Abstract — Flat-top narrow band optical spectral response can be shaped by cascading resonant-grating reflectance filters. Theoretical calculation shows that cascading one-pair of wavelength-offset and asymmetrical lines guided-mode resonance elements (GMRE) results in reflectance spectral response with abruptness factor of 1.44, insertion loss ~ 1.2 dB, contrast ratio 8.71 and possible narrow bandwidth of < 3-nm. Flat-top narrow band optical filters are potential candidates for WDM applications.

Keywords — Diffraction grating, diffractive optical element, guided-mode resonance, narrow-band optical filter, optical waveguide, resonant waveguide grating filter, thin-film optics.

I. INTRODUCTION

The pronounced resonance effect observed in waveguide grating structures at certain wavelengths arise due to coupling an incident wave to a leaky waveguide mode [1-4]. This resonance effect causes a high-efficiency reflection in narrow spectral band (possibly subnanometer full-width half maximum (FWHM)). The shape of the spectral response linewidth is predetermined by the resonant-grating structure [5]. Due to their unique narrow-band response properties realized with only a few thin-films (two or three layers), resonant-waveguide structures are potential alternatives for many optical narrow-band filter applications.

To be useful as optical filters, resonant-grating structures must be designed such that their spectral responses fulfill the optical filter’s criteria. The first criterion is high reflectance efficiency. The second is controllable sideband levels, the third is controllable resonant peak location and the fourth is controllable linewidth. High efficiency resonant-waveguide grating optical filters have been fabricated and demonstrated in the laboratory [6-7]. The key success to obtain high reflectance efficiency is careful fabrication that results in low scattering centers and using low-loss thin film materials. The sideband responses can be suppressed by applying antireflection (AR) thin-film structure for region away from the peak wherein the effective-medium characteristic of zero-order grating must be accounted for [8-9]. The peak location of the response is determined by the optical properties of the element such as refractive indices of the waveguides, the thickness of the waveguide layers and the period of the grating [10]. The peak location is sensitive to the incident angle and polarization state [11]. The number of guided modes in the waveguide grating determines the number of response peaks [11]. For a certain purpose, we may only need one peak from the filter. Thus, the waveguide grating structure should be designed to permit only a single mode by considering the thickness of supporting layers [12]. The shape of the peak response curve is determined by the waveguide grating structure, where optical filter spectral responses are mostly required to be symmetric and have low sidebands. Lorentzian shape is the most familiar curve response [13]. The linewidth is measured by its FWHM and determined by its loss factor of the grating and its materials [13].

Lorentzian shape is not perfect for filter functions. It requires that the filter response shape should be flat top. Jacob et al. [14] showed that multimode GMRE structures exhibit broader angular selectivities than those of single-mode structures. Moreover, Jacob et al. [15] proposed a method to achieve flat-top narrow-band spectral response by stacking several identical GMRE elements with separation films in between, grown on top of an optical substrate. The separation region between GMRE elements is designed to obtain a condition such that the filter elements are interfering π out of phase. The GMRE stack structure, theoretically exhibits flattened spectral and angular linewidth response in comparison to individual GMRE. By careful design and by incorporating antireflective structure in every individual GMRE structure in the GMRE stack, the total antireflection in the off-resonance region can be maintained low, where the net response of the sidebands is approximately the sum of the individual GMRE response. Beside having flat-top linewidth response, another key advantage is the improvement of the abruptness of the spectral bandpass ratio. The main drawback of this method is the attendant complex fabrication process required by the method proposed by Jacob.

Magnusson et al. show a possible way to suppress both sideband responses by cascading 2 resonant waveguide grating filters that have been adjusted to have the same resonant wavelength [16]. The fundamental concept is a simple multiplication of the cascaded filter response curves: \( f_d(\lambda) = f_1(\lambda) \times f_2(\lambda) \), where \( f_1(\lambda) \) is the output response, \( f_2(\lambda) \) and \( f_2(\lambda) \) are individual filter responses. Besides sideband suppression, the final response also exhibits a narrowed linewidth [17].
work suggests that there is a possible way to control the output response $f_\text{output}(\lambda)$ of the cascading resonant-waveguide grating filters by carefully designing the individual filter response $f_1(\lambda)$ and $f_2(\lambda)$.

III. MODELLING AND CALCULATION

Using the same multiplication idea of cascading filters above [16-17], this paper shows a possible way to shape the filter response to be a flat-top response by cascading resonant filters that are not resonant in the same wavelength. This work is based on theoretical calculation. This yields a flattened linewidth response and sideband suppression.

Figure-1 shows the alignment of a cascaded GMRE pair (GMRE-a and b), where both GMREs have the same parameters, except that the grating periods differ slightly. The angles of incidence are taken to be identical; alternatively identical structure with slightly differing angles can be used. In fact, arbitrary GMREs can be cascaded with this approach, as the angle of incidence is a free parameter. The output response is shown in Figure-2.

![Figure-1. Wavelength-offset cascading setup.](image)

In order to have a tool to measure how close the shaped response in Figure-2 is to the ideal shape, Figure-3 is introduced. In general the square-like shape filter response can be illustrated as a trapezoid. The following parameters are used to describe the reflectance properties [18]: $R_{\text{max}}$, the maximum of the reflectance in the reflectance zone; $\lambda_0$, the central wavelength of the filter response; $R_{sb}$, the sideband reflectance; $\Delta\lambda_{0.5}$, half-width of the high reflectance band at 0.5 $R_{\text{max}}$ level; $\Delta\lambda_{0.1}$, half-width of the high reflectance band at 0.1 $R_{\text{max}}$ level; $\eta = \Delta\lambda_{0.1}/\Delta\lambda_{0.5}$, a coefficient characterizing the abruptness of the transition from pass-band to stop-band; $C_R = R_{\text{max}}/R_{sb}$, a coefficient characterizing the contrast ratio between the maximum response and the average of the sideband response.

![Figure-3. General illustration of near-ideal filter response.](image)

In terms of these measures, the result in Figure-2 obtains the abruptness factor of $\eta \approx 1.6$. However, this system suffers an insertion loss of $\approx 4$ dB. The contrast ratio is $C_R \approx 35$ or 15.44 dB.

To improve the abruptness of the transition from pass-band to stop-band, cascading of elements with asymmetrical resonance lineshape may be performed. Day et al. [5] showed that when the resonance peak is forced by the grating period to coincide with the minimum of the native spectral response of the GMR structure, the GMRE spectral response will have symmetrical shape. However, if the resonance peak is pushed away from the minimum position to the right side (longer-wavelength), the spectral response becomes asymmetrical with a high sideband on the right as shown in Figure-4. In reverse, if the resonance peak is pushed away to the left side (shorter wavelength), the spectral response becomes asymmetrical with a high sideband on the left as shown in Figure-5.

To realize the idea, it is necessary to create 2 GMREs (a and b) with asymmetrical spectral response. Both elements are designed as a single-layer GMRE, with highly asymmetrical spectral response. An example design is shown in Figure-4. The structure of GMRE-a is a single-layer GMRE with $n_H = 1.87$; $n_L = 1.46$; $f = 0.5$; waveguide-grating thickness 192 nm with grating period of 324.4 nm and laid on top of fused-silica ($n_S = 1.46$) substrate. The incident angle is designed to be 38°, to avoid total internal reflection by the GMRE structure, which would obliterate the reflected resonance peak. The GMRE-a is designed such that it has a native spectral response minimum at 544 nm. Then by setting the grating period to 324.4 nm results in a resonance peak at 770.15 nm as shown in Figure-5. GMRE-a has its low sideband on the left and the high sideband on the right, and hence it is designed to contribute as the left spectral part of the cascade pair.
The structure of GMRE-b is a single-layer GMRE with $n_H = 1.78$; $n_L = 1.46$; $f = 0.5$; waveguide-grating-thickness 340 nm with grating period 321.85 nm and laid on top of fused-silica ($n_S = 1.46$) substrate. The incident angle is designed to be 38°, again to avoid total internal reflection by GMRE structure. The GMRE-b is designed such that it has a native spectral response curve minimum at 923 nm. By setting the grating period to 321.85 nm results in a resonance peak at 772 nm, shown in Figure-6. GMRE-b has its low sideband on the right and the high sideband on the left, and hence it is designed to contribute as the right spectral part of the cascade pair.

When GMRE-a and b with spectral responses shown in Figures-5 and 6 are aligned as in Figure-4, the resulting spectral response becomes that shown in Figure-7. There is a significant improvement in the abruptness of the transition from pass-band to stop-band in comparison to regular symmetrical Lorentzian-shape resonance line. The line-shape abruptness factor $\eta$ is approximately the same for all GMREs with rectangular grating profile ($\eta \approx 3.1$); for ideal (square) filter $\eta = 1$. The filter shown in Figure-7 gives abruptness factor of $\eta \approx 1.44$. However, the cascade yields an insertion loss of 1.186 dB. The contrast ratio is only $C_R \approx 8.71$ or 9.4 dB.

![Figure 7](image7.png)

Improved line-shape abruptness factor $\eta$ and contrast ratio $C_R$ can be realized with multiple cascading. Figure-8 illustrates cascading with two cascade pairs with the resulting spectral response shown in Figure-9.
The double-cascade GMRE pairs shown in Figure-8 with spectral response in Figure-9, has abruptness factor $\eta \approx 1.38$. However, this system suffers an insertion loss of 2.37 dB. The contrast ratio is $C_r \approx 75.24$ or 18.76 dB.

IV. CONCLUSIONS

A method suitable for realization flat-top narrow band optical filters was presented, resulting in reflectance spectral response with abruptness factor of 1.44, insertion loss ~ 1.2 dB, contrast ratio 8.71 and narrow bandwidth of < 3-nm. Multiply-cascaded GMRE-pairs can improve the contrast ratio $C_r$. However, for the elements in this example, the abruptness factor $\eta$ is minimally affected. In order to improve the abruptness factor, it is necessary to design each GMRE component to be highly asymmetrical.

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