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Multiple wavelength resonant grating filters at oblique incidence with broad angular acceptance

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Abstract: Multilayer, multimode waveguides are utilized in resonant grating filters having a broadened angular acceptance bandwidth for multiple wavelengths at a single oblique angle of incidence. It is shown that the waveguide grating structure should support a few leaky modes in order to support a multiwavelength resonant filter at oblique incidence with broadened angle acceptance at each wavelength.

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1. Introduction

Resonant grating filters are passive optical devices that consist of a planar waveguide in the presence of a periodic perturbation of the structure’s geometric and material properties, i.e. a diffraction grating. Subwavelength gratings allowing only 0th-order propagation have been widely shown, both theoretically and experimentally, to function as efficient narrow spectral bandpass optical filters in both reflection and transmission [1-4]. And while these filters have
been observed to possess an angular bandwidth broad enough to accommodate incident finite beams at normal incidence [5], the angular bandwidth of the resonant response at oblique incidence is considerably narrowed in most cases [6, 7]. In recent papers [7,8], Sentenac and Fehrembach presented a method of obtaining a broadened angular resonance bandwidth at oblique incidence through the simultaneous coupling to two counter-propagating leaky modes having propagation constants of differing magnitudes.

In cases of both normal and oblique incidence, the interaction of two complex zeros of the waveguide grating’s modal dispersion relation that results in a broadened angular acceptance can be related to the opening of a “k-gap” [9]. Near the flattened dispersion band edge that results from interacting with these two modes, a plane wave incident from a broader range of angles can couple energy into the modes supported by the structure than is usually the case when coupling to only a single mode occurs. It was observed that at normal incidence, symmetry conditions result in coupling to only the upper band edge frequency, while at oblique incidence, this symmetry condition is broken and coupling may occur at both the upper and lower band edge frequencies [7,8]. Yet while this coupling may occur at both the upper and lower band edges, a broadened angular acceptance only occurs at one of the two frequencies. In this paper, we apply the idea of coupling to counter-propagating modes, to develop multilayer, multimode resonant grating filters that simultaneously filter multiple wavelengths with a broadened angular acceptance at a single oblique angle of incidence.

2. Angular broadening with only two leaky modes

The flattening of a structure’s modal dispersion curves and the creation of dispersion bands associated with the interaction of two leaky modes have been described, in a phenomenological sense, by Sentenac and Fehrembach [7]. A resonant grating filter having a narrow spectral bandwidth with broadened angular acceptance at oblique incidence was designed using a bi-atom grating placed on top of a three layer waveguide, similar to Fig. 1.

Fig. 1. A drawing of a waveguide grating that supports two leaky modes, as well as the material and structural parameters for the material and geometry.

In order to quantify these modal dispersion properties of such a structure, the complex dispersion bands for this structure and all subsequent structures were calculated using an RCWA/S-Matrix approach with incorporated Perfectly Matched Layer boundary conditions as described in Cao et. al [10]. By solving the generalized eigenvalue problem defined by this “longitudinal” scattering matrix, the complex dispersion properties of multiple leaky modes for a single wavelength can be determined from a single matrix operation constructed from four separate single layer scattering matrices and two separate single layer eigenvalue problems [11]. Similar results can be obtained through searching for the complex poles of a multilayer “transverse” scattering matrix [12], although in practice with this method each individual leaky mode/pole of a multimode structure must be searched for in a separate iterative search of the complex solution plane. In either case, the scattering matrix calculation is utilized to determine each leaky mode’s complex propagation constant, \( \beta - j\alpha = k_0n_{\text{mode}} - j\alpha \).
Figure 2 shows the 0th order spectral reflection of the two leaky mode resonant grating filter defined in Fig. 1 at normal incidence, as well as the corresponding complex dispersion band structure, and the angular reflection spectrum at the peak of each spectral resonance. For both the spectral reflection and complex band structure plots, the vertical axis, $\Lambda/\lambda$, represents the free space wave number, $k_0 = 2\pi/\lambda$, normalized by the magnitude of the grating vector, $K = 2\pi/\Lambda$. The horizontal axes for the dispersion curves represent the modal propagation constants. For the plot of the real part of the dispersion curves, we show the real part of the propagation constants, $\beta = k_0n_{\text{mode}}$, normalized by the magnitude of the grating vector, $(\Lambda/\lambda)n_{\text{mode}}$, as well as the propagation constants for the corresponding counter-propagating modes added to the second multiple of the grating vector magnitude, $-(\Lambda/\lambda)n_{\text{mode}}+2K$, which are then also normalized by the grating vector magnitude, $-(\Lambda/\lambda)n_{\text{mode}}+2$. While omitted, the horizontal axis for all real dispersion curves shown varies from 0.75 to 1.25 with a central value of 1. For the peak of each spectral resonance, a horizontal line is placed on the dispersion plot at the appropriate wavelength, and a vertical line is placed at a value of $1-(\Lambda/\lambda)\sin\theta_{\text{incident}}$ representing the input plane wave. The real part of each modal dispersion curve is bounded by the modal substrate cut-off lines, $(\Lambda/\lambda)n_{\text{substrate}}$ and $-(\Lambda/\lambda)n_{\text{substrate}}+2$. The complex part of the modal dispersion is plotted directly as $\alpha_{\text{mode}}$ and $-\alpha_{\text{mode}}$ with appropriate
horizontal lines for each spectral resonance. Fig. 3 shows the same complex modal dispersion band structure, but includes the reflection spectra associated with a 1° angle of incidence.

As can be seen by comparing Fig. 2 and Fig. 3, the resonances associated with the angular spectra at normal incidence are much broader than at a 1° angle of incidence. When the angle of incidence is increased to nearly 5°, as shown in Fig. 4, the angular response associated with the localized upper band edge is considerably broadened while the resonance associated with the lower band edge wavelength remains narrow.

Fig. 3. The complex modal dispersion, as well as the 0th order reflection response for all of the resonances of the system at a 1° angle of incidence for the two leaky mode resonant grating.
Fig. 4. The complex modal dispersion, as well as the 0th order reflection response, for all of the resonances of the system at a ~5° angle of incidence for the two leaky mode resonant grating.

By focusing in on the modal dispersion properties near the off-normal band edge, as shown in Fig. 5, the slope of the upper and lower dispersion band edges can be seen to have significantly different properties. At the upper band edge, the slope of the modal dispersion lines change more gradually upon entering the “k-gap,” but these modal dispersion lines do not actually cross until nearly at the lower band edge wavelength. At the lower band edge wavelength, the change in the slope of the dispersion curves between values inside and outside the “k-gap” occurs much more rapidly. This more gradually changing modal dispersion at the upper band edge is the cause of the larger angular acceptance at the upper band edge wavelength.
For the purposes of this paper, the more important point regarding the relationship between the upper and lower band edges is that the peak reflections for each resonance occur at separate angles of incidence. In designing multi-wavelength resonant filters, it would be desirable to design the structure such that a broadened angular acceptance could occur for all desired wavelengths at a single angle of incidence. Such a structure would allow its use with a single multi-wavelength source. Consequently, a resonant grating filter supporting only two leaky modes of separate magnitude cannot easily support separate spectral resonances having broadened angular acceptance centered at a single angle of incidence. To do so would most likely require some very sensitive material and geometric optimization. Furthermore, in the presence of materials having loss or gain, the peak reflection and minimum transmission may not occur at the same combination of wavelength and angle, and may result in a broadened (loss) or narrowed (gain) spectral response with reduced (loss) or increased (gain) peak reflection. While this paper only considers real-valued materials, the effect of materials with loss or gain on resonant gratings has been considered previously [13,14].
3. Multiple wavelengths angular broadening at a single incident angle with three or more leaky modes

In an effort to show the importance of the waveguide’s properties in determining the resonant response of the structure, the structural parameters of the grating layer (thickness, periodicity, fill factor) were held constant at their previous values, but an additional high refractive index and low refractive index layer were added to the system as shown in Fig. 6.

![Fig. 6](image)

Fig. 6. A drawing of a waveguide grating that supports three leaky modes, as well as the material and structural parameters for the material and geometry.

Through a hand-driven variation of the 5 layer thickness values, the angular locations of the upper and lower band edges resulting from the interactions of the TE$$_0$$/TE$$_1$$ & TE$$_1$$/TE$$_2$$ leaky waveguide modes were brought to nearly the same central value of approximately 2.5 degrees, as shown in the modal dispersion curves and angular resonance spectra in Fig. 7.
Fig. 7. The complex modal dispersion, as well as the $0^{th}$ order reflection response, for all of the resonances of the system at a $\sim 2.5^\circ$ angle of incidence for the three leaky mode resonant grating. At this angle of incidence, the upper band edge resonances are nearly, but not quite aligned in their central angles.

In order to optimize the location of both resonances to a single angle of incidence, a parameter scan involving a variation of thicknesses for the bottom two waveguide layers was performed while maintaining a constant total thickness, as shown in Fig. 8.
This choice of optimization parameters was arbitrary, as any of the waveguide grating’s structural parameters could be utilized for performing this optimization. Although choosing to vary the vertical permittivity distribution is a pertinent choice, because the growth of multilayer thin films can be controlled to very tight tolerances. Fig. 9 shows how the complex modal dispersion curves change as the value of $\Delta h$ is varied from -100 nm to +100 nm.
Fig. 9. Plots showing different views of the change of the real (a) & (c) and imaginary (b) & (d) parts of the waveguide grating's modal dispersion as a function of $\Delta h$. 

\[
\Lambda / \lambda \left( -\frac{\Lambda}{\lambda} n_{\text{mode}} + 2 \right) - \alpha_{\text{mode}}, \alpha_{\text{mode}} \Delta h (\mu m)
\]
By narrowing in on the two dispersion band edges of interest, as shown in Fig. 10, a clearer understanding can be obtained for the effects that a changing vertical permittivity distribution has on these dispersion bands.

![Fig. 10](image)

In this structure, negative values of Δh, which decreases the amount of high index material, alter the band edge locations considerably and cause a serious misalignment of the angular resonance locations. On the other hand, positive values of Δh, which increase the amount of high index material, have a smaller effect on resonance separation in this structure. A value of Δh ≈ 64 nm brings about the angular alignment being sought. Fig. 11 shows the 0th order wavelength reflection spectrum and complex modal dispersion bands associated with this final design.

![Fig. 11](image)
The angular alignment of the resonances at separate wavelengths can be seen in Fig. 12 along with the relevant dispersion band edges, and the associated resonance wavelengths, spectral bandwidths, and angular bandwidths can be seen in Table 1. Further tailoring of the structure’s dispersion properties could be performed to equalize the angular bandwidths or baseline reflection of the separate resonance wavelengths.

![Figure 12](image)

**Fig. 12.** (a) Plot showing the angular resonances associated with the optimized multilayer resonant grating structure. The resonances at wavelengths of 1.507 μm and 1.604 μm are both centered at an input angle of 3.17º and have broadened angular bandwidth due to the simultaneous interactions of separate pairs of leaky modes. (b) The real part of the modal dispersion diagram showing the band edges of interest. The circles are numbered and color-coded to the resonance curves from (a).
Table 1. Resonance property values at ~3.17° and ~3.24° angle of incidence for the resonance in Fig. 12.

| resonance | 1  | 2  | 3  | 4  | 5  |
|-----------|----|----|----|----|----|
| $\lambda_{\text{resonance}}$ (μm) | 1.444 | 1.508 | 1.527 | 1.604 | 1.614 |
| Δ$\lambda$ (nm) | .0251 | .0654 | .0103 | .0269 | .0049 |
| Δθ (mrad) | .0040 | .2278 | .0878 | .1055 | .0423 |
| (degrees) | .0023 | .1305 | .0500 | .0605 | .0242 |
| 1-(Λ/λ)sin θ | 0.9655 | 0.9670 | 0.9674 | 0.9689 | 0.9691 |

When considering the potential for fabrication of the structures considered in this study, it is important to remember that the tolerances for the layer thicknesses required are on the same order of magnitude (a few nanometers) as other highly selective spectral filters, and that the total number of alternating layers required for these devices is much less than traditional thin film Bragg filters for WDM applications. Furthermore, if the refractive indices of the two materials utilized are well known and characterized, then a new numerical optimization of the structural parameters can be performed after the growth of each layer is completed taking into account the completed layer thickness values. Once all layer growth is complete, further numerical optimization/adjustment of the grating parameters (fill factor, period, depth) could then be performed to set the final desired etching properties for grating fabrication.

4. Summary

Multiple wavelength resonant grating filters at oblique incidence with broad angular acceptance are designed using multi-mode wave guiding structures. By analyzing the complex dispersion properties of a multilayer resonant waveguide grating, it was shown that while a resonant grating filter supporting two separate leaky modes can be utilized to produce a broadened angular acceptance for obliquely incident waves, the two mode structure does not provide adequate broadening and angular collocation to act as a multiwavelength filter. Through properly designing a resonant grating filter supporting three leaky modes, a broadened angular acceptance for two separate wavelengths can be designed to occur at a single angle of incidence. Using similar design logic to that presented in this paper, an N-line wavelength filter with broadened angular bandwidths at a single oblique angle of incidence could be designed for a resonant grating filter supporting N+1 leaky modes. Further optimization of the structure presented in this paper would allow for the design of equivalent angular acceptance bandwidths and minimal broadband reflection.