Japanese Journal of Applied Physics
Vol. 46, No. 8B, 2007, pp. 5431–5434

Experimental and Theoretical Demonstration of Resonant Leaky-Mode in Grating Waveguide Structure with A Flattened Passband

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(Received January 15, 2007; accepted March 15, 2007; published online August 23, 2007)

In this study, the first experimental demonstration of the strongly modulated refractive index of gratings with two distinct filling factors within one period is carried out for broadband guided mode resonance (GMR) filters. The proposed filters are realized by utilizing a single-layer poly-silicon film deposited on a quartz substrate. In order to clarify the unique features of strongly modulated gratings caused by subwavelength profiles with two filling factors in the lateral direction, dispersion relations and spectral responses are analyzed. A flattened bandstop spectral response of 85 nm with a transmittance of lower than −20 dB at a central wavelength of 1.22 µm and a high immunity to the angular deviation of incident wave up to 20° are experimentally obtained. Compared with the strongly modulated gratings achieved using longitudinal cascaded GMR filters, the proposed two-filling-factor gratings have a more compact design and are more suitable for further integration with other optoelectronic components. [DOI: 10.1143/JJAP.46.5431]

KEYWORDS: dispersion relations, cascaded GMR filters, two filling factors, guided-mode resonance, eye-patterned forbidden areas

1. Introduction

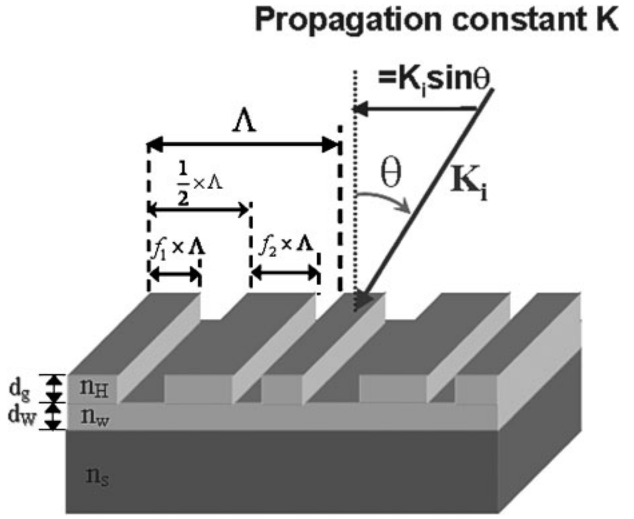
Since the guided mode resonance (GMR) filters with gratings strongly modulated in terms of refractive index can be designed to be used as a broadband filter with a high immunity for the angular deviation of incident wave, it is a potential candidate for applications associated with the broadband light source with a nonplanar wavefront such as light-emitting devices and the sun light. In order to realize strongly modulated gratings, there have been several significant efforts devoted into theoretical and experimental demonstrations of filters based on the GMR effect. The most common type of strongly modulated grating is realized by utilizing longitudinal cascaded GMR filters. Thurman and Morris presented a 200 GHz wavelength division multiplexing (WDM) filter with a passband wavelength of approximately 1 nm using a stack of four identical GMR elements.[1] The interference effect often used in the design of traditional thin-film filters results in a broad passband around the resonance wavelength. Jacob *et al.* introduced a separation layer to determine the overall spectral response of a cascaded resonant grating reflection filter.[2] The bandpass spectrum can be improved using the interference effect in the cascaded structure. Hsu *et al.* reported the first experimental demonstration of a flattened stopband filter by multiplying the spectral responses of the two cascading GMR elements with similar resonance wavelengths.[3] However, the complexity of the stacked structure makes it difficult to put into practical realization. Moreover, the cascaded structure suffers from the problem of strict alignment between GMR elements. Applying two identical GMR filters to the cascaded structure is almost impossible.

Liu and Magnusson presented the first theoretical demonstration of a single GMR element consisting of a grating sandwiched between two waveguides.[4] Their proposed resonant optical filter can be regarded as a monolithically cascaded structure of two GMR elements combined with a single grating layer. A broadband reflection spectrum of 16 nm was obtained by coupling evanescent waves from several diffracted orders into multiple leaky waveguide modes. Within a specified wavelength range, the interaction of adjacent resonant modes forms multiple reflection peaks in the spectrum. Therefore, the realization of a broad-band filter on a single GMR device is essential for numerous applications.

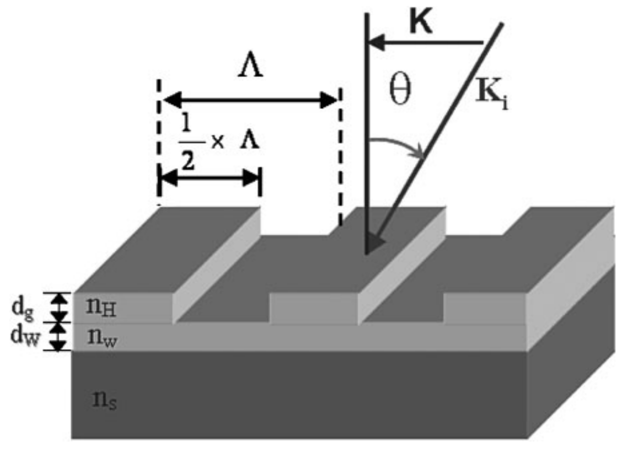
Brundrett *et al.* employed the high-index difference structure of silicon on sapphire to experimentally achieve strongly modulated gratings filters with suitable angular sensitivity.[5] Mateus *et al.* also theoretically and experimentally proposed the design of a broad-band mirror using strongly modulated gratings on the basis of the another high-index difference structure of silicon-on-insulator (SOI) material.[6,7] However, broadband filters based on a single GMR structure with an angular sensitivity greater than 10° have not been reported until now. Recently, Ding and Magnusson have theoretically reported the design of resonant-leaky-mode filters based on binary gratings with two distinct filling factors within one period.[8] The two-filling-factor gratings referred to as the asymmetric gating profile by Ding and Magnusson could translate the single resonance mode in the symmetric structure to a nondegenerate state with two distinct resonance modes under a normal incidence condition. The proposed wideband TE reflector has a high reflectance that is larger than 99% and a reflectance spectrum of 600 nm. Furthermore, the wideband resonance structures are associated with a wide angular aperture of $\Delta\theta_{\mathrm{FWHM}} > 40°$. Therefore, two-filling-factor gratings are a candidate of much simpler filter of a applications associated with the broadband light sources with nonplanar wavefronts.

2. Simulation Results and Analysis

In order to develop strongly modulated gratings with two filling factors, a structure consisting of a one-dimensional diffraction grating and a planar waveguide layer in a single-layer polycrystalline silicon (poly-Si) film deposited on a quartz substrate as shown in Fig. 1(a) is proposed. The refractive indices of poly-Si and quartz are an $n_{\text{poly-Si}}$ of 3.48 and an n_{Quartz} of 1.46, respectively. The structure parameters are denoted as follows: grating period, Λ; filling factors, f_1 and f_2; the grating depth, d_g; and the waveguide thickness, d_w. As illustrated in Fig. 1(a), two rectangular groove

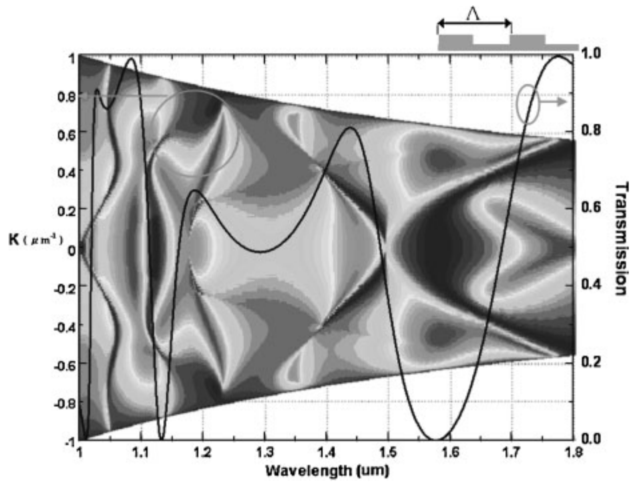


(a)

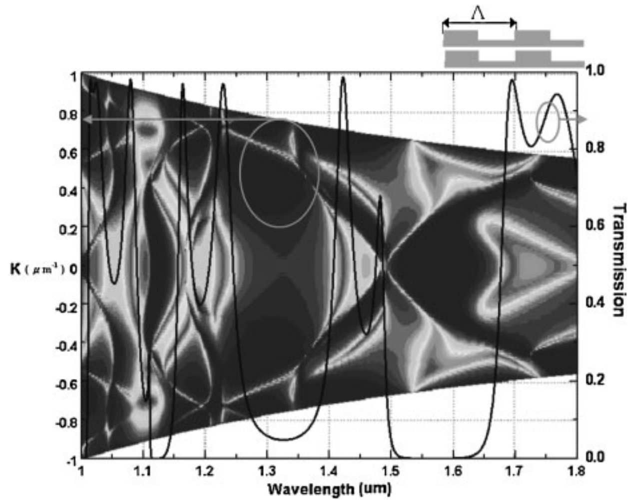


(b)

Fig. 1. Schematic of proposed filter. (a) The two rectangular groove structures with arbitrary filling factors of f_1 and f_2 are individually disposed in the two half periods. (b) One-filling factor GMR filter with same structure parameters of (a). $K = K_i \sin\theta$, θ is the incident angle, K is the propagation constant of the grating waveguide, and K_i is the incident wave vector.



(a)

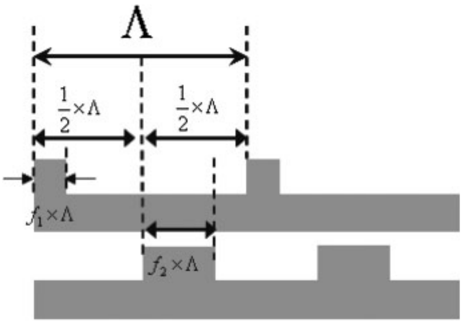


(b)

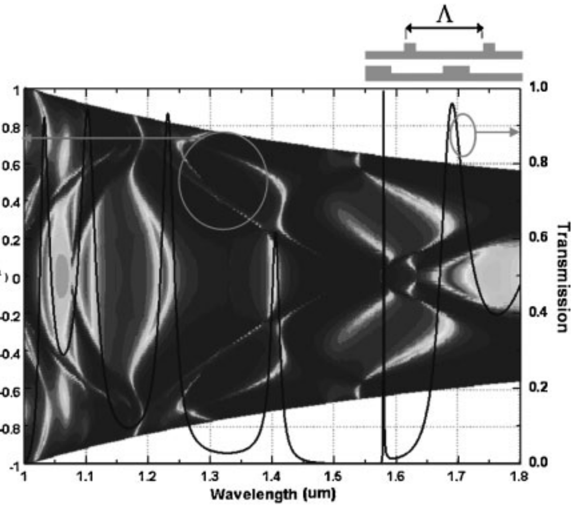
Fig. 2. Band diagrams and corresponding transmitted spectra at normal incidence of one-filling-factor GMR filters. (a) Single-device-type. (b) Cascaded-type. The unit of K is $\sin\theta/\lambda$. The red color corresponds to the high transmittance and the blue one corresponds to the low transmittance in the band diagram.

structures with arbitrary filling factors of f_1 and f_2 are individually disposed in the two half periods. To show that the proposed two-filling-factor GMR filter possesses a strong modulation effect in gratings similarly to the longitudinally cascaded type of the one-filling factor GMR filter, the rigorous coupled-wave analysis (RCWA) is used to analyze the dispersion relations (band diagrams) and the spectral responses of the GMR structures. As shown in Fig. 1(b), the one-filling factor GMR filter with the same structure parameters as the two-filling-factor filter of Fig. 1(a) is applied in the following analysis. The Λ, d_g, and d_w of 0.7, 0.4, and 0.1 µm, respectively, are chosen for both GMR filters. The TE polarized plane wave with the wave vector K_i is adopted as the incident wave. Comparison with the spectra of the so-called symmetric gratings with one filling factor of 0.5, the sum of two filling factors of the asymmetrical gratings within one period is the same as the filling factor 0.5 of the symmetric gratings.

As shown in Figs. 2(a) and 2(b), the band diagrams, i.e., the dispersion relation for the propagation constant $K = K_i \sin\theta$ and wavelength λ, where θ is the incident angle and K is the propagation constant of the grating waveguide, as well as the corresponding transmitted spectra at a normal incidence, i.e., $K = 0$, of the one-filling-factor GMR filters, including single-device-type and cascaded one are simulated. Figure 2(a) shows results of the single one-filling-factor GMR filter with a filling factor of 0.5. As illustrated in this figure, there are two resonance peaks occurring at 1.57 and 1.13 µm for reflection and their full spectral widths at half-maximum (FWHM) are 296 and 25 nm, respectively. The spectral response shows that the single symmetric GMR filter possesses strong modulation gratings because two identical GMR filters with a filling factor of 0.5 are stacked to form a longitudinally cascaded GMR filter. As shown in Fig. 2(b), the longitudinally cascaded structure induces a strong modulation effect in gratings. Consequently, the single resonance peak at 1.6 µm for the single GMR filter with one filling factor becomes a flat bandstop spectral response with a power suppression as low as −20 dB within the broad spectral range of 125 nm for the cascaded



(a)



(b)

Fig. 3. The cascaded structure is interlaced with a lateral shift of 0.5Λ, and the filling factors are 0.12 and 0.38. (a) Schematic of structure. (b) Simulation results. The unit of K is $\sin\theta/\lambda$.The red color corresponds to the high transmittance and the blue one corresponds to the low transmittance in the band diagram.

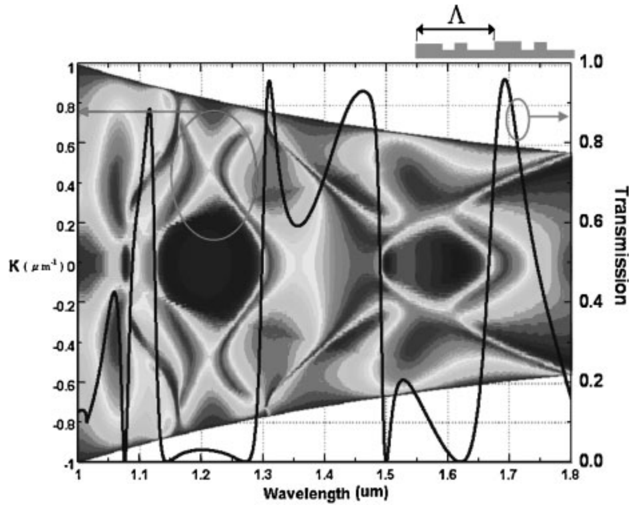


Fig. 4. Band diagrams and corresponding transmitted spectra at normal incidence of two-filling-factor GMR simulation results. The unit of K is $\sin\theta/\lambda$. The red color corresponds to the high transmittance and the blue one corresponds to the low transmittance in the band diagram.

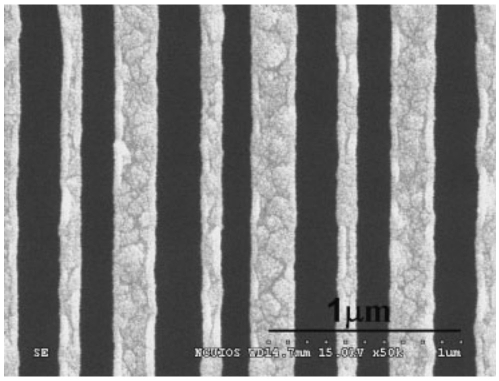


Fig. 5. Image of fabricated GMR filter observed by scanning electron microscopy.

structure. This means that the strongly modulated gratings of the cascaded structure can effectively reject a broadband light source from the filter. In order to study the influence of two filling factors in one period, the cascaded structure is interlaced with a lateral shift of 0.5Λ as shown in Fig. 3(a). Moreover, the single filling factor of 0.5 is replaced by two different factors of 0.12 and 0.38. The simulation results shown in Fig. 3(b) reveal that the interlaced GMR filter also shows a strong modulation effect in gratings and can be used as a flat bandstop filter at 1.5 μm. If the interlaced GMR filters are longitudinally merged together, they will transformed into a two-filling-factor GMR filter as shown in Fig. 1(a). RCWA is also carried out to study the dispersion relation and the spectral response of the two-filling-factor GMR structure, and simulation results are shown in Fig. 4. As shown in this figure, a strong modulation effect occurs and induces a flat bandstop response in the range of 1.14–1.28 μm. It is clear that two eye-patterned forbidden areas formed in the band structure of the two-filling-factor GMR filter within the wavelength regions of 1.14–1.28 and 1.50–1.62 μm. Moreover, these eye-patterned forbidden areas reveal that the proposed two-filling-factor GMR filter allows various wave vectors of incident waves. Therefore, the subwavelength profiles with two filling factors in the lateral direction result in the strongly modulated gratings.

3. Experimental Results

In order to experimentally test the two-filling-factor GMR filter, its fabrication procedures are described below. Initially, a poly-Si film is deposited onto a quartz substrate by plasma-enhanced chemical vapor deposition (PECVD). Then, the pattern of the intended grating profile which is defined in poly(methyl methacrylate) (PMMA) by e-beam lithography followed by inductive-coupled-plasma (ICP) dry etching is used to transfer the patterned structure to the deposited poly-silicon. Finally, the device is completed by the removal of residual PMMA. Figure 5 shows a scanning electron microscopy (SEM) image of the fabricated grating structure. The grating profile is observed with an average period of approximately to 0.72 μm. The filling factors f_1 and f_2 corresponding to the average period are about 0.11 and 0.31, respectively. The grating depth and waveguide thickness are 0.4 and 0.1 μm, respectively. Figure 6 shows the measured transmittance spectrum of the proposed structure under a normal incidence condition. A flattened stopband at the center wavelength of 1.22 μm is observed. Its transmittance of bandstop spectrum can be suppressed to as low as −20 dB within a broad spectral range of 85 nm, and

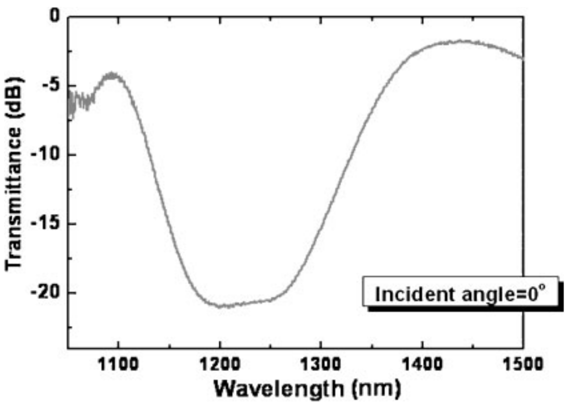


Fig. 6. Measured transmittance spectrum of proposed structure under normal incidence.

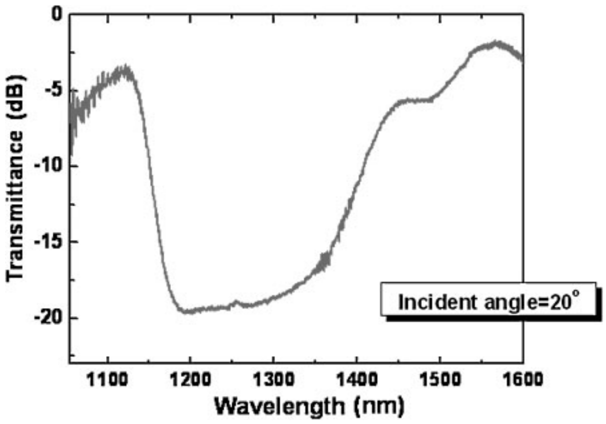


Fig. 7. Measured transmittance spectrum of proposed structure under oblique incidence.

its corresponding $\Delta\lambda/\lambda$ is larger than 6%. The slight deviation between the experimental and simulated results may haved resulted from the structural variation in the surface roughness of the gratings as shown in Fig. 5.

As illustrated in Fig. 7, the spectra under oblique incidence were also measured to investigate angular stability. As the incident angle increases to 20°, the resonance wavelength remains at approximately 1.22 μm, and the average transmittance in the flattened stopband remains lower than −20 dB before the angle of oblique incidence approaches 16°. The loose angular tolerance results from the high contrast between the refractive indices of poly-Si and air as well as the comparatively deep grating groove. The high immunity to the angular deviation of incident wave is consistent with the eye-patterned forbidden area of the band structure shown in Fig. 4. The loose angular tolerance means that the superior angular stability of the proposed notch filter makes it useful for practical applications.

4. Conclusions

In this study, the strongly modulated refractive index of gratings based on binary rectangular grooves with two distinct filling factors within one identical period are theoretically and experimentally demonstrated for the first time for broadband guided mode resonance (GMR) filters. The measurement results verify that a flattened bandstop spectral response of 85 nm with a transmittance of lower than −20 dB at the central wavelength of 1.22 μm and a high immunity to the angular deviation of incident wave up to 20° are achieved using the proposed device.

Acknowledgments

This work was supported by the MOE Program for Promoting Academic Excellence at Universities under grant number NSC95-2221-E-008-118-MY3.

1) S. T. Thurman and G. Michael Morris: Appl. Opt. **42** (2003) 3225.
2) D. K. Jacob, S. C. Dunn, and M. G. Morris: Appl. Opt. **41** (2002) 1241.
3) C. L. Hsu, Y. C. Liu, C. M. Wang, M. L. Wu, Y. L. Tsai, Y. H. Chou, C. C. Lee, and J. Y. Chang: J. Lightwave Technol. **24** (2006) 1922.
4) Z. S. Liu and R. Magnusson: IEEE Photonics Technol. Lett. **14** (2002) 1091.
5) D. L. Brundrett, E. N. Glytsis, and T. K. Gaylord: Opt. Lett. **23** (1998) 700.
6) C. F. R. Mateus, M. C. Y. Huang, Y. Deng, A. R. Neureuther, and C. J. Chang-Hasnain: IEEE Photonics Technol. Lett. **16** (2004) 518.
7) C. F. R. Mateus, M. C. Y. Huang, L. Chen, C. J. Chang-Hasnain, and Y. Suzuki: IEEE Photonics Technol. Lett. **16** (2004) 1676.
8) Y. Ding and R. Magnusson: Opt. Express **12** (2004) 5661.