Optik 124 (2013) 5158–5160

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Non-polarizing guided-mode resonance grating filter for telecommunications

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ARTICLE INFO

Article history:
Received 14 October 2012
Accepted 13 March 2013

Keywords:
Guide-mode resonance (GMR)
Polarization-independent
Telecom band
Filter

ABSTRACT

A five-layer grating structure is designed to generate polarization-independent filter in the telecom band. It is demonstrated theoretically that in the five-layer grating structure, by adjusting the thickness of the interlayer sandwiched between two dielectric layers with high permittivity, the resonance wavelengths of transverse magnetic (TM)- and transverse electric (TE)-polarized light can locate at the same wavelength with the same guide-mode resonance structure parameters and the filter efficiency can achieve above 95%. The influence of incident angle and thickness of the interlayer on the shift of reflective peak are discussed. The peak locations for both TE and TM are proved to have a linear relation with the thickness of interlayer.

1. Introduction

Guide-mode resonance (GMR) is excited when an incident wave is phase-matched to a leaky waveguide mode, which is promising and well developed these years [1–4]. The GMR was typically observed in substrates with geometrically designed multilayer thin films that constructed with grating and waveguide layers [5–7]. This neotype optical device [8] combines principles of diffraction by periodical structures with waveguide properties and antireflection (AR) thin-film characteristics to yield almost 100% reflectivity for a given operating wavelength [9,10]. It is promising in applications such as laser cavity devices, polarizers, light modulators, and band pass filters [11–14].

Filters with high reflectivity that more than 98%, very narrow or wide spectrum, low sideband, and insensitive polarization are fully researched [15,16]. Structures with only one grating layer (acts as waveguide layer) or one grating layer with an antireflection layer [5,6] that can make the GMR filter polarization-independent are fully studied. However, in single grating layer filters, refractive indices of their surface layer and substrate layer are different, it may cause Fresnal reflection and its sideband reflection that are hardly reduced. We can add an antireflection layer to construct a double-layer filter to solve this problem, but the waveform is still not symmetrical enough. If we get more layers in a filter, we will have more parameters to control to make the resonance waveform better, but the difficulty for fabrication will increase at the same time. We should face lots of problems like guaranteeing the adhesive strength and stability of the filters. Therefore, the number of layers should be neither too big nor small. In this paper, a five-layer structure grating was designed, and we used just two kinds of materials to minimize adhesive strength and stability problems. We let resonance wavelength of both TE and TM mode light be the same in C band of optical telecommunication band, which can reduce the energy loss.

2. Structure and emulation

The rigorous coupled-wave analysis (RCWA) method, which is an accurate calculating method from Maxwell's equations for the electromagnetic diffraction of grating structures, has been widely used to design GMRF structures [1–9]. In accordance with the principle of optical thin films [17], if the grating layers can be well matched with each other, they can be able to play a role of antireflection. We used a five-layer GMR filter in Fig. 1, to construct a GMR filter to generate guided-mode resonance in C band of optical telecommunication. The layers from top to bottom are grating layer (n_H = 2.298 (TiO_2), n_L = 1, d_g = 38.2 nm), layer 1 (n_1 = 1.44, d_1 = 460 nm, SiO_2), layer 2 (n_2 = 2.298, d_2 = 372 nm, TiO_2), layer 3 (n_3 = 1.44, d_3 = 167.7 nm, SiO_2) and layer 4 (n_4 = 2.298, d_4 = 360 nm, TiO_2). Refractive indices of substrate layer and cover layer are n_s = 1.51 (glass) and n_c = 1 (air). The incident angle is 45°. The period of the grating is Λ = 1297.6 nm [1,2], and the filling factor is f = 0.5. Optimized one step by another with RCWA method, we find peak values of TE and TM modes nearly linear move toward each other by adjusting d_3.

GMR is a result of the interaction between the incident light and the grating waveguide structure. Under resonance condition, a normal transparent structure becomes a mirror and the resonant light is significantly reflected, and the wavelength of the resonance

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http://dx.doi.org/10.1016/j.ijleo.2013.03.095

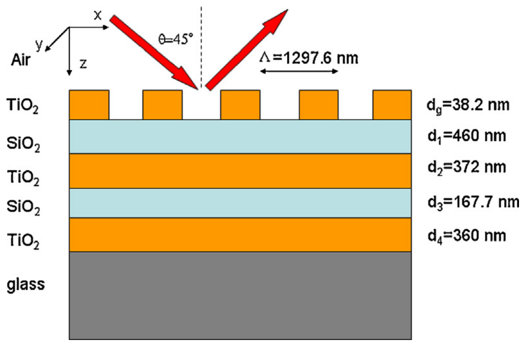

Fig. 1. Structure of the non-polarizing guided-mode resonance filter.

light is sensitive to the grating material, thickness of each layer, grating period, etc.

According to the RCWA theory [18–21], the reflectance equations for TE and TM polarized mode are

$$R = \begin{cases} R_{\mathrm{TE}} = \dfrac{(|R_{i,x}|^2 + |R_{i,y}|^2 + |R_{i,z}|^2) Re(k_{zi})}{k \cos\theta} & (1) \\ R_{\mathrm{TM}} = \dfrac{Re(k_{zi}|R_i|^2)}{k \cos\theta} & (2) \end{cases}$$

where $R_{i,x}$, $R_{i,y}$ and $R_{i,z}$ are reflectivity of x, y and z direction, $k = 2\pi/\lambda$ is the wave number and k_{zi} is the i grade z part of k. According to Eqs. (1) and (2), the resonance wavelengths of TE and TM polarized mode can be calculated.

From Eqs. (1) and (2), we got the appropriate waveguide parameters d_g, d_1, d_2, d_3 and d_4 that can make the GMRF polarization independent in C band. By adjusting the thickness, non-polarizing GMR filter can be obtained, and the result is shown in Fig. 2. The reflective losses at the center of resonance peaks are just 5.57% for both TE and TM modes. These results are all calculated by Eqs. (1) and (2).

As is shown in Fig. 1, there are five layers in the filter. After series of emulation and calculation, we find that d_1 and d_2 play a dominated role in determining the location of the generation of resonance, while d_3 and d_4 do the work of fine adjustment. On the large range, when d_1 increases, the location of the resonance peak for both TE and TM modes shifts to low frequency range considerably. For the change of d_2, the result is just opposite. As d_3 increases, the location of the resonance peak of TE mode moves toward right direction and TM mode shifts toward left direction, and the former one changes less than the later. As is shown in Fig. 2, every equivalent change of d_3 makes an identical size shift of the resonance wavelength for both TE and TM modes respectively. For d_4, it is just on the contrary. Therefore, by tuning the thickness of d_3, it is possible for us to adjust the resonant peaks of TE and TM modes to the same position (see Fig. 2).

According to our calculation, we describe the relation between the resonant peaks of TE/TM modes and d_3 in Fig. 3, the black line represents TE mode and the red line represents the TM one. As d_3 varies from 164 to 170 nm, the resonant peak of TE mode moves right from 1545.5 to 1548 nm, while the TM one shifts left from 1549.3 to 1545.2 nm. We proved that the shifts of the resonance peaks for both TE and TM modes are almost perfect linear relation with the shift of d_3. As shown in Fig. 3, the TE mode line crosses the TM mode line at $d_3 \sim 168$ nm. In other words, we can use descriptive geometry solution to find out an exact position where the GMR filter becomes polarization-independent.

After lots of simulation we find that the guided-mode resonance effect can generate resonance reflecting peak without layer 3 and layer 4. However, the resonant peaks for TE and TM modes can hardly locate at the same wavelength position. And a four-layer

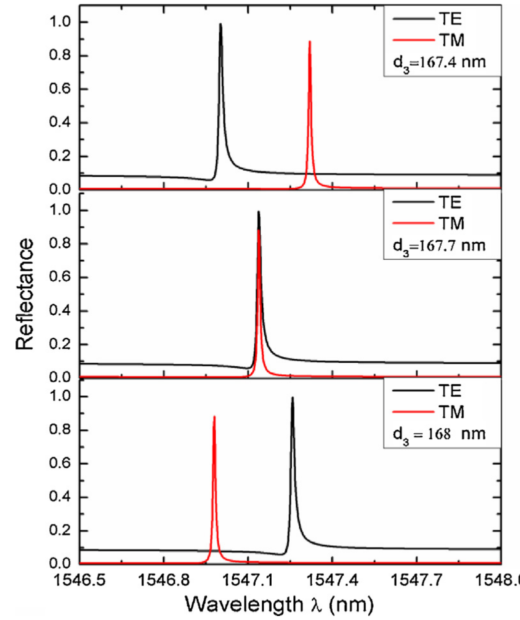

Fig. 2. Phenomenon of non-polarizing filter and peaks shifts of TE and TM modes by adjusting d_3. Incident light of TE and TM modes generate reflecting peaks at the same wavelength for d_1 = 460 nm, d_2 = 372 nm, d_3 = 167.7 nm, d_4 = 360 nm. Other parameters are the same with the illustration of Fig. 1.

structure cannot make the filter polarization-independent either. So as to achieve the goal of polarize independent we choose to add a layer 4 above the substrate.

From Eqs. (1) and (2), we can know that the wavelength of resonant peak of the GMR also varies serious for the other parameters (such as wavelength or incident angle). As is shown in Fig. 4, with 1° shift of incident light, the resonant peak moves ~13 nm for TM mode and ~11 nm for TE mode respectively. The relation between resonance peak value and incident angle is linear. As incident θ increasing, peak values of TM and TE mode all shift toward left direction. The difference is that the resonant shifting pace of TM mode is faster than that of TE mode.

3. Summary

In conclusion, to make the polarizing independent filter, we designed a five-layer structure as shown in Fig. 1.We demonstrated that the resonant peak of TE and TM modes can be generated at the same wavelength in tele-communication band. We also find that the resonance peak for both TE and TM modes are linear relation

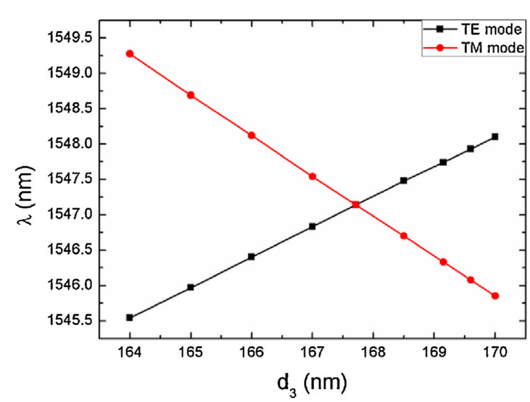

Fig. 3. The linear relation between d_3 and reflective resonant peaks of TE and TM mode. As d_1 = 460 nm, d_2 = 372 nm, d_4 = 360 nm, d_3 alters from 164 to 170 nm. Other parameters are the same with the illustration of Fig. 1.

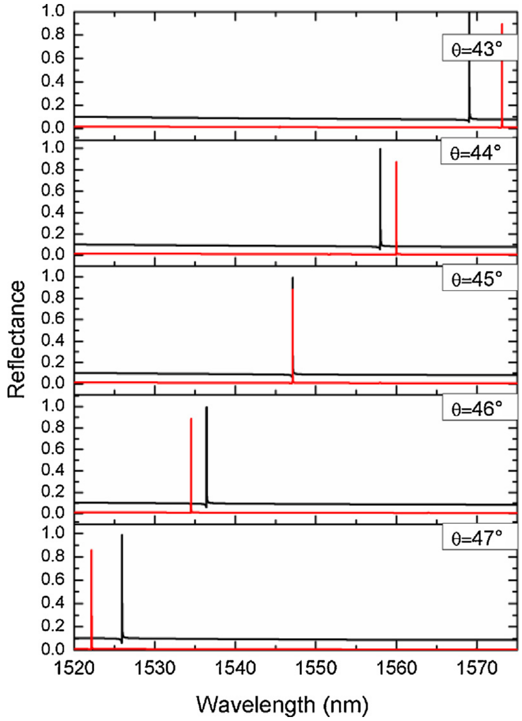

Fig. 4. Spectrum comparison for different incident angles for both TE and TM modes. The red line represents TM mode and the black one represents TE mode. Relative parameters above is the same with Fig. 2, the difference is only the incident angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

with the thickness of the third layer, d_3, and incident angles. This work helps us to find the conjunct resonant peak much easier, and help reduce energy loss that can be applied in fiber communication.

Acknowledgments

This work was partly supported by Shanghai Committee of Science and Technology (grant no. 11ZR1425000), Ph.D. Programs Foundation of Ministry of Education of China (20093120120007), the Innovation Fund Project For Graduate Student of Shanghai (JWCXSL1102), the Leading Academic Discipline Project of Shanghai Municipal Government (S30502), and National Natural Science Foundation of China (61007059, 11174207, 61138001, 61205094).

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