SOI-based bandwidth-tunable grating filter with a large tuning range

Danhua Wu, Li Yu, Huaxiang Yi* and Zhiping Zhou*
State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing, 100871, China
*Corresponding emails: zjzhou@pku.edu.cn, yihuaxiang@pku.edu.cn

ABSTRACT

A polarization-independent bandwidth-tunable filter with a large tuning range using binary blazed grating based on silicon on insulator (SOI) is proposed and designed. This grating filter can show different spectral bandwidths under different angles of incidence. When the angles of incidence ranges from 42º to 48º, the grating functions as an ultra-narrow filter, and its minimal full width at half-maximum (FWHM) is about 0.6nm. More importantly, its resonant wavelength shifts linearly with respect to changes in the angle of incidence, with a slope of 4.5nm/°, regardless of the polarization states. When the angle of incidence is changed to 10º, it turns into a broadband filter, which has a reflectivity of over 99% in the wavelength range of 1510nm~1600nm for both polarization states.

Keywords: polarization-independent, bandwidth-tunable, large tuning range, binary blazed grating

1. INTRODUCTION

Guided-mode resonance grating filters (GMRGFs) have been of interest due to their unique advantages over classical multilayer structures and fiber Bragg grating filters in a system of dense wavelength demultiplexing (DWDM) [1]. A GMRGF normally consists of a waveguide layer and a grating layer, where the incident light can be coupled into a guided mode. Compared with the other aforementioned filters, GMRGFs offer the possibility to achieve property of polarization-independence and flexible bandwidth [2]. Since guide mode resonance depends essentially on polarization states of the incident light, and this characteristic limits the usage of the device in the field where the polarization state is unknown or unstable. Various methods are proposed to achieve polarization-independent GMRGFs with waveguide grating structures. Dominique et al. theoretically demonstrated a polarization-independent GMRGF with only a one-dimensional grating in conical mounting [3]. In addition, the realization of filters with tunable resonant wavelength is of particular interest in fiber communication systems as such filters can potentially offer passive control. Some research work has been done to realize a tunable GMRGF. Guido et al. have designed a tunable, oblique-incidence resonant grating narrow filter that covers the C band as an add–drop device for incident TE-polarized light [4]. Furthermore, they have presented the design, analysis and characterization of a polarization-independent tunable resonant grating narrow filter [5].

Besides polarization-independence, property of tunable bandwidth has attracted more and more attentions since several applications require resonators with a tunable bandwidth. Long Chen et al. have demonstrated a novel design of compact microring resonators on silicon-on-insulator platform with tunable bandwidth using interferometric couplers and thermal tuning [6]. However, to our knowledge, little attention is paid to the property of tunable bandwidth of resonant filter based on grating structure. While a GMRGF with narrow bandwidth can be used in DWDM system and laser, a GMRGF with a wide bandwidth can be used in electro-optic modulators [7], light-matter interfaces [8], lasers [9], and detectors [10]. So realization of a resonant waveguide grating filter with property of tunable bandwidth will be of great significance in terms of the application.

In this letter, we propose a polarization-independent and bandwidth-tunable grating filter with a large tuning range based on binary blazed grating structure. By adjusting the angle of incidence, this grating filter can show an interesting phenomenon of tunable bandwidth and polarization-independence.
2. DESIGN

Figure 1 illustrates an SOI-based binary blazed grating structure in conical mounting. A linearly polarized electromagnetic plane wave is obliquely incident on a binary blazed grating. $\theta$ is the angle of incidence, and $\alpha$ is called conical angle. When $\alpha = 0^\circ$, the incident plane is orthogonal to the grating grooves, and it’s called classical incidence. When $\alpha = 90^\circ$, the incident plane is parallel to the grating grooves, and it’s called full conical incidence. $\varphi$ is the angular deviation of the principle electric field direction away from transverse electric (TE) towards transverse magnetic (TM), $\varphi = 0^\circ$ for pure TE, and $\varphi = 90^\circ$ for pure TM. The grating period is $T$, including three subparts, with the same etching depth $t_g$, but with different widths and fill factors, which are $f_1, f_2, f_3$, respectively. The thickness of the silicon waveguide is $t_w$.

Compared with uniform grating structure, binary blazed grating structure has multi-subpart profile, and the subpart profile can work to move the leaky mode degeneracy of the grating permit the interaction of the resulting modes, which opens the possibility of a flat or narrow reflection band [11]. So in our design, we can flexibly adjust the profile to change the reflection band. Meanwhile, the high index contrast of SOI structure enables this grating filter to get a very high reflectivity at the resonant wavelength.

Based on the theoretical model in previous work [4] [5], we know that it is not possible to achieve a polarization-independent grating filter with property of tunable resonant wavelength for classical incidence [6], so we choose full conical incidence in our case, where the incident plane is parallel to the grating grooves. For full conical incidence, both polarization states can couple into only TE or TM mode in the waveguide, and we can make the resonance conditions corresponding to both polarization states coincide by optimizing grating parameters, which results in polarization-independence of this device. Then we focus on adjusting the angle of incidence to obtain different reflection properties. The parameters of this structure are set as: $t_g = 70\,\text{nm}$, $t_w = 250\,\text{nm}$, $T = 700\,\text{nm}$, $f_1 = 0.134$, $f_2 = 0.567$, $f_3 = 0.825$. Rigorous coupled-wave analysis (RCWA) [12] is adopted to calculate the reflectivity of this grating filter.

3. SIMULATION RESULTS AND DISCUSSION

![Figure 1. Structure of binary blazed grating in conical mounting.](image1)

![Figure 2. Spectral reflectivity of the grating filter for two different polarization states when $\theta = 45^\circ$.](image2)
Figure 2 shows the spectral reflectivity of the grating filter for two different polarization states when the angle of incidence $\theta = 45^\circ$. In order to demonstrate the filter’s polarization-independence, we get the reflection curves for two different polarization states ($\phi = 0, 90^\circ$). We can see that both reflection curves are almost symmetric with a reflectivity of almost 100% at the resonant wavelength and comparatively narrow bandwidths. The FWHM for TE polarization is 0.6nm and for TM polarization is 1.6nm, this might be caused by the fact that the coupling efficiency depends on the polarization states. In addition, the resonant wavelengths stay at the same position (1.545μm) for two different polarization states, which indicates that this grating filter is polarization-independent in this case. In fact, under the circumstances of other angles of incidences around 45°, this filter is polarization-independent as well, which is shown in Figure 3.

Figure 3 shows the spectral reflectivity of the grating filter for two different polarization states when the angle of incidence is in the range of 42°–48°. It’s very clear that the resonant wavelength of this grating filter shifts from 1558.5nm to 1531.5nm when the angle of incidence ranges from 42° to 48°. Plus, the curve shape stays almost constant over the whole tuning range with different bandwidths. So we can make a conclusion that this grating filter is polarization-independent with property of tunable resonant wavelength when the angle of incidence varies around 45°.

The best way to show the filter’s tunability is to plot the so-called $\lambda$-$\theta$ map, as shown in Figure 4. We can see that two lines on this map almost coincide, indicating polarization-independence is perfectly achieved, which enables this device to be applied in the field where the polarization state is unknown or unstable, such as fiber-based long haul communication system. The dependence of the resonance wavelength on the angle of incidence is approximately linear, with a slope of 4.5nm/°, which means that this grating can be used to filter out another wavelength when the angle of incidence is slightly changed around 45°. This characteristic makes this device more flexible and applicable in the DWDM system.
During the simulation process, we have also investigated the relationship between the bandwidth property and the angle of incidence. As shown in Figure 5, this grating filter shows different spectral bandwidths for three different angles of incidence. When $\theta = 45^\circ$, it has very narrow bandwidths for both polarization states. When $\theta = 22^\circ$, the reflection band starts to broaden. When $\theta = 10^\circ$, the reflectivity of this grating filter is higher than 99% in the wavelength range of 1.51~1.60 $\mu$m for two different polarization states, meaning that this grating filter has a broad bandwidth (90nm). Property of polarization-independence is always maintained for these three angles of incidence.

In order to illustrate how the angle of incidence affects the bandwidth property, we plot the transmissivity on logarithmic scale for three different angles of incidence [13]. As displayed in Figure 6(a), when $\theta = 45^\circ$, there is only one transmittance dip in the given wavelength range for both polarization states, which corresponds to a guided-mode resonance, proving that properties of narrow bandwidth and polarization-independence are achieved. As displayed in Figure 6(b), when $\theta$ is changed to $10^\circ$, there are two transmittance dips at separate wavelengths for each polarization state, and the distance between either pair is large enough, which makes the bandwidth of this filter become broader. As a matter of fact, when we adjust the angle of incidence, the position where the guided-mode resonance occurs will change correspondingly and this will result in the change of the bandwidth. We can take advantage of this property to
design a bandwidth-tunable grating filter. Like using thermal tuning in microring resonator, angle of incidence is regarded as a controllable external factor which could be easily used to change the reflection property of resonant filters.

4. SUMMARY AND CONCLUSIONS

We have proposed and successfully designed a polarization-independent bandwidth-tunable filter using binary blazed grating. The spectral reflectivity of this grating filter is investigated by RCWA method. It is demonstrated that the bandwidth of this grating filter can be changed from 0.5nm to 90nm by adjusting the angle of incidence, which is a large tuning range. In addition, when it functions as a narrow filter, the resonant wavelength has a linear relationship with the angle of incidence in the range of 42º~48º for both polarization states. These characteristics make this device have a large number of potential applications in the laser devices and optical communication systems.

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