Infrared Physics and Technology 93 (2018) 81–86

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

Regular article

Wide wavelength range tunable guided-mode resonance filters based on incident angle rotation for all telecommunication bands

Zhibin Ren*, Yahui Sun, Shuqing Zhang, Kaipeng Zhang, Zihao Lin, Songli Wang

School of Astronautics, Harbin Institute of Technology, Harbin 150001, China

ARTICLE INFO

Keywords:
Guided-mode resonance filter
Subwavelength structure
Diffraction grating
Telecommunication band

ABSTRACT

The comparison among one-layer, two-layer and three-layer guided-mode resonance filters (GMRFs) has been discussed by the numerical simulations. The rigorous coupled-wave analysis (RCWA) is used to calculate the reflection spectra of the designed GMRFs. As the reflection sidebands of two-layer GMRFs are not satisfactory, tunable three-layer GMRFs for all telecommunication bands have been designed and fabricated. The grating structures of the GMRFs are patterned by interference lithography with two ultraviolet laser beams. The reflection spectra of the GMRF samples at different incident angles are measured by rotating a motorized stage. The negative first-order diffraction resonances located at 1701.4, 1549.3, 1424.4 1309.5, and 1188.9 nm are measured at the incident angles of 3°, 11.4°, 20°, 30.2°, and 45°, respectively. The experimental results are in good agreement with the theoretical simulation ones. We show experimentally a large spectral shift over 510 nm of wavelength that covers all telecommunication bands.

1. Introduction

Optical filters have been widely exploited as versatile elements in a variety of applications, encompassing dense wavelength division multiplexing (DWDM) devices, CMOS image sensors, display devices, three-dimensional projection systems, biosensors, and photovoltaic cells. The guided-mode resonance filter (GMRF) that consists of a surface-relief grating and thin-film waveguides is a promising optical element. The guided-mode resonance (GMR) is due to the excitation of leaky guided modes in the periodic waveguide structure. GMRFs have attracted a lot of interest because of their super wavelength-selecting ability. Thus, GMRFs have been exploited as wavelength filters for the telecommunication wavelength bands. In 2005, A. Mizutani simulated the reflection spectra of a GMRF in a wavelength range of 1450–1650 nm with the nonlinear finite-differential time-domain method [1]. In 2006, Hsu et al. provided a GMRF based on a free-standing silicon-nitride membrane suspended on a silicon substrate by using bulk micromachining technology [2]. In 2010, D. W. Peters et al. designed and fabricated a two-dimensional (2D) GMRF with near-identical responses for both transverse-electric (TE) and transverse-magnetic (TM) polarizations at normal incidence in the telecommunication wave band [3]. In 2011, Alasaarela et al. demonstrated a one-dimensional (1D) non-polarizing GMRF with sinusoidal grating profile [4]. In 2013, Luo et al. designed a five-layer grating structure to generate polarization-independent filter for the telecommunication wavelength C-band [5]. In 2014, Monmayrant et al. demonstrated experimentally 1D crossed gratings for polarization-independent high-Q filtering operating in a wavelength range of 1500–1600 nm [6]. In the same year, Lee et al. presented the design, fabrication, and characterization of GMRF linear polarizers that operated in the telecommunication wavelength C-band near a wavelength of 1550 nm [7]. A broadband polarizer based on GMR has also been designed for the telecommunication wavelength band in 2014 [8].

Recently, tunable GMRFs for telecommunication wavelength bands have attracted much interest. In conventional devices, the resonance wavelength was tuned by changing the structural parameters of GMRFs. In 2013, simulations and designs were provided to illustrate the spectral tunability by changing the thickness of the metal layer of a GMRF operating in the telecommunication wavelength C-band [9]. In 2016, Sheng et al. fabricated a polarization-independent wedged 2D GMRF that was tunable in a wavelength range of 1599.9–1621.5 nm [10].

As the resonance wavelength can be tuned with invariable structural parameters, tunable GMRFs by rotating the angle of incidence have attracted a lot of interest [11–13]. In 2004, Niederer et al. designed a tunable, oblique-incidence three-layer GMRF covering the C-band as an add–drop device for incident TE-polarized light [11]. The measurements of the three-layer GMRF indicated a negligible change in shape of the resonance peak from 1526 nm at a 45° angle of incidence to

* Corresponding author.
E-mail address: rzb@hit.edu.cn (Z. Ren).

https://doi.org/10.1016/j.infrared.2018.07.015
Received 14 May 2018; Received in revised form 8 July 2018; Accepted 10 July 2018
1350-4495/

1573 nm at a 53° angle. In 2012, Uddin et al. fabricated a two-layer GMRF that exhibited blue, green, and red color responses at incident angles of 8°, 20°, and 35°, respectively [12]. This GMRF exhibited a spectral tuning range of 505 nm–607 nm, but the sidebands were not effectively suppressed. In 2016, Wang et al. proposed a tunable reflective GMRF incorporating a twisted nematic liquid crystal [13]. The fabricated four-layer GMRF exhibited a large spectral shift of resonance wavelength from 710 nm to 430 nm at the angles of incidence from 0° to 50° with high sidebands.

In this paper, we describe the design of tunable GMRFs based on incident angle rotation for all telecommunication bands. The characteristics of the GMRFs under TE polarized light illumination are studied theoretically. We show experimentally a large spectral shift over 510 nm of resonance wavelength that covers all telecommunication bands. The tunable properties of the proposed GMRFs are measured and the experimental results agree closely with the simulations. Compared with previous reported tunable GMRFs, the spectral tuning range of the proposed structure is remarkably improved.

On the other hand, this type of GMRF proposed in this paper can be regarded as a linear high Q grating filter. Another kind of filter with circular grating structure can also achieve high Q modes [14,15]. Therefore, the type of 1D GMRF proposed in this paper is a promising device due to the simplicity of structure.

2. Design principles and simulation results

2.1. Design principles

The tunable GMRFs by rotating the angle of incidence proposed by Uddin et al. [12] and Wang et al. [13] both operated in the visible spectral region. Though the three-layer GMRF [11] indicated a negligible change in shape of the resonance peak from 1526 nm at a 45° angle of incidence to 1573 nm at a 53° angle, the spectral tuning range was merely 47 nm. We should take this approach further and choose appropriate structural types, materials, structural parameters, and incident angles to obtain a large spectral shift of resonance wavelength that covers all telecommunication bands.

The one-layer, two-layer, and three-layer GMRFs under consideration are illustrated in Fig. 1. From top to bottom, the one-layer GMRF includes a grating layer (n_1 = 1.62, photoresist) and a waveguide substrate layer (n_s = 2.10, Ta_2O_5). The two-layer GMRF includes a grating layer (n_1 = 1.62, photoresist), a waveguide layer (n_2 = 2.10, Ta_2O_5), and a substrate layer (n_s = 1.5, glass). For the three-layer GMRF, there is one additional waveguide layer (n_3 = 1.81, ITO) between the Ta_2O_5 waveguide layer and glass the substrate. The position and intensity of the resonance peak of the GMRF can be tuned by varying the structural parameters such as period, thickness, and fill factor [16,17]. The goal of the proposed design is to obtain a sharp peak that is generated by the GMR effect over small parameter ranges. Rigorous coupled-wave analysis (RCWA) [18,19] is used to calculate the spectral responses for all the GMRFs. All the examples in this paper are 1D grating structures that operate with TE polarized light (the electric field vector is parallel to the grating grooves).

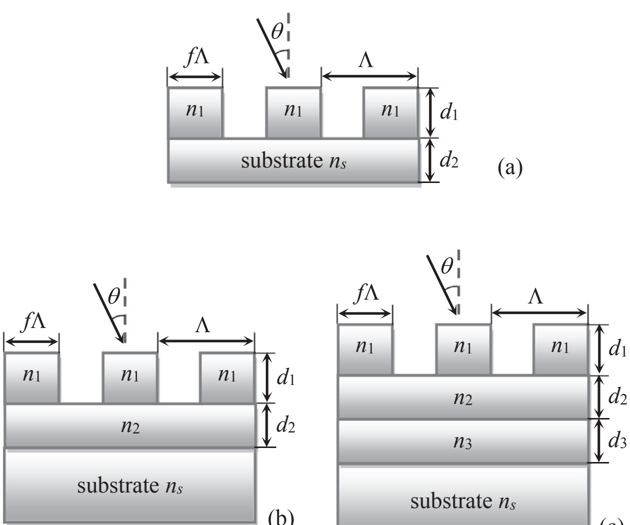

Fig. 1. Illustration of the GMRFs under consideration. The first layer is a grating layer with refractive index of n_1; the second layer and third layer are homogeneous waveguides with refractive indices of n_2 and n_3; d_1, d_2, and d_3 are layer thicknesses; n_s is the refractive index of the substrate; Λ is the grating period; f is the grating fill factor, and θ is the angle of incidence. (a) One-layer GMRF, (b) Two-layer GMRF, (c) Three-layer GMRF.

There is only one resonance peak at normal incidence because the positive first-order and negative first-order resonances excited by symmetric grating profile merge into one. An asymmetric double Rayleigh anomaly occurs at oblique incidence, and the separation of the positive and negative first-order resonances exhibits two resonance peaks at different wavelengths [17,20]. To achieve a large spectral shift of resonance wavelength covering all telecommunication spectral bands, the resonance wavelength at normal incidence can be set near 1100 nm or 1800 nm. Thus one resonance falls outside the telecommunication spectral band due to the separation of the positive and negative first-order resonances at oblique incidence.

2.2. Simulation results for positive first-order diffraction

The resonance wavelength is first set near 1100 nm at normal incidence. As the angle of incidence increases, the resonance wavelength of the negative first-order diffraction shifts toward shorter wavelength, which falls outside the telecommunication spectral band. Fig. 2 shows the positive first-order resonance spectra of the designed one-layer GMRF at oblique incidence under TE polarized light illumination. The structural parameters are Λ = 780 nm, f = 0.5, d_1 = 240 nm, and d_2 = 107 nm. The resonance wavelengths of the positive first-order diffraction at incident angles of 5°, 19.3°, 27.4°, 37°, and 45° are 1154.8, 1309.5, 1413.7, 1551.0, and 1675.2 nm, respectively. Though the resonance wavelengths of the one-layer GMRF in Fig. 2 can be tuned by adjusting the angle of incidence, all the reflection sidebands are very high.

Fig. 3 shows the positive first-order resonance spectra of the designed two-layer GMRF at oblique incidence under TE polarized light illumination. The structural parameters are Λ = 720 nm, f = 0.5, d_1 = 240 nm, and d_2 = 107 nm. The resonance wavelengths of the positive first-order diffraction at incident angles of 5°, 17.2°, 28°, 34.2°, and 45° are 1174.0, 1310.1, 1455.2, 1550.1, and 1727.4 nm, respectively. Though the resonance wavelengths of the two-layer GMRF in

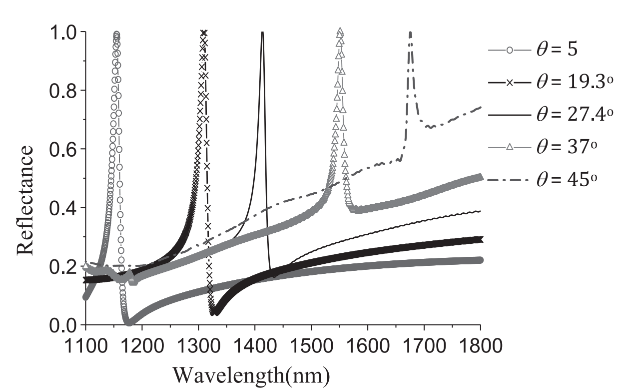

Fig. 2. Positive first-order resonance spectra of the designed one-layer GMRF at oblique incidence. The structural parameters are Λ = 780 nm, f = 0.5, d_1 = 240 nm, and d_2 = 107 nm.