Experimental demonstration of ultrasharp unpolarized filtering by resonant gratings at oblique incidence

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The peaks in the reflectivity spectrum of waveguide gratings observed when the incident beam couples to a mode of the structure are promising features for many applications. However their weak angular tolerance and their strong polarization sensitivity, especially under oblique incidence, limit their interest in practice. These problems can be overcome by forming slow degenerate modes outside the usual high symmetry points of the Brillouin zone with a complex periodic pattern [Fehrembach, Appl. Phys. Lett. 86, 121105 (2005)]. We show experimentally that spectrally sharp, \( \lambda/\Delta\lambda \approx 4000 \), polarization-independent, angularly tolerant optical resonances can be obtained by exciting these modes under oblique incidence. © 2009 Optical Society of America

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1. INTRODUCTION

A resonant grating filter is basically a periodically structured planar waveguide that reflects and transmits light specularly. When the incident beam is grating-scattered into one mode of the waveguide, one observes a peak in the reflectivity spectrum. The potential of these components for free-space filtering or sensing has been quickly put forward, and many theoretical and experimental studies, essentially in the one-dimensional case under classical mounting, have been conducted in order to understand and control the resonance phenomenon [1–4]. Yet major limitations still hinder the use of these components for practical applications. The first difficulty is that, except under normal incidence with bi-dimensional gratings that are invariant by a rotation smaller than \( \pi/2 \) [4–6], or for special grating designs [7–11], the resonance depends in general on the polarization of the incident light. The second issue is that the spectral and angular selectivities of the resonance go together. Thus, resonances with very narrow spectral linewidth can be observed only with impractically large collimated incident beams [12]. These two problems are particularly acute in configurations where oblique incidence is required, as often, to avoid the use of beam separators. Hence, in the recent experimental works addressing the issue of unpolarized filtering under oblique incidence, the quality factor \( \lambda/\Delta\lambda \) of the resonances remained below 500 [13,14].

In this work, we sketch the physical mechanisms that permit one to overcome these two issues simultaneously under oblique incidence [10]. We report the first experimental observation, to our knowledge, of polarization-independent, angularly tolerant, ultrasharp resonances obtained under oblique incidence with a waveguide grating.

2. THEORETICAL BASIS AND DESIGN

We consider a periodically perturbed planar waveguide illuminated with a plane wave. The optical properties of the system are usually that of the planar structure, except when the incident wavelength \( \lambda \) and the in-plane wave vector \( \mathbf{k}_{\text{inc}} \) match that of a guided wave through scattering by the grating. For a two-dimensional grating with Bragg vectors \( \mathbf{K}_x \) and \( \mathbf{K}_y \), the phase matching condition through the \((m,n)\) scattering orders reads

\[
\| \mathbf{k}_{\text{inc}} + m\mathbf{K}_x + n\mathbf{K}_y \| = k_m,
\]

where \( k_m \) is the wavenumber of the guided wave. At the resonance, one observes a peak in the reflectivity spectrum that reaches theoretically 100\% [1]. The peak spectral bandwidth is directly linked to the coupling strength between the incident wave and the mode that involves the \((m,n)\) Fourier coefficient of the grating permittivity [3,12]. The weak angular tolerance of the resonance is due to the fact that, because of the strong modal dispersion, the matching equation is rapidly unsatisfied when the polar incident angle \( \theta \) is varied for a fixed incident wavelength.

Thus, it has been proposed to excite the locally dispersionless eigenmodes that exist, in periodical structures, at the crossing of the periodized dispersion curves of the guided wave, i.e., when Eq. (1) is satisfied for two pairs of integers \((m_1,n_1)\) and \((m_2,n_2)\) with opposite signs. At this point, the two counterpropagative guided waves couple via the grating and form two dispersionless eigenmodes with different frequencies. The coupling strength that monitors the frequency gap between the modes depends on the \( \pm(m_1-m_2,n_1-n_2) \) Fourier coefficient of the grating permittivity. The larger the latter, the better the angular
tolerance of the resonance [3]. The excitation of the grating eigenmode by an incident beam depends also on the overlap integral between the incident and the mode field. This expresses the fact that a TE or TM mode cannot be excited with any polarization. Hence, to obtain polarization-independent resonances, it is necessary to excite two degenerate modes, i.e., modes with different field repartition but identical electromagnetic energy [4].

Polarization independence and angular tolerance are easily obtained with a square array illuminated under normal incidence [5]. The four guided waves that are excited with the (0, 1), (0, −1), (1, 0), and (−1, 0) orders of the grating form four dispersionless eigenmodes, two of which are degenerate; see Fig. 1(a).

The simultaneous excitation of four guided waves can also be obtained under oblique incidence with a waveguide grating supporting two different TE guided waves with wave numbers $k_{m1}$ and $k_{m2}$ ($k_{m1} > k_{m2}$) and by illuminating the structure along the bisector plane of the directions of periodicity [7,10]; see Fig. 1(b). In this case, it is possible to find a nonnull incident in-plane wave vector satisfying the coupling condition for both modes,

$$\begin{align*}
|k_{\text{inc}} + k_x| &= |k_{\text{inc}} + k_y| = k_{m1} \\
|k_{\text{inc}} + k_x| &= |k_{\text{inc}} + k_y| = k_{m2}.
\end{align*}$$

If the plane of incidence is a plane of symmetry of the structure [7], the four guided waves couple to each other to form two pairs of eigenmodes with opposite symmetry properties with respect to that plane and orthogonal polarizations. These modes are dispersionless because they stem from counterpropagative guided waves that are coupled to each other through the $(±2,0)$ Fourier coefficient of the grating permittivity. Moreover, it has been shown that by tuning the $(−1,1)$ Fourier coefficient of the grating permittivity, it is possible to obtain the mode degeneracy [10] between the orthogonal modes. The appropriate $(1,0), (2,0)$ and $(−1,1)$ Fourier coefficients that are required to produce the narrowband, angularly tolerant, polarization-independent resonance can be obtained by designing a periodic structure with a complex cell made of four holes with different diameters; see Fig. 2(a) [10].

3. FABRICATION AND CHARACTERIZATION

The designed component—see Fig. 2—is composed of four layers ($\text{SiO}_2/\text{Ta}_2\text{O}_5/\text{SiO}_2/\text{Ta}_2\text{O}_5$) coated on a silica substrate using an e-beam evaporation technique with a reactive ion beam assistance. The multilayer is optimized to present an antireflection behavior about the filtering

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**Fig. 1.** (Color online) Graphical representation of coupling condition for four guided waves. (a) At normal incidence. (b) At oblique incidence.

**Fig. 2.** Description of the manufactured component designed with the Fourier modal method [15]. (a) Top view of component: periodic pattern (period $d=890\,\text{nm}$) of four air holes A, B, C (diameters $d_A=257\,\text{nm}, d_B=347\,\text{nm}, d_C=170\,\text{nm}$). (b) Four-layer stack of $\text{Ta}_2\text{O}_5$ and $\text{SiO}_2$ on a glass substrate [refractive indices $n(\text{air})=1, n(\text{Ta}_2\text{O}_5)=2.093, n(\text{SiO}_2)=1.47$, and $n(\text{glass})=1.443$, and layer thickness from top to bottom of 220, 109, 63, and 126 nm; first is engraved].
wavelength and to support two TE modes. We use electron-beam lithography followed by a CHF$_3$-based reactive ion etching process to prepare a 2D hole grating in 220 nm thick silicon oxide. The grating extension was restricted to 1 mm $\times$ 1 mm.

Optical transmission and reflection spectra were measured in a range of 1520–1570 nm using a tunable erbium fiber laser with a resolution better than 50 pm. The experiment (and the simulations) were performed with an incident Gaussian beam of 580 $\mu$m diameter at waist. The transmitted and reflected light were detected with a photodiode placed as close as possible to the resonant grating in order to collect all the transmitted and reflected signal. The absolute transmittance (reflectance) was determined by normalizing the transmission (reflection) with a reference signal measured in the absence of the grating (with a mirror) with the same photodiode. Thereafter, the plane of incidence was adjusted to be a bisector plane of the array axis with an accuracy of 0.5°.

In Fig. 3, we plot the polar incidence angle $\theta$ corresponding to a minimum in transmission with respect to the wavelength for both $\hat{p}$ (squares) and $\hat{s}$ (crosses) polarizations [corresponding to an electric field parallel and orthogonal to the plane of incidence, respectively; see Fig. 2(b)]. These curves are a good indicator of the dispersion relation of the grating modes [1]. They show, as expected, the existence of two pairs of dispersionless $\hat{p}$ and $\hat{s}$ eigenmodes that are degenerate at the band edges. The spectral shift between the experimental and theoretical results is mainly due to the layers’ optical thickness uncertainties.

Note that the left and center parts of the top curves in Fig. 3 should be taken with caution. Indeed, we believe that in these regions, the coupling of the incident beam into the eigenmodes vanishes because of the null overlapping between the incident field and the mode. This phenomenon is similar to what happens under normal incidence where the mode, made of four guided waves propagating in opposite directions, is either even or odd at the M point of the Brillouin zone. In the latter case, it cannot be coupled to the incident plane wave. In oblique incidence, the reason for the disappearance of the resonance on the left of the extremum of the dispersion relation is not as clear as in normal incidence, because the four different guided waves do not propagate exactly along opposite directions. Thus the resulting mode does not present a simple odd or even field repartition.

We plot on Fig. 4 the calculated and measured transmittivity versus the wavelength at an incidence angle corresponding to the bottom bandedge $A$ and $A'$ ($\theta=5.8^\circ$ experimentally and $\theta=5.765^\circ$ theoretically) and outside the band edge at points $B$ and $B'$ ($\theta=5.465^\circ$ theoretically and $\theta=5.465^\circ$ experimentally). Outside the band edge (points $B$ and $B'$), we observe that the $\hat{s}$ and $\hat{p}$ resonances are split and that they are scarcely marked. This is due to the

Fig. 3. (a) Calculated and (b) measured resonance positions with respect to the angle of incidence ($\theta$) and wavelength ($\lambda$) for both polarizations $\hat{s}$ (squares) and $\hat{p}$ (crosses). Inset: Scanning electron microscopy image of the component.

Fig. 4. (a) Calculated resonance at $\theta=5.765^\circ$ of incidence (point $A$) and at $\theta=5.465^\circ$ (point $B$). (b) Measured resonance at $\theta=5.8^\circ$ (point $A'$) and at $\theta=5.5^\circ$ (point $B'$).
weak angular tolerance of the resonance, estimated theoretically at 0.02°, compared with the incident beam divergence of 0.2° [6,11,16]. On the contrary, at the band edge (points A and A’) the $\hat{p}$ and $\hat{s}$ resonances occur at the same wavelength and the transmission peak is narrower and deeper. Indeed, the angular tolerance of the unpolarized resonance at this point is estimated at 0.17°. The deterioration of the filtering due to the use of a divergent beam is thus less pronounced.

At the band edge, the experimental transmission minimum and the spectral bandwidth are 52% and 0.4 nm compared with 36% and 0.2 nm obtained theoretically. In addition, the experimental reflectivity spectrum exhibits a maximum of 28% at the resonance wavelength (64% theoretically). Hence, we observe a loss of energy of 20%. The finite size of the manufactured grating most probably accounts for these discrepancies [11]. Indeed, we have observed with numerical simulations that the total field intensity obtained just above the grating spreads beyond the incident Gaussian beam spot and beyond the actual grating boundaries. Thus, part of the incident intensity is transmitted, unaffected, by the planar multilayer and part of the energy is trapped in guided waves that are not diffracted back into free space. Scattering by the etching imperfections appears to be negligible, as we have observed that all the incident energy is reflected and transmitted in the specular direction.

4. CONCLUSION

This work shows that resonant gratings are a sustainable solution for very narrow band unpolarized filtering applications. Improvement of the filter performance should be obtained with larger grating size or structures presenting a better angular tolerance, such as those proposed by Greenwell et al. [17].

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REFERENCES AND NOTES


16. The angular tolerance of the resonance is estimated by calculating the FWHM of the reflectivity peak with respect to the incidence angle when the grating is illuminated by a plane wave.