Polarization independent broadband reflectors based on cross-stacked gratings

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Abstract: We report here a broadband reflector based on a two cross-stacked grating structure. This type of broadband reflector is polarization-independent, with ~100% reflectance over a designed spectral range of 1.4 to 1.6μm. The reflection phase differences between TE and TM polarizations remain almost a constant value of 1.2π over the same high reflection spectral range. The reflector performance tolerance was also investigated by varying the grating structure parameters. Two types of Fabry-Perot cavities can be configured based on two cross-stacked grating structures, for both polarization independent and polarization dependent resonance cavity mode control. All these characteristics associated with the cross-stacked grating reflectors enable a new type of resonant cavity or wave plate design for a large range of photonic applications.

OCIS codes: (050.2770) Gratings; (050.6624) Subwavelength structures; (050.5080) Phase shift; (140.3948) Microcavity devices.

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1. Introduction

Sub-wavelength gratings (SWGs) have long been widely used in integrated optoelectronic areas, such as couplers, filters, splitters, and lasers, etc. Recently, more interests are paid in applications of high index contrast SWGs (or HCGs) by utilizing Fano resonance [1], or guide-mode resonances (GMR) effect [2,3], such as filters [4], reflectors [5–8], vertical cavity surface emitting lasers (VCSELs) [9,10], wave plates [11], micro-lens [12], etc. With proper design, these high index SWGs can function as broadband surface-normal reflectors with very high (>99%) reflectivity and extraordinarily broad reflection band over a wide wavelength range [8]. However, comparing to the conventional quarter-wavelength distributed Bragg reflectors (DBRs) and two dimensional (2D) photonic crystal (PC) slab reflectors [13], SWG reflectors are intrinsically polarization-dependent due to the asymmetry of one-dimensional (1D) grating structures. Recently, complex grating structures including multipart or multilayer configurations have been proposed for polarization insensitive SWG reflectors [14] or wave plate [11]. These multi-layer polarization insensitive grating structures are mostly designed to be in parallel to each other [11,14]. Since a single layer SWG with one group structure parameters (thickness, period and fill factor) must be polarization sensitive, one can understand that the polarization independent property in these complex SWG structures origins from the fact that different grating parts satisfy high reflectance for the transverse electric (TE) or the transverse magnetic (TM) polarized light, respectively. While such polarization independent reflectors are polarization independent in reflection amplitude, the reflection phase response is indeed polarization dependent [11].

In this work, we propose a new type of grating framework with two cross-stacked SWG layers to realize polarization independent reflectors, with relatively simple fabrication processes. In what follows, we first study the reflection spectra and the reflection phase response for different TE and TM polarized incident light, using the finite difference time domain (FDTD) method. Secondly, we investigate the influences on the reflection and phase of different grating structure parameters for practical applications. Finally, we demonstrate the features of the resonant modes inside the FP cavities composed of such cross-stacked SWG reflectors.

2. Reflectivity and polarization of cross-stacked grating broadband reflectors

We first consider a single layer SWG (sl-SWG, or HCG) formed by silicon with the refractive index $n_{Si} = 3.48$, the thickness t = 240nm, the period Λ = 980nm and the fill factor f = 0.2, as show in Fig. 1(a). The grating strip direction is aligned along Y axis. Under normal incidence, the reflection of this sl-SWG is polarization sensitive, as displayed in Fig. 1(b), where only TE wave (*E* field is parallel to the grating strip, *y* direction) has a flat-broad and very high reflectance in the wavelength range of 1.2 to 1.6μm. If such a sl-SWG is cross-stacked onto another one, we expect to form a polarization-independent reflector according to the rotation symmetry for both TE and TM incident waves. Figure 1(c) shows the geometry of two cross-stacked SWGs (cs-SWGs). The two sl-SWGs can have different grating thicknesses, periods and fill factors. Of course, for such a cs-SWG, it is not rigorous symmetric in the same plane. The two sl-SWGs will influence each other. In order to obtain a broad high reflection band for both TE and TM polarizations, we can tune and choose the proper grating structure parameters. For example, here we choose the thickness $t_1 = t_2$ = 230nm, the period $\Lambda_1 = \Lambda_2$ = 980nm and the fill factor $f_1 = f_2 = 0.2$. Figure 1(d) demonstrates the ultra-high and broadband reflections for both TE and TM polarizations at different incident azimuth angles (ψ) in xy plane. One can clearly find that the reflections of all the cases overlap with each other, which

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indicates such a cs-SWG can function as a polarization independent reflector, similar to the 2D PC slab reflectors [13]. In addition, it can also be seen that, comparing to sl-SWG, the reflection band of cs-SWGs becomes narrower due to the interactions between two sl-SWGs.

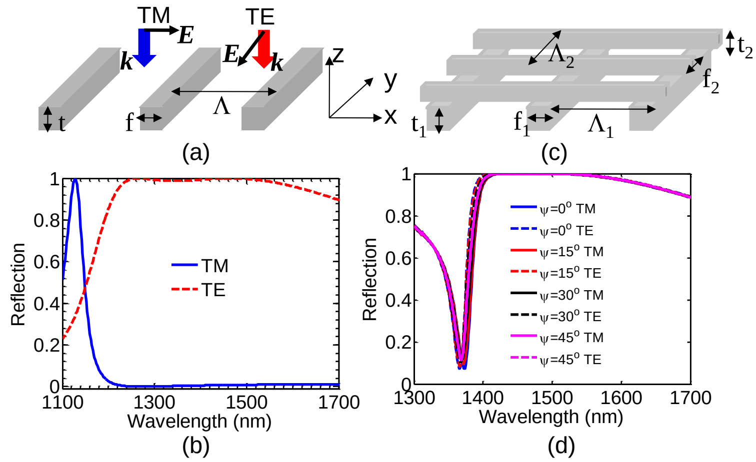

Fig. 1. (a) and (c): Sketches of the subwavelength grating Fano reflectors with a single layer and two cross-stacked layers, respectively; (b) and (d): The reflections of TE(dash lines) and TM(solid lines) polarization of sl-SWG and cs-SWG, respectively.

3. Reflection phase properties of cs-SWGs

The polarization-independent reflection in cs-SWGs is based on the cross-stacking of two individual polarization-dependent sl-SWGs, i.e., TE and TM waves are reflected by the bottom and the top sl-SWGs, respectively (more discussions in Section 4). These two sl-SWGs are not in the same plane. Hence the reflected light undergoes different optical path lengths. The reflection phase ϕ_R must not be the same for two polarizations, similar as the structures in [11]. We investigate ϕ_R of cs-SWGs, following a similar calculation procedure reported in [15].

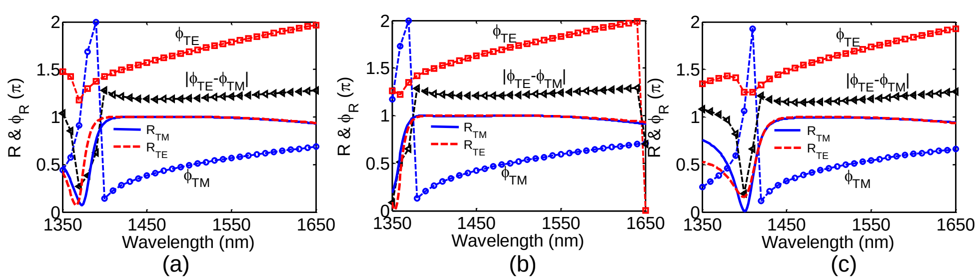

Fig. 2. Simulated reflection amplitude R for both TE (red dash lines) and TM (blue solid lines) polarizations, simulated reflection phase ϕ_R for TE (red dash lines with square holes) and TM (blue dash lines with circle holes), as well as the calculated phase difference between TE and TM $|\phi_{TE} - \phi_{TM}|$ (black dash lines with triangle holes) for cs-SWG structures with Si thickness $t_1 = t_2 = 230$nm, grating period $\Lambda = 980$nm, fill factors $f_1 = 0.2$, and different fill factors f_2: (a) $f_2 = 0.2$; (b) $f_2 = 0.18$; (c) $f_2 = 0.22$.

Figure 2(a) shows the calculated reflection phases of the cs-SWG, for both TE and TM polarizations. As a reference, the reflection amplitude R is also shown. One can see, in the spectral range of 1.4 to 1.65µm, ϕ_{TE} increases from 1.4π to 2π, while ϕ_{TM} increases from 0.2π to 0.7π. Although ϕ_{TE} and ϕ_{TM} have different spectral profiles, their difference $|\phi_{TE} - \phi_{TM}|$ almost keeps a constant 1.2π in the entire high reflection band. This suggests that, the

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reflected TM polarization light has a phase retard of 1.2π than the reflected TE polarization light. If such a cs-SWG is used as a wave plate, it will results in a linear-to-ellipse polarization conversion.

4. Influences of the grating fill factor, thickness, period and substrate

Here we investigate the proposed cs-SWG performance tolerance by varying grating structure parameters, such as the grating fill factors, thicknesses and periods, as well as different substrates. We will also investigate hybrid cs-SWG structures where two sl-SWGs have different structural parameters.

Figures 2(b) and 2(c) demonstrate the reflection amplitude and phase response with changing fill factor f_2. For $t_1 = t_2 = 230$nm, $\Lambda_1 = \Lambda_2 = 980$nm, $f_1 = 0.2$ and $f_2 = 0.18$, the results are plotted in Fig. 2(b). We can find the overlapped high reflection spectra for both TE and TM polarizations still remain broad and flat. Compared to Fig. 2(a), R_{TE} and R_{TM} have an obvious blue shift due to the effective refractive index reduction. When f_2 increases to 0.22, the overlapped R_{TE} and R_{TM} with high and broadband spectra can be also obtained, as seen in Fig. 2(c). In this case, R_{TE} and R_{TM} have an obvious red shift due to the effective refractive index increase. Comparing these three cases, one can also find another interesting features of R_{TE} and R_{TM}. For $f_1 \neq f_2$, the overlap between R_{TE} and R_{TM} is better than that of $f_1 = f_2$. It can be regarded that the asymmetry in the grating fill factor in these two sl-SWGs compensates their rotation asymmetry to some extent.

The Si layer thickness influence on the reflection was also investigated. The results are shown in Fig. 3. Here, we change the Si layer thickness t_2 from 220nm to 240nm and keep the grating fill factor $f_1 = f_2 = 0.2$, $t_1 = 230$nm, and grating period $\Lambda_1 = \Lambda_2 = 980$nm. For all three cases shown in Fig. 3, polarization independent TE/TM reflection band can be obtained over a large spectral range (1400-1520nm). One can also find R_{TM} bandedge shifts (red-shift with increase in thickness) much fast with the change of t_2, while R_{TE} bandedge almost does not shift. This indicates that the thickness of t_2, has a more profound influence on R_{TM}. We can also obtain a better overlap in the high reflection spectra region between R_{TE} and R_{TM} by choosing an optimal t_2 value. Note $t_1 \neq t_2$ here. Different thicknesses also compensate the rotational asymmetry. Figure 3(c) shows that when $t_2 > 240$nm (large thickness variation), the overlapped region of R_{TE} and R_{TM} begins to reduce.

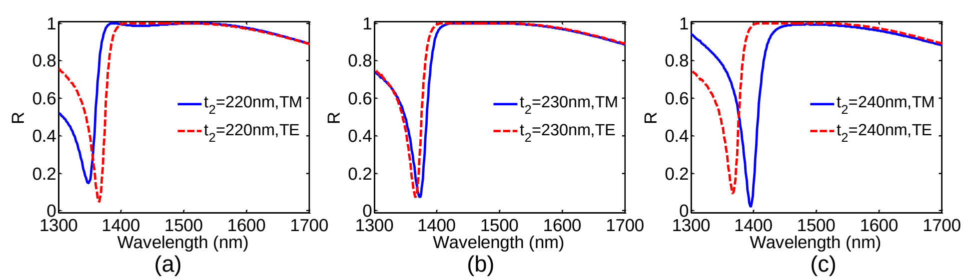

Fig. 3. Reflection of TE (red dash lines) and TM (blue solid lines) polarizations at $t_1 = 230$nm, $\Lambda_1 = \Lambda_2 = 980$nm, $f_1 = f_2 = 0.2$: (a) $t_2 = 220$nm; (b) $t_2 = 230$nm; (c) $t_2 = 240$nm.

The grating period variation also impacts the reflection overlapping profile. The results are shown in Fig. 4, where the grating period Λ_2 varies from 960nm to 1000nm, $f_1 = f_2 = 0.2$, $t_1 = t_2 = 230$nm, and $\Lambda_1 = 980$nm. As Λ_2 increases, both TE and TM reflection spectra shifts towards longer wavelengths (red-shift), with R_{TE} bandedge moves much faster than R_{TM} bandedge. This may mostly be due to the fact that the period Λ_2 has a much larger impact on R_{TE}.

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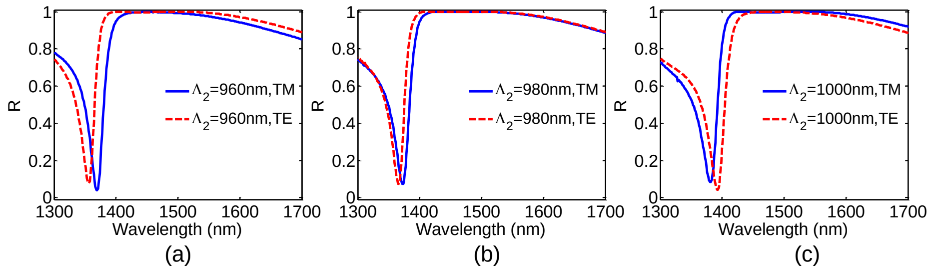

Fig. 4. Reflection of TE(red dash lines) and TM(blue solid lines) polarizations at Λ_1 = 980nm, $t_1 = t_2$ = 230nm, $f_1 = f_2$ = 0.2: (a) Λ_2 = 960nm; (b) Λ_2 = 980nm; (c) Λ_2 = 1000nm.

Typically, these SWG structures can be fabricated directly on SOI (silicon on insulator) substrates, as well being transferred via a crystalline semiconductor nanomenbrane stamp process onto other foreign substrates, such as glass substrate, etc [16]. Considering practical applications, we consider cs-SWG structures on these two types of substrates: glass and SOI. The results with glass (n_{SiO2} = 1.48) and SOI substrates are shown in Figs. 5(a) and 5(b), respectively, where $t_1 = t_2$ = 230nm, $\Lambda_1 = \Lambda_2$ = 980nm, $f_1 = f_2$ = 0.2, and the SiO_2 BOX (buried oxide) layer thickness for SOI substrate is optimally chosen to be 1.2μm. Due to the introduction of substrate, the reflection spectra are red shift and the overlapped high flat R_{TE} and R_{TM} band still covers the broad wavelength range from 1.45 to 1.65μm. Of course, the SiO_2 thickness also influences the reflection performance of such cs-SWGs reflectors with SOI substrate. From the above results, one can find the proposed cs-SWG reflector structure has a reasonably large design and fabrication tolerances.

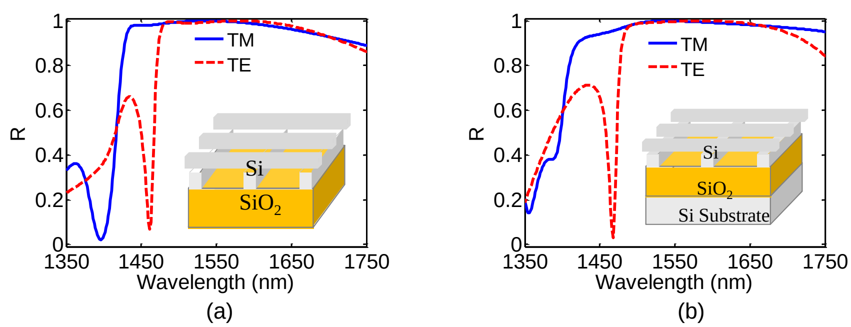

Fig. 5. Reflection of TE (red dash lines) and TM (blue solid lines) polarizations at $t_1 = t_2$ = 230nm, Λ = 980nm, $f_1 = f_2$ = 0.2: (a) with glass substrate; (b) with SOI substrate.

5. Resonant modes in FP cavities composed of two cs-SWGs

Finally, we investigate the property of resonant modes in the FP cavities which consist of two cs-SWG reflectors. Although such cs-SWG reflectors are polarization-independent, their reflection phase is still polarization dependent. The FP cavity mode is always related to both the reflection amplitude and the reflection phase. Therefore, such a cs-SWG FP cavity may have polarization dependent property. Here, we consider two configurations of cs-SWGs reflector alignment: face-to-back (FtB) and face-to-face (FtF) structures, as shown in Figs. 6(a) and 6(b), respectively.

Inside FtB FP cavity, if the incident light is TE (or TM) mode with respect to the bottom cs-SWG, then the reflected wave shall be TM (or TE) mode with respect to the upper cs-SWG. Hence, for light travelling inside the FP cavity in a complete round-trip, the total reflection phase change shall be the same for both TE and TM modes. Consequently, the resonant mode inside FtB FP cavity is polarization independent. For an example, we choose

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the cavity length L_c = 6μm. The resonant cavity mode is found according to the phase resonant condition of FP cavity, $4\pi L_c/\lambda - \Phi_{TE}(\lambda) - \Phi_{TM}(\lambda) = m \cdot 2\pi$ if m is equal to an integer, as shown in Fig. 6(c). The resonant TE/TM modes overlap at 1490nm.

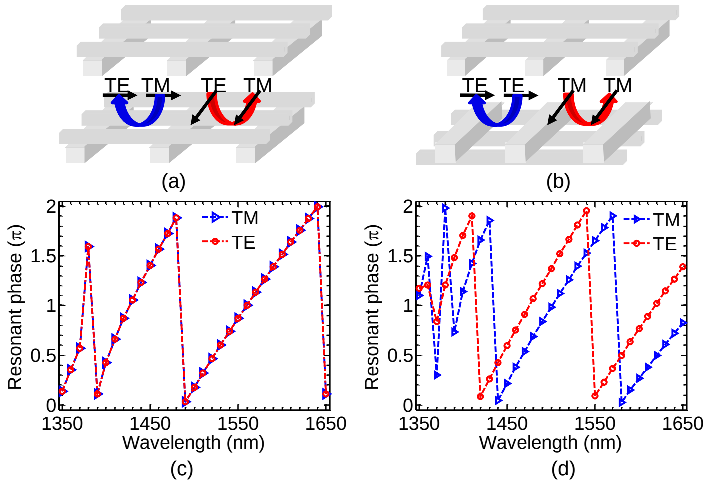

Fig. 6. Configurations of FP cavities with two cs-SWGs: (a) face to back (FtB); (b) face to face (FtF). Phase changes in a round trip of the travel light inside the FP cavities with the cavity length L_c = 6um; (c) FtB cavity; (b) FtF cavity.

On the other hand, for the light travelling inside FtF FP cavity, the reflected wave remains the same polarization with respect to both reflectors. According to the phase resonant condition, the resonant TE and TM modes are completely different, as shown in Fig. 6(d), due to different ϕ_{TE} and ϕ_{TM} values, even although such cavities have same reflection amplitude and the cavity length.

6. Conclusion

In conclusion, we have investigated the reflection amplitude and the reflection phase properties of the proposed two cross-stacked subwavelength grating reflectors. Comparing to the single layer SWG reflectors, this type of cs-SWG reflectors not only keep high reflectance, flat-broad reflection band, but also are realized to be polarization independent according to rotation symmetry of TE and TM mode under normal incident. Due to the absence of full symmetry in structure, similar to other types of multilayer SWGs, the reflection phase of such two cross-stacked SWG reflectors is still polarization dependent, though the differences in TE/TM polarization reflection phase remain to be a constant over the entire broadband reflection band. With proper design of the FP cavity based on the proposed cs-SWG reflectors, it is possible to achieve polarization independent design as well. All the results and conclusions can be very helpful for such kind of cs-SWG reflectors into a wide range of photonic applications.

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