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Active optical switches based on polarization-tuned guided-mode resonance filters for optical communication

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ABSTRACT

An active optical switch based on polarization-tuned guided-mode resonance filter (GMRF) for the optical communication wave band is experimentally demonstrated. The proposed active optical switch consists of a linear polarizer, a twisted nematic liquid crystal (TN-LC) polarization rotator and a GMRF from top to bottom. Two fabricated optical switches exhibit high resonance peaks with wavelengths around 1310 and 1550 nm in the voltage-off status. In the voltage-on status, weak light signals without resonance peaks pass through the optical switches. Thus light signal can be tuned by controlling the applied voltage on the TN-LC of the optical switch.

1. Introduction

The guided-mode resonance filter (GMRF) that consists of a surface-relief grating and a thin-film waveguide is a promising optical element. GMRFs attract a lot of interest because of their super wavelength-selecting ability. The guided-mode resonance (GMR) is due to the excitation of leaky guided modes in the periodic waveguide structure. Thus, lossless spectral filters with very narrow and tunable bandwidth appear to be feasible by using GMRFs. GMRFs have been widely exploited as versatile elements in a variety of applications, encompassing dense wavelength division multiplexing devices, CMOS image sensors, display devices, three-dimensional projection systems, biosensors and photovoltaic cells. In the field of passive optical elements, GMRFs have been exploited as wavelength filters for the optical communication wave bands [1–15]. To obtain active GMRFs, studies on tunable GMRFs incorporating liquid crystals have attracted increasing attention in both theory [16] and experiment [17,18]. In 2008, the tunable GMRF actuated by optically induced trans–cis isomerization of an azobenzene liquid crystal was designed and fabricated [17]. In 2016, a full-color and reflectance-tunable filter based on a GMRF with a twisted nematic liquid crystal (TN-LC) film as cladding was fabricated [18]. In 2017, an electro-optically switchable infrared filter based on GMR in a zenithal-bistable liquid crystal grating was designed and theoretically investigated [16].

However, active optical switches based on tunable GMRFs for the optical communication wave bands are obviously more desirable. In this letter, we propose an active optical switch composed of a linear polarizer, a TN-LC polarization rotator and a GMRF. We describe the design of two active optical switches that operate in the optical communication O-band and C-band near wavelengths of 1310 and 1550 nm. The characteristics of the GMRFs illuminated by TE and TM polarized lights are studied theoretically. The transmission spectra of two optical switch samples are measured and the experimental results agree closely with the simulations. The measured spectra of the two optical switch samples exhibit high peak efficiencies and low sidebands. We show experimentally that light signal can be tuned by controlling the applied voltage on the TN-LC polarization rotator of the optical switch.

2. Design principles and simulation results

2.1. The physics of the device

The GMRFs in this paper are all one-dimensional (1D) grating structures that operate with TE polarized light (the electric field vector is parallel to the grating grooves) and TM polarized light (the electric field vector is perpendicular to the grating grooves). The free-standing GMRF under consideration is composed of a 1D grating layer (Ag, n_1) and a waveguide layer (Si_3N_4, $n_2 = 1.97$) as illustrated in Fig. 1. The complex refractive index $n_1 (n_1 = n + ik)$ of the ultrathin Ag film with thickness between 0 and 2 μm used in simulations are from Palik [19]. Grating theory is used to elaborate on the physics of the device, in particular to calculate the modes of the Si_3N_4 waveguide layer in the presence of the periodic metallic grating. 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. The period of the grating is chosen so that the positive first-order

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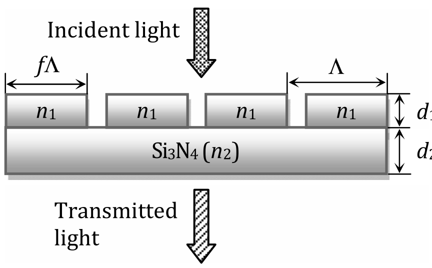

Fig. 1. Illustration of the free-standing GMRF. The first layer is a grating layer with refractive index of n_1; the second layer is a homogeneous waveguide layer with refractive index of n_2; d_1 and d_2 are layer thicknesses; Λ is the grating period, and f is the grating fill factor.

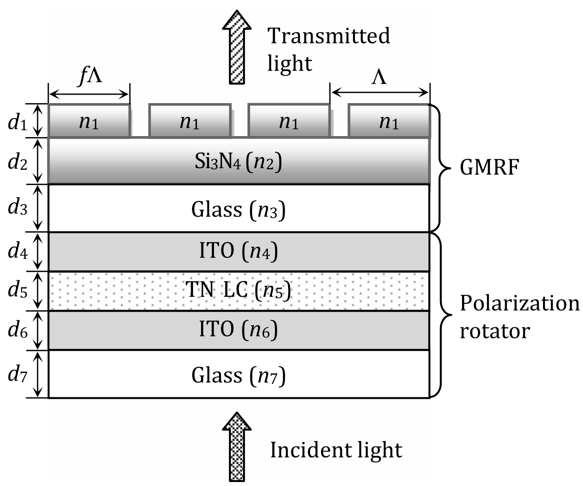

Fig. 2. Illustration of the active GMRF under consideration. Here, $d_1, d_2, d_3, d_4, d_5, d_6$, and d_7 are layer thicknesses; $n_1, n_2, n_3, n_4, n_5, n_6$, and n_7 are the refractive indices of the layers.

and negative first-order resonance wavelengths are trapped in the Si_3N_4 thin film. At normal incidence, the positive first-order and negative first-order resonances can occur in the interval [20]

$$\Lambda \leq \lambda_R \leq n_2\Lambda, \tag{1}$$

where λ_R is the resonance wavelength. Hence $\Lambda = 748$ and 884 nm are selected in order to place the GMR in the optical communication O-band and C-band respectively. This type of GMRF exhibits a polarization selectivity, in which the TM polarized waves are transmitted through the slits to the waveguide, whereas the TE polarized waves are almost totally reflected by the metallic membrane [20].

2.2. Simulation results of the active GMRF

The proposed active GMRF is composed of a GMRF and a TN-LC polarization rotator as illustrated in Fig. 2. From top to bottom, the active GMRF includes a grating layer (Ag, n_1, d_1), a waveguide layer (Si_3N_4, $n_2 = 1.97, d_2$), a GMRF substrate layer (glass, $n_3 = 1.5, d_3$), an electrode layer (ITO, $n_4 = 1.81, d_4$), a TN-LC layer (TN-LC, n_5, d_5), another electrode layer (ITO, $n_6 = 1.81, d_6$), and a substrate (glass, $n_7 = 1.5, d_7$).

In this work, the 5CB type of nematic liquid crystal (NLC) [21–23] supplied by Merck Co. is employed to fabricate the TN-LC layer. The refractive index of TN-LC layer is tuned by applying different voltages. The refractive index of TN-LC layer is first fixed at 1.55, and then varies in a certain range. Rigorous coupled-wave analysis (RCWA) [24–26] is used to calculate the spectral responses for the active GMRFs in this

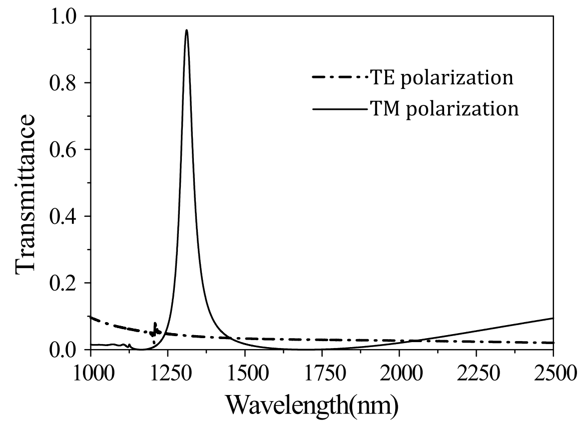

Fig. 3. Transmission spectra of the designed active GMRF under TE and TM polarized light illuminations at normal incidence. The structural parameters are $\Lambda = 748$ nm, $f = 0.901$, $n_5 = 1.55$, $d_1 = 24$ nm, $d_2 = 308$ nm, $d_3 = 1$ mm, $d_4 = 200$ nm, $d_5 = 15$ μm, $d_6 = 200$ nm, and $d_7 = 1$ mm.

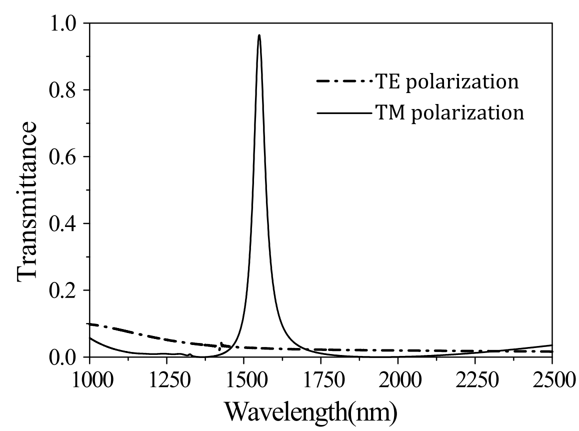

Fig. 4. Transmission spectra of the designed active GMRF under TE and TM polarized light illuminations at normal incidence. The structural parameters are $\Lambda = 884$ nm, $f = 0.928$, $n_5 = 1.55$, $d_1 = 30$ nm, $d_2 = 368$ nm, $d_3 = 1$ mm, $d_4 = 200$ nm, $d_5 = 15$ μm, $d_6 = 200$ nm, and $d_7 = 1$ mm.

paper. The calculated transmission spectra of the active GMRF for O-band at normal incidence are presented in Fig. 3. There is one resonance peak located at 1310.1 nm with a full width at half-maximum (FWHM) of 45.1 nm under TM polarized light illumination. Under TE polarized light illumination, the active GMRF exhibits no resonance peak and the transmittance is below 0.1. Furthermore, the resonance wavelength of the active GMRF can be tuned by changing the structural parameters. Fig. 4 shows the transmission spectra of the designed active GMRF for C-band at normal incidence. There is also one resonance peak located at 1550.2 nm with a FWHM of 43.3 nm under TM polarized light illumination. Similarly, the active GMRF exhibits no resonance peak and the transmittance is below 0.1 under TE polarized light illumination. The transmission spectra of the two active GMRFs under TM polarized light illumination exhibit high peaks and low sidebands.

The refractive index of TN-LC layer changes when a voltage is applied on electrode layers [21–23]. Therefore, it is necessary to study the dependence of the transmission spectra on the refractive index n_5. The transmission spectra of the two active GMRFs are recalculated when refractive index of 5CB type NLC varies from 1.53 to 1.71 at 23 °C without the consideration of polarization change. The numerical results show that the transmission spectra of the two active GMRFs remain invariable with different refractive indices of the TN-LC layer.