

# Enhancement transmission filter using a two-dimensional subwavelength periodic membrane

Jiangu Zhou<sup>1</sup>, Tian Sang, Junlang Li, Rui Wang, La Wang and Jian Gao

Department of Photoelectric Information Science and Engineering, School of Science, Jiangnan University, Wuxi 214122, China

E-mail: sangt@jiangnan.edu.cn

**Abstract.** Enhancement transmission filter using a two-dimensional (2-D) subwavelength periodic membrane is proposed. It can be found that strong refractive-index modulation of the silicon periodic membrane can support the excitation of multiple guided-mode resonances (GMRs) in a reflection band, and every GMR relates a transmission peak on its edge, therefore the overlapping of the edges of these resonances can be tailored to create enhancement transmission. The location of the transmission peak is shifted linearly with a slope of 1.51 as the period is varied. Enhancement transmission with multiple channels near 1310 nm can also be achieved using the interaction of the nondegenerate GMRs at oblique incidence.

## 1. Introduction

Guided-mode resonance (GMR) gratings have attracted considerable interests due to their simple structures with versatile spectral characteristics [1,2]. As the incident light illuminates on a periodic surface structure, the leaky waveguide modes can be resonantly excited as the phase-matching condition is satisfied. At resonance, the incident light is totally reflected with highly angular and spectral selectivity maintained. This phenomenon is also called as leaky mode resonance [3,4]. It has been proposed that optical elements such as optical filters [4,5], optical switch devices [6], photonic detectors [7-8], sensors [9], and ultrabroadband mirrors [10,11,12] can be obtained by using the resonant leaky modes.

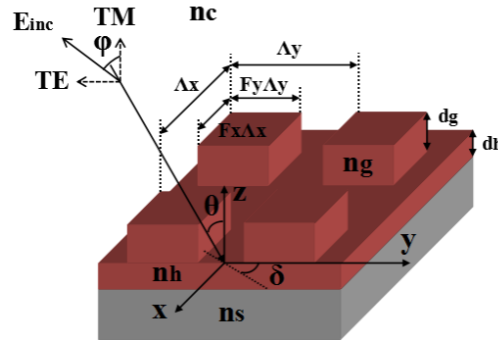
For all we know, most research to date has mainly focused on the reflection properties of these elements, with the resonance effect providing a reflection peak or a reflection band [1,2,3,4,5,6,7,8,9,10,11,12]. Much less attention has been paid to the resonant transmission properties. In 1995, Magnusson and Wang [13] put forward the concept of resonant bandpass filtering by integrating the resonant waveguide gratings into a dielectric multilayer structure. Later, Tibuleac and Magnusson [14,15] showed that these diffractive thin-film structures yield high efficiency narrowband transmission. Last few years, it has been shown that by tailoring the overlapping of the edges of the GMRs, the enhancement transmission filter can be achieved in one-dimensional (1-D) periodic membrane structure [16]. Unfortunately, the 1-D periodic structure is sensitive to the polarization, which limits its application in unpolarized filtering.



In this paper, the enhancement transmission filter using a 2-D subwavelength periodic membrane is proposed. It can be found that strong refractive-index modulation of the silicon periodic membrane can support the excitation of multiple GMRs, and the interaction and coupling of the GMRs can be used to obtain the broadband reflection. Furthermore, the overlapping of the edges of GMRs can be tailored to create enhancement transmission by slightly changing the structural parameters, and the geometric symmetry of the 2-D construction [17] ensures the nonpolarizing property of the enhancement transmission filter at normal incidence. The location of the transmission peak is shifted linearly as the period is varied. Enhancement transmission with multiple channels near 1310 nm can also be achieved at oblique incidence for both the TE and TM polarizations.

## 2.Design of broadband mirror

As illustrated in figure 1, the general structure of the 2-D subwavelength periodic membrane consisting of the cubic arrays, a homogeneous layer and the substrate. The material of the periodic membrane is silicon and air, which can support the excitation of the leaky mode resonances in a reflection band [18,19]. The geometric symmetry of the 2-D construction at normal incidence is used to ensure the nonpolarizing property of the structure in our design. For the design of broadband mirror, the optimal parameters are:  $n_c=1$ ,  $n_s=1.48$ ,  $n_g=n_h=3.48$ , the membrane thicknesses  $d_g=0.4377 \mu\text{m}$ ,  $d_h=0.0534 \mu\text{m}$ , the periods  $\Lambda=\Lambda_x=\Lambda_y=0.63 \mu\text{m}$ , the filling factors  $F=F_x=F_y=0.6$ ,  $\theta=\delta=0^\circ$ ,  $\varphi$  can be taken any angle for the nonpolarizing property. ( $\theta$  is the incident angle,  $\delta$  denotes the angle between the incident surface and the y-axis,  $\varphi=0^\circ$  and  $\varphi=90^\circ$  denote the TM polarization and the TE polarization, respectively.)

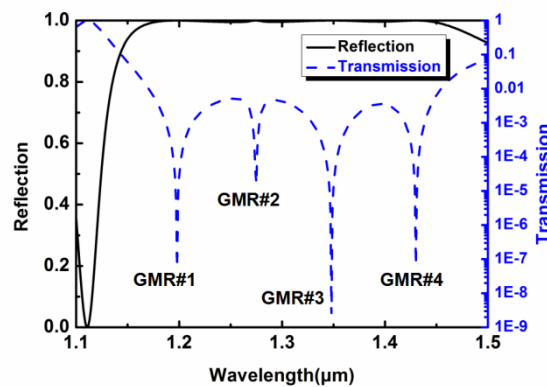


**Figure 1.** Schematic diagram of the 2-D subwavelength periodic membrane.

For the subwavelength periodic membrane structure, the range condition for allowed GMRs can be simplified to

$$\frac{m^2 + n^2}{N^2} < \frac{\Lambda^2}{\lambda^2} \quad (1)$$

where  $m$  is the diffraction order in the x-axis,  $n$  is the diffraction order in the y-axis,  $\lambda$  is the free space wavelength.  $N^2=n_c^2$  in the cover region, and  $N^2=n_s^2$  in the substrate region. The period  $\Lambda$  is sufficiently small, such that only the zero-order transmitted and reflected waves propagate under our design [20].



**Figure 2.** Spectrum of the unpolarized broadband mirror of the 2-D subwavelength periodic membrane at normal incidence. The parameters are:  $n_c=1$ ,  $n_s=1.48$ ,  $n_g=n_h=3.48$ ,  $d_g=0.4377 \mu\text{m}$ ,  $d_h=0.0534 \mu\text{m}$ ,  $\Lambda=\Lambda_x=\Lambda_y=0.63 \mu\text{m}$ ,  $F=F_x=F_y=0.6$ ,  $\theta=\delta=0^\circ$ .

Figure 2 is the spectrum of the unpolarized broadband mirror of the 2-D subwavelength periodic membrane at normal incidence. As illustrated in figure 2, the broadband reflection spectrum ( $R>99\%$ ) can be obtained with the bandwidth of  $\sim 285 \text{ nm}$  at the central wavelength of  $1310 \text{ nm}$ , and this unpolarized broadband mirror can be used in many fields such as an alternative to distributed Bragg reflectors (DBRs) especially for vertical-cavity surface-emitting laser (VCSEL) applications [17].

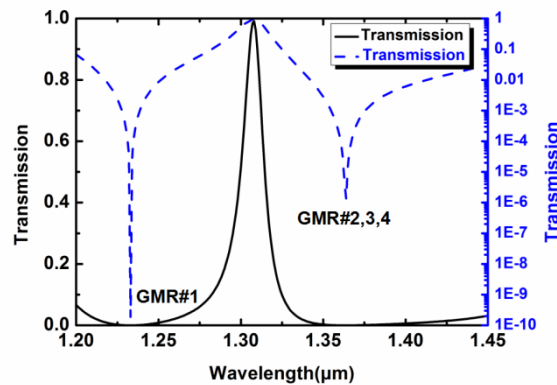
Furthermore, the locations of the four GMRs in the broadband reflection spectrum can also be indicated by using the transmission spectrum in logarithmic scale. The GMRs are almost evenly distributed on the broadband at the locations of  $1196 \text{ nm}$ ,  $1274 \text{ nm}$ ,  $1348 \text{ nm}$ , and  $1431 \text{ nm}$ , respectively, and the reflection peak of each is much larger than  $99\%$ . Thus it can be drawn that the interaction and coupling of these GMRs with large bandwidths, resulting in the unpolarized broadband reflection spectrum. The spectral response, as for others presented in this paper, are based on rigorous coupled-wave analysis [21].

### 3. Enhancement transmission filter

Since the four GMRs can be excited in the spectral band of the 2-D subwavelength periodic membrane, the interaction of these resonances can be tailored by slightly varying the structure parameters.

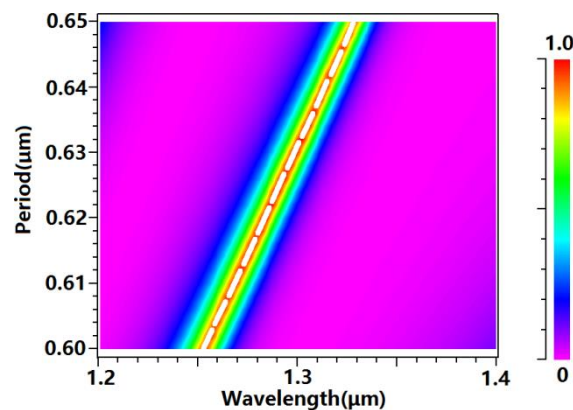
Figure 3 is the transmission spectrum of the nonpolarized enhancement transmission filter at  $1310 \text{ nm}$  which can be achieved by slightly changing the parameters of the broadband mirror. The optimal parameters of the nonpolarized enhancement transmission filter are:  $n_c=1$ ,  $n_s=1.48$ ,  $n_g=n_h=3.48$ ,  $d_g=0.5 \mu\text{m}$ ,  $d_h=0.054 \mu\text{m}$ ,  $\Lambda=\Lambda_x=\Lambda_y=0.635 \mu\text{m}$ ,  $F=F_x=F_y=0.6$ ,  $\theta=\delta=0^\circ$ .

As can be seen in figure 3, a nonpolarized transmission peak with very high transmissivity of  $99.1\%$  at  $1310 \text{ nm}$  arises from the overlapping of the edges of the GMRs which can be seen by the transmission spectrum in logarithmic scale. The full width half maximum of the transmission peak is about  $15 \text{ nm}$  which can be measured easily, thus the quality factor  $Q$  of the transmission filter defined as  $\lambda_{\text{peak}}/\Delta\lambda$  is about  $87.3$ . The GMR#2, GMR#3 and GMR#4 are overlapped with each other during the process of parameters adjustments. The new resonance GMR#2,3,4 and GMR#1 distributed on both sides of the transmission peak form two broad reflection background sidebands, and the overlapping of the edges of GMR#1 and GMR#2,3,4 creates the transmission peak.



**Figure 3.** Spectrum of the nonpolarized enhancement transmission filter. The parameters are:  $n_c=1$ ,  $n_s=1.48$ ,  $n_g=n_h=3.48$ ,  $d_g=0.5 \mu\text{m}$ ,  $d_h=0.054 \mu\text{m}$ ,  $\Lambda=\Lambda_x=\Lambda_y=0.635 \mu\text{m}$ ,  $F=F_x=F_y=0.6$ ,  $\theta=\delta=0^\circ$ .

For the practical unpolarized enhancement transmission filter, it's expected that the transmission peak can cover a wide range of wavelength band. In the process of changing all parameters, it's found that the period value changes almost linearly with the position of the transmission peak. Figure 4 is the color-coded transmission map of the unpolarized enhancement transmission filter as a function of period, the other parameters are the same as those in figure 3.



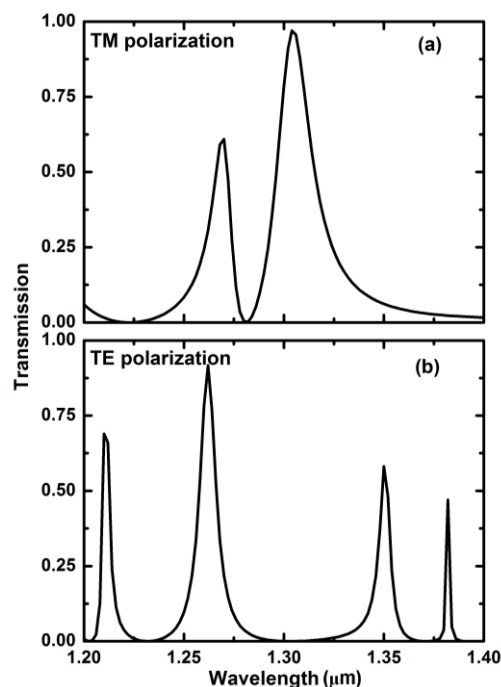
**Figure 4.** Color-coded transmission map of the unpolarized enhancement transmission filter as a function of period, the other parameters are the same as those in figure 3.

As shown in figure 4, in the wavelength range of 1250 nm to 1330 nm, the linear full coverage of the transmission peak can be obtained only by adjusting the period in a suitable range from 0.6  $\mu\text{m}$  to 0.65  $\mu\text{m}$ . The white dash line indicates the position of the transmission peak which displays a redshift with the increase of period, and the bandwidth of the transmission peak remains 15 nm, two flat low sidebands distributed on both sides of the transmission peak are also maintained. The analytic relationship between  $\lambda_{\text{peak}}$  and period in a suitable range can be obtained by fitting the white dash line in figure 4, that is:

$$\lambda_{\text{peak}} = 1.51 * A + 0.3475 \quad (2)$$

The location of the transmission peak is shifted linearly with a slope of 1.51 by fitting the data as period is varied, thus the transmission peaks can be tuned to the design values by selecting the proper period.

For the 2-D subwavelength periodic membrane, the geometric symmetry of the structure is broken at oblique incidence, and the transmission spectra will show different characteristics. Figure 5(a) and 5(b) are the transmission spectra of TM and TE polarizations at the incident angle of  $10^\circ$ , respectively. It can be seen that under the TM polarization, two transmission peaks with relative wide bandwidths appear while four sharper transmission peaks appear under TE polarization. Similar to the 1-D grating structure [22], it is speculated that the multiple enhancement transmission peaks arise from the interaction of the nondegenerate GMRs under oblique incidence. The interaction of multiple nondegenerate GMRs squeeze out multiple transmission peaks, which is helpful for the design and application of multi-channel transmission filtering.



**Figure 5.** (a) Spectrum of TM polarization at the incident angle of  $10^\circ$  (b) Spectrum of TE polarization at the incident angle of  $10^\circ$ ; the other parameters are the same as those in figure 3.

#### 4. Conclusion

The unpolarized enhancement transmission filter using a 2-D subwavelength periodic membrane is proposed. It can be found that strong refractive-index modulation of the silicon periodic membrane can support the excitation of multiple GMRs, and the interaction and coupling of the GMRs can be used to obtain the broadband reflection. Furthermore, the overlapping of the edges of GMRs can be tailored to create enhancement transmission by changing the parameters slightly, and the geometric symmetry of the 2-D construction ensures the nonpolarizing property of the enhancement transmission filter at normal incidence. The location of the transmission peak is shifted linearly with a slope of 1.51 as the period is varied. Enhancement transmission with multiple channels near 1310 nm can also be achieved using the interaction of the nondegenerate GMRs under oblique incidence.

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