Oblique incidence and polarization effects in coupled gratings

Ángela Coves,[1,*] Benito Gimeno,[2] and Miguel V. Andrés[2]

[1]*Departmento de Ingeniería de Comunicaciones, Universidad Miguel Hernández de Elche, Elche, 03202, Spain*
[2]*Departmento de Física Aplicada y Electromagnetismo-ICMUV, Universidad de Valencia, Spain*
[*]*angela.coves@umh.es*

Abstract: Oblique incidence and polarization orientation of the input beam have dramatic effects on the spectral response of coupled dielectric waveguide gratings. Coupled gratings with small periodic perturbations can be described as a problem of two coupled resonances at strictly normal incidence, but we find that the device involves four coupled resonances when oblique incidence and polarization effects are included in the analysis. Very small deviations from normal incidence change qualitatively the spectral response and four peaks are observed, whereas only two peaks are present at normal incidence. Polarization misalignments produce a decrease of the reflectance of the resonances at normal incidence, but a simultaneous shift of the spectral position of the peaks is observed at oblique incidence.

OCIS codes: (050.1970) Diffractive optics; (310.2790) Guided waves; (120.2440) Filters.

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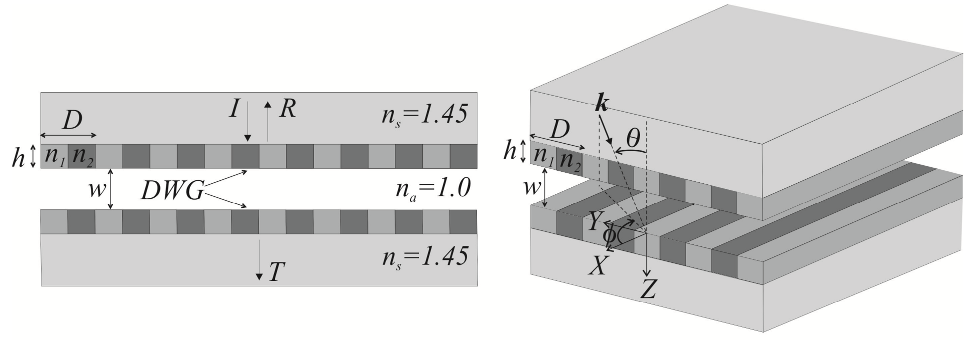
1. Introduction

Dielectric waveguide gratings (DWG) and multilayered dielectric structures containing one or several DWGs have been subject of great interest for many years. In such structures, leaky modes can be excited, producing total reflection at the guided-mode resonance wavelengths [1,2]. These structures have a great interest for optics and microwave applications as passive components and, in particular, as filters with a high Q factor [3–5]. The design and experimental implementation of dynamic structures with tunable or reconfigurable capabilities is a challenge, and very few proposals have been presented: a semiconductor based DWG [6] and some DWGs fabricated with nonlinear materials [7–9].

Recently, we can find two proposals for tunable non-interferometric high Q filters, which are based on varying the coupling between the surface modes of two Bragg reflectors [10], in the first case, and two dielectric gratings [11,12], in the second case. The overlap of the evanescent fields of these resonant reflectors determines the coupling and the splitting of the otherwise degenerate resonances. Thus, the spectral position of the new resonances is controlled by changing the gap width. These structures give rise to a new type of tunable device that resembles a Fabry-Perot filter, but the principle of operation is not interferometric and the response is not periodical neither with the gap width nor with the optical frequency. The filter based on two Bragg reflectors has a spectral response limited by the bandwidth of the photonic bandgap, while in the case of using two gratings this limitation is not present.

In this paper, we study the polarization effects and the consequences of oblique incidence in the spectral response of two coupled DWGs. Our full wave analysis of multilayered waveguide gratings is based on a vector modal method [13,14]. Once the reflection and transmission coefficients of a single layer are obtained, the study of the multilayered structure is accomplished by the cascade connection of components characterized by their scattering parameters. Our results are complementary to those previously reported [11] where different separations and alignment conditions were analyzed.



(a) (b)

Fig. 1. Basic structure, consisting of two back-to-back substrates with overlaid DWGs, separated by a small air gap: normal incidence (a) and 3-D incidence (b). The outer substrate surfaces are effectively extended to infinity.

2. Coupled gratings as tunable double wavelength filter

In order to illustrate the polarization and oblique incidence effects, first we describe the basic properties of a pair of coupled gratings with an ideal normal incidence. The structure that we consider in our simulations is depicted in Fig. 1. We consider plane wave incidence from a uniform medium made of SiO_2 with a refractive index of 1.45. The separation between coupled DWGs is a narrow air gap. In this section, only TE-polarized light is considered, in which the incident plane wave is perpendicular (θ = 0°) and the electric field is entirely perpendicular to the inner interfaces of the DWGs (ϕ = 90°). The case of TM-polarized incidence corresponds to ϕ = 0° and gives rise to similar response than the TE-polarized beams, but at a rather different wavelength range. The DWG consists of alternating high-/low-index dielectric bars. The refractive indices of the high- and low-index bars are taken to be $n_1 = 2.5$ and $n_2 = 2.49$ which are representative of the values for TiO_2 and doped TiO_2, and their widths are fixed at $D/2$, where D is the period of the DWG, being h its thickness. We neglect material absorption.

Each isolated DWG placed onto the SiO_2 substrate ($n_s = 1.45$) shows a total reflection peak at the resonance wavelength of the grating, centered at $\lambda = 1.5$ µm at normal incidence. When both gratings are coupled through a narrow air gap, as shown in Fig. 1, a double resonance appears due to the evanescent coupling of the DWG resonances. Figure 2 illustrates the tunable filter application previously proposed [11]. The reflectance of the structure has been calculated for the values $D = 723$ nm, and thickness $h = 300$ nm. The main features of this filter are the high Q of the resonances and the large spectral range in which the double-peaks of the filter can be adjusted. For small periodic perturbations, the separation of the line-pairs can be predicted using classical coupled-mode theory by computing the overlap of the evanescent fields [15]. In Fig. 2 we compare the computed wavelength separation of the line-pairs as a function of the air-gap width w with that predicted by the coupled-mode theory, showing a perfect agreement.

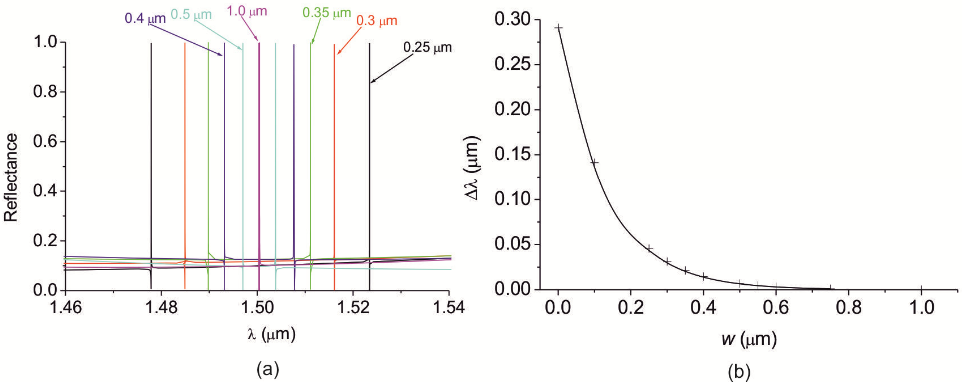


Fig. 2. (a) Reflectance as a function of wavelength of two coupled DWGs for different air-gap widths depicted in the figure, at normal plane-wave TE incidence. (b) Separation of the line-pairs as a function of the air-gap width *w*: comparison between the vector modal method (solid line) and the approximated solution obtained by the coupled mode theory (crosses).

Having in mind that the implementation of volume DWG's as those depicted in Fig. 1 may present serious technological difficulties in their manufacturing process, we propose to replace such DWGs by equivalent shallow surface-relief gratings (SRG) [5] (see Fig. 3(a)). SRGs could be manufactured using a combination of photolithographic and etching techniques. The SRG equivalent to the DWG that we consider here for the simulations could be made of a TiO_2 layer placed onto the SiO_2 substrate, with periodic shallow grooves of depth $t = 7$ nm, being $h = 300$ nm. As an example, Fig. 3 illustrates the spectral response of a pair of SRGs coupled through an air gap of 0.5 µm. We compare this spectrum with the previously computed for the coupled DWGs. Having in mind this equivalence, through out the rest of this work we will carry out the simulations using the equivalent SRGs as a most realistic implementation of the filters.

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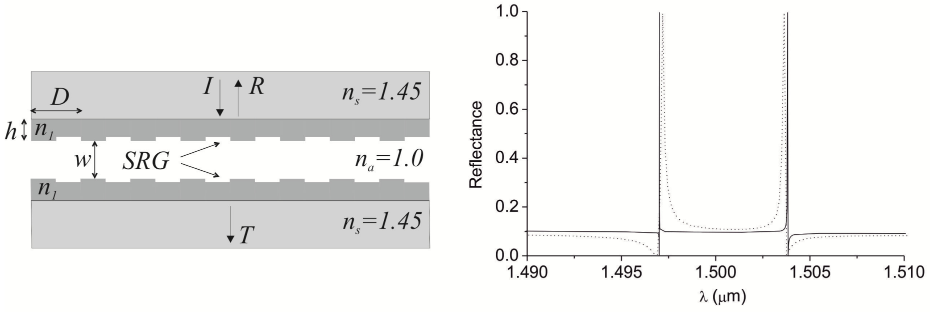
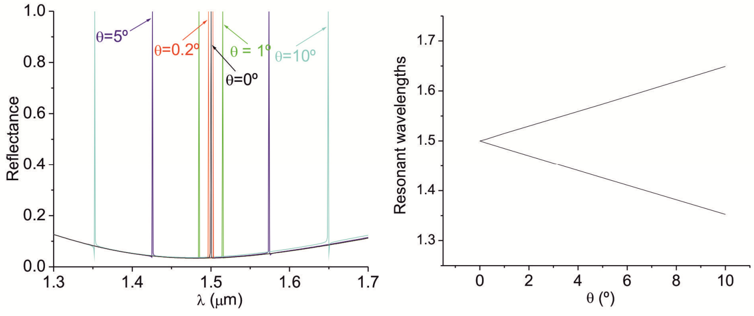


(a) (b)

Fig. 3. (a) Equivalent two coupled shallow SRGs. (b) Comparison of the reflectance of two coupled DWGs with an air-gap w = 0.5 μm (solid line) with the reflectance of two coupled shallow SRGs (dotted line).

3. Oblique incidence effects

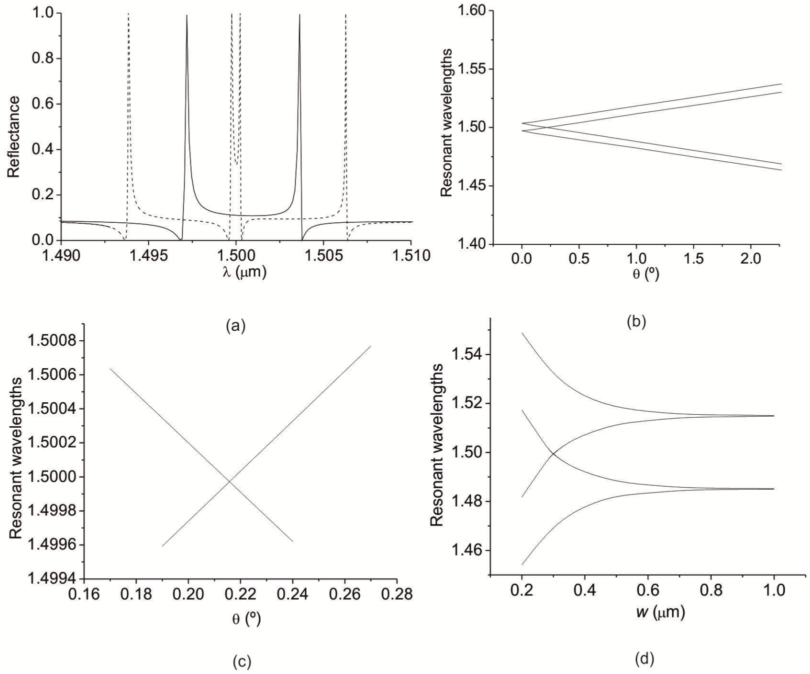
First, we will analyze the case of oblique incidence, i.e., incidence with $\theta \neq 0$ and $\phi = 90°$ (see Fig. 1). The oblique incidence preserves the TE-polarization, and gives rise to the splitting of the normal-incidence resonances of a single DWG structure, or its equivalent SRG. This effect has been both experimentally and theoretically studied [4,13] and it is due to the break of symmetry that the oblique incidence produces in the phase matching condition for the propagating and counterpropagating Bloch waves of the DWG. Figure 4 shows several reflectance spectra of a single SRG at oblique incidence. We include in Fig. 4 the detail of how the wavelengths of the resonances shift with the angle θ. The splitting of these resonances grows fast with the angle of incidence. In fact, a single DWG behaves as a double-peak filter, tunable by changing slightly the angle of incidence θ at around normal incidence. Thus, this filter exhibits qualitatively the same response than the filter formed by two coupled DWGs, but with a more simple experimental arrangement. However, the two coupled DWGs structure adds a new mechanism of tuning of the resonances appearing in such structure through the variation of the air-gap width, which may be technologically simpler than varying the angle of incidence of the source.



(a) (b)

Fig. 4. (a) Reflectance spectra of a single SRG at oblique incidence for several angles of incidence θ. (b) Resonant wavelengths versus the angle of incidence θ.

Next, we will demonstrate that oblique incidence has qualitative consequences in the case of the coupled gratings since the system is not any more the result of coupling between the evanescent fields of two modes, but it is a four modes coupled system. Figure 5(a) gives the reflectance spectra for two coupled SRGs with w = 0.5 μm, at normal incidence (solid line) and with θ = 0.2° (dashed line). In Fig. 5(b) we give detailed information on how the wavelengths of the four resonances change with the angle of incidence at constant separation *w*. For this particular value of *w*, a crossing point is produced at $\theta \approx 0.21°$ (see Fig. 5(c)) in which two of the resonances are degenerate at λ = 1.5 µm, but no coupling is produced since this two branches are the result of the hybridization in the coupled DWG of two orthogonal modes. The variation of the resonance wavelength versus the separation *w* at an angle of incidence of θ = 1° is plotted in Fig. 5(d). When *w* increases, the coupling between the two gratings reduces and, consequently the four resonances degenerate and, in the limit, the two remaining resonances correspond to the resonances of a single grating at oblique incidence θ = 1 °. Again in this plot one can observe the degeneracy of two resonances at $w \approx 0.3$ µm.



(a)

(b)

(c)

(d)

Fig. 5. (a) Reflectance spectra of a pair of coupled SRGs with *w* = 0.5 µm at normal incidence (solid line) and at oblique incidence, θ = 0.2° (dashed line). (b) Wavelength of the four resonances versus the angle of incidence with *w* = 0.5 µm. (c) Zoom of the crossing point of two of the resonances represented in Fig. 5(b). (d) Variation of the resonance wavelength versus the separation *w* at an angle of incidence of θ = 1°.

4. Polarization effects

At normal incidence, the effect of having $\phi \neq 90°$ is equivalent to a pure change of the input polarization. If we consider a TE incidence with ϕ = 90°, then ϕ = 0° will correspond to TM incidence. Thus if we have TE incidence with ϕ = 90°, a small deviation of the polarization of the input beam with respect the grating orientation will produce, at normal incidence, a partial transfer of power to the TM resonance and a decrease of the reflectance of the TE resonances. Figure 6 depicts this effect. In fact for ϕ = 0° no resonance is observed around 1500 nm. This result confirms the polarizing effect that DWGs exhibit: the spectral position of the TE resonance does not change, but the amplitude of the effective reflectance decreases since the TE component of the electric field is decreasing when $\phi \neq 90°$.

The situation is qualitatively different when we consider the case of oblique incidence and $\phi \neq 90°$. Figure 7 shows the result of computing the reflectance versus wavelength around

1500 nm with $\theta = 0.2°$ and several values of ϕ. In this case, since oblique incidence breaks the degeneracy of the resonances, a deviation of the angle ϕ has two effects. On the one hand, it decreases the reflectance of the resonances as in the case of normal incidence and, on the other hand, it modifies the asymmetry that the oblique incidence produces in the phase matching condition for the propagating and counterpropagating Bloch waves of the DWG. Consequently, at the same time that the amplitude of the resonances changes, they shift in the spectrum.

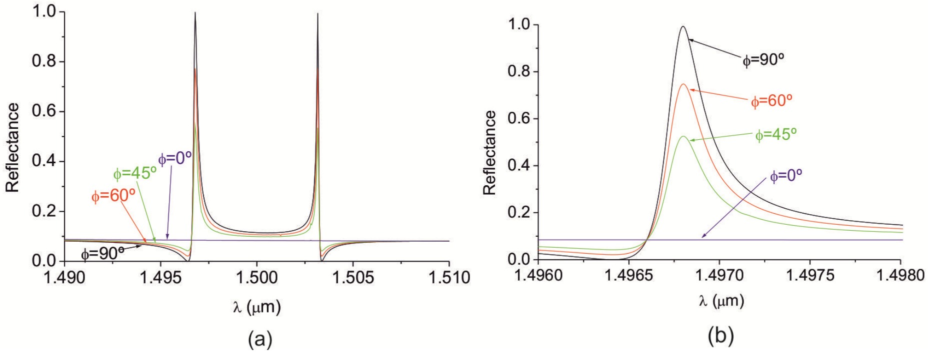


Fig. 6. (a) Reflectance spectra of the pair of coupled SRGs of Fig. 5(a) at normal incidence for different angles ϕ. (b) Detail of one of the resonances.

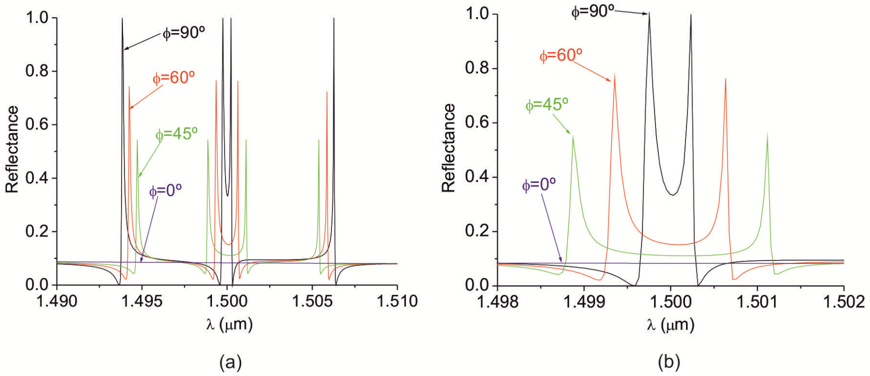


Fig. 7. (a) Reflectance spectra of the pair of coupled SRGs of Fig. 5(a) at oblique incidence ($\theta = 0.2°$) for different angles ϕ. (b) Detail of the central resonances.

5. Conclusion

The study of oblique incidence and polarization effects on coupled gratings demonstrates that the use of this type of device as a non interferometric tunable filter has severe limitations. A small deviation from normal incidence changes qualitatively the response since the system switches from being a problem of two coupled resonances to a problem of four coupled resonances. Thus, oblique incidence produces two new peaks in the reflectance spectra of the devices, giving a total of four peaks which shift with the gap width w and with the angles θ and ϕ. Some of the results presented here could be exploited in some particular applications where special spectral and polarization filtering is required. For example, the use of a pair of coupled gratings as a laser mirror can provide longitudinal mode filtering and simultaneous polarization filtering in a single device.

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