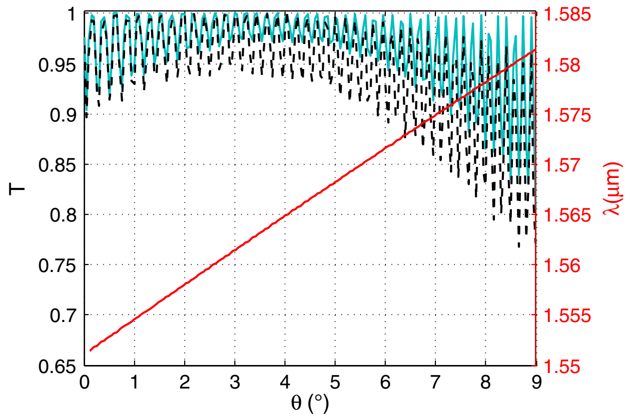

Fig. 6. Same as in Fig. 5, but for structure D_2.

In a second step, for each angle of incidence, we calculated, at the resonance wavelength, the upper and lower bounds of the transmittivity when the polarization takes any state, even nonlinear polarization states. These bounds are calculated from the transmittivity matrix of the structure as explained in [5,25], and are obtained for polarizations that are mutually orthogonal (these polarizations are not necessarily the same all along the angular range represented in Figs. 5 and 6). We plot in Figs. 5 and 6 the value of the upper (straight cyan line) and lower (dashed black line) bounds of the transmittivity at the resonance wavelength, with respect to θ (left axis). We emphasize that knowing the bounds (when the incident polarization takes any state) of the transmittivity gives important information on the behavior of the structure with respect to the incident polarization: the transmittivity of the structure for an incident wave with any polarization state (even if it is nonpolarized) necessarily lies between the two curves, and the structure is polarization independent when the two curves are superimposed. For

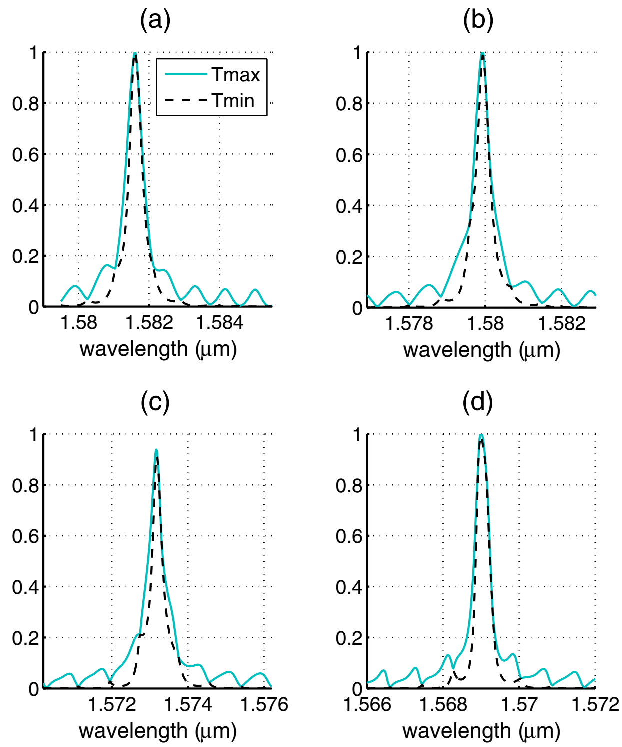

Fig. 7. Transmittivity spectra for the structure D_1 at (a) $\theta = 5.2°$, (b) $\theta = 5.65°$, (c) $\theta = 7.45°$, (d) $\theta = 8.55°$: upper (straight cyan line) and lower (dashed black line) bounds of the transmittivity when the incident plane wave takes any polarization state.

both structures, we observe oscillations which are related to Fabry–Perot resonances due to the thick substrate, as for the reflection filter [11]. We present in Fig. 7 the spectra for the angles marked with the straight green lines in Fig. 5. We observe that the peaks are barely distorted and that the polarization independence property is quite well kept over a wide range of angles and wavelengths. The sames remarks are true for structure D_2.

Finally, structure D_1 presents a transmittivity greater than 95% whatever the incident polarization for wavelengths between 1.575 μm (for 7°) and 1.59 μm (for 3°), and its bandwidth is around 0.4 nm. Structure D_2 presents a transmittivity greater than 90% whatever the incident polarization for wavelength between 1.552 μm (for 0.2°) and 1.572 μm (for 5.8°), and its bandwidth is around 0.35 nm.

Beyond those performances, some particular features need to be discussed. First, the fact that in the structure D_1 the excitation occurs though the $+1$ diffraction orders means, as mentioned earlier, that the modes excited in the whole structure cannot be considered as being simply TE or TM guided modes. Second, in Figs. 5 and 6, we see that the optimum functioning point, that is to say the angle for which the component is polarization independent, is not obtained for 7° as expected from the design. Structure D_1 shows a range of angles around 5° where the upper and lower bounds of transmittivity both reach 100%. Similarly, for the structure D_2, a decrease of the amplitude of the oscillations is observed around 4°, but the oscillations remain large. Third, we checked that the polarizations corresponding to the bounds of transmittivity are not linear polarizations with an angle $\psi = 45°$ and 135° with respect to the s but are rather elliptic polarizations. These are consequences of the fact that the modes of the two half structures couple to each other through the zeroth (propagative) order when assembled. The fact that the coupling is important can be explained as follow. First, as explained at the end of the third paragraph, the grating is engraved in a high index material, which makes a strong perturbation on the guided modes of the multilayer stack. Second, at resonance, for the upper structure, both polarizations (for $\psi = 135°$ which is resonant, and $\psi = 45°$, which is not resonant) are transmitted. Hence, the transmitted field inside the thick substrate has a polarization which is a mix between theses two polarizations, and consequently it is able to couple the two modes to each other.

5. CONCLUSION

As a conclusion, we showed that the $2 \times 1D$ crossed gratings configuration can be fit for functioning in transmission. We used a strongly modulated grating (air trenches in a high index material such as silicon) to create a half structure that is a transmission filter for one polarization and antireflective for the orthogonal polarization. The design of such a half structure is tricky, and we resort to an optimization algorithm (CGO) combined with our FMM numerical code. This is the first time, to our knowledge, that the CGO algorithm is used for guided mode resonance grating optimization.

Combining two of these half structures in a $2 \times 1D$ crossed configuration, we achieved polarization independent transmission filters. We demonstrated two different designs of transmission filters with a quality factor about 4000, tunable over more than 15 nm when the angle of incidence varies over a range of 4°, and with a transmission at resonance greater than 95% whatever the incident polarization. This result validates the principle of $2 \times 1D$ crossed strongly modulated gratings for narrowband polarization independent transmission filtering tunable with the angle of incidence. However, improving the performances (especially the rejection rate) may be difficult for two reasons. First, the optical function required for one half structure is complicated. Second, the two half structures are not independent from each others: a coupling occurs between the modes of the two half structures when they are assembled. These difficulties were not observed for the $2 \times 1D$ crossed gratings reflection filter. The response of the whole filter cannot be predicted from that of the two half structures and necessarily requires the use of a numerical code able to deal with gratings periodic along two nonorthogonal directions. Nevertheless, we hope that the $2 \times 1D$ crossed strongly modulated gratings can find applications. One possibility may be polarization control, since they seem to generate polarization mixing.

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