Narrow Bandstop Filters Using Suspended Membrane Type of Guided-Mode Resonance Structures Based on Silicon

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Abstract--- *In this paper, the suspended-membrane-type guided-mode resonance (GMR) filter based on silicon with a narrow bandstop spectrum is experimentally demonstrated. The resonance wavelength of proposed GMR filter is controlled at 1580.6 nm with a bandwidth less than 0.92 nm. The improved spectral performance including the sideband can be extended as far as 415 nm with the maximum transmittance greater than 93%.*

Keywords: *guided-mode resonance filter, wet etching.*

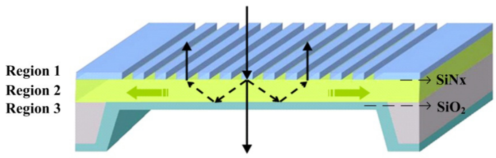
INTRODUCTION

The guided-mode resonance (GMR) filters are commonly composed of dielectric thin-film structures incorporating sub-wavelength (sub-λ) gratings with periodic modulation of refractive indices to couple energy diffracted from an incident wave to a leakage mode of the waveguide layer included in the structure. Optical filters based on the GMR effect have attracted considerable interests because of their simple structures of much fewer layers and superior properties of high efficiency in transmission and reflection [1], versatile spectral selectivity for broad-band or narrow-band spectral widths [2], and feasible band-tailoring for band-pass or band-stop [3].

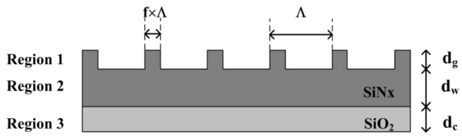
In this paper, we present the experimental demonstration of suspended-membrane-type GMR filters with a narrow stop-band and a very large sideband of over 415 nm can be achieved with a fewer-layer GMR filter. Moreover, a very weakly-modulated grating, which is formed with a lower grating index-contrast, a shorter grating depth, and a smaller grating filling factor, is chosen to maintain the narrow stop-band of only 0.92 nm at the resonance wavelength of 1580.6 nm.

DESIGN OF GRATING WAVEGUIDE STRUCTURE

In the proposed structure, a two-layer silicon-based and suspended-membrane-type GMR filter with a narrow band-stop spectrum and a very large sideband is presented. The structure consists of a one-dimensional diffraction grating and a planar waveguide layer in a single-layer SiN_x film deposited on a silicon substrate as shown in figure 1. The GMR structure includes a suspended SiN_x film acts as a surface-relief sub-λ grating (Region 1) and a planar waveguide (Region 2). The SiN_x membrane suspended on silicon substrate can be realized by totally removing the rear of the silicon substrate beneath the SiN_x layer to form an etched cavity. Therefore, the SiN_x layer on a silicon substrate can be directly adopted as the guided structure of GMR filters without introducing an additional low-refractive-index material between the SiN_x layer and the silicon substrate. The SiO_2 layer (Region 3) placed on the bottom side of SiN_x layer is utilized to modulate the spectral response of sideband by altering its thickness. The refractive indices of SiN_x membrane and SiO_2 layer are assumed to be n_{SiNx} of 2.02 and n_{SiO2} of 1.46, respectively.



(a)

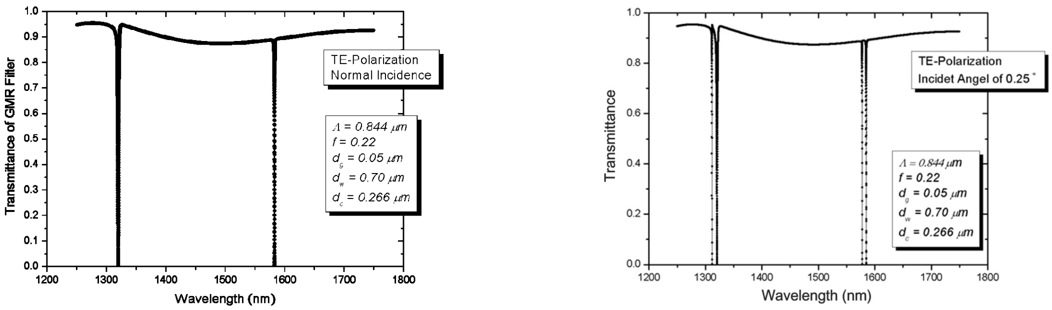


(b)

Figure 1. Schematic viewings of the proposed GMR filter.

The rigorous coupled-wave analysis (RCWA) is used to analyze the resonance behavior of the proposed GMR structures. To excite a resonance in the GMR filter at the center wavelength near 1580 nm, the structure parameters given in the following analysis include the grating period Λ= 0.844 μm, the grating filling factor f = 0.22, the grating depth d_g = 0.05 μm, the depth of planar waveguide d_w = 0.7 μm, and the cladding-layer depth d_c = 0.266 μm. Figure 2(a) shows the simulated and normalized transmittance spectrum of the proposed GMR filter as a function of incident wavelength at normal incidence with TE polarization. The resonance wavelength λ_C of

1583 nm with corresponding bandwidth $\Delta\lambda$ about 0.37 nm is obtained. The maximum transmission efficiency T_{max} at sideband is around 0.94 due to Fresnel reflection induced by the non-quarter-wave thickness of weakly-modulated gratings. Although two resonant dips corresponding to two guided modes are observed in the spectrum of proposed GMR filter, its sideband width (λ_2 -λ_1) at $0.9T_{max}$ can be extended as far as 423 nm. λ_1 and λ_2 are two wavelengths adjacent to the resonance wavelength at both sides. According to the above simulation, the relative bandwidth $\Delta\lambda/\lambda_C$ = 0.0234% and the relative spectral range $(\lambda_2 - \lambda_1)/\lambda_C$ = 26.7% can be calculated for the proposed GMR filter under the normal incident wave with TE polarization. Its quality factor (Q-factor) is enhanced to be 4278. Moreover, Figure 2(b) shows that the spectrum under oblique incidence of 0.25° is also studied to investigate the angular tolerance of the proposed GMR filter. The resonance bandwidth is not only broadened up to 0.345 nm but also the resonance wavelength is divided into two peaks, one is 1575 nm, and the other is 1589 nm, respectively. The tight angular tolerance may results from the weakly modulated grating with a depth of only 50 nm.

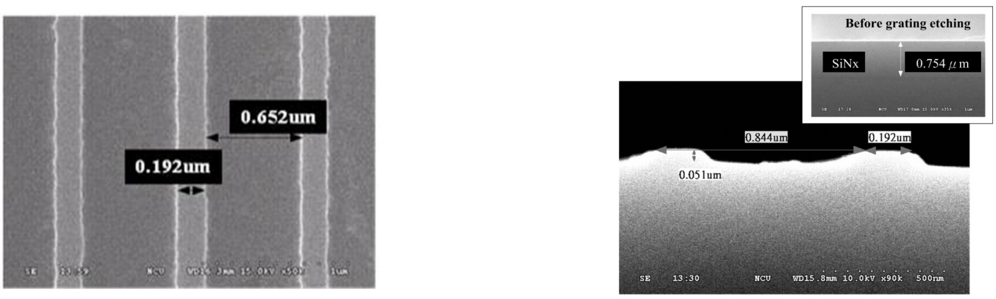


(a) **(b)**

Figure 2. The simulated transmittance spectrum of the proposed GMR filter. (a) The incident wave is at normal incidence with TE polarization. (b) The incident wave has an oblique angle at 0.25° .

EXPERIMENTAL RESULTS

The process flow of proposed GMR filter is described as below. Low-stress SiN_x thin films are deposited onto both sides of the silicon substrate by using the low-pressure chemical vapor deposition (LPCVD) for an intended thickness. A square hole is pattern and then opened on the backside SiN_x by using photolithography and inductively coupled plasma (ICP) etching system. The sub-λ grating on the topside is patterned by using the electron-beam lithography. The membrane structure is formed by using the anisotropic wet etching of KOH solution. Finally, the SiO_2 cladding layer is deposited on the bottom side of the SiN_x layer. Figures 3(a) and 3(b) show the photos of fabricated grating structure observed by the scanning electron microscope (SEM). The grating profile is observed with an average period close to 0.844 μm. The filling factor corresponding to the average period is about 0.22. The grating depth and waveguide thickness are controlled at 51 and 703 nm, respectively. The thickness of SiO_2 cladding layer is controlled at 266 nm.



(a) **(b)**

Figure 3. SEM photos of the proposed GMR filter. (a) The grating linewidth is around 0.192 μm, corresponding to the designed filling factor of 0.22. (b) The side-view photo of fabricated GMR grating, and its inset reveals the overall SiNx thickness is 0.754 μm, equal to the designed sum of grating and waveguide layer.

As illustrated in figure 4, the measurement setup consisting of a white-light source with a bandwidth of 500 to1750 nm, a single-mode fiber with a gradient reflective index (GRIN) collimator, a TE polarizer, and an optical spectrum analyzer is employed to study the spectral response and the angular tolerance of the fabricated GMR filter. The separation between the GRIN collimator and the GMR filter is 5 cm to obtain a collimated light. The grating size for our sample is 1.5×1.5 mm^2, and the illuminating diameter of incident beams is approximately 1 mm, making sure the edge effect for GMR filter less affects the spectral response [4].

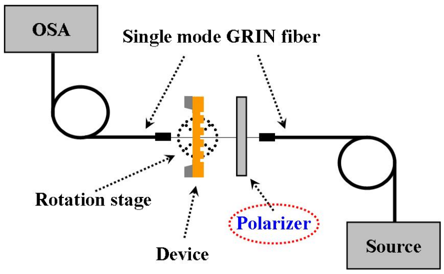


Figure 4. A schematic drawing of spectrum measurement setup for the GMR filter.

The measurement result for the transmission spectrum of proposed GMR filter is shown in figure 5(a) for the incident wave at normal incidence with TE polarization. Its spectral response is summarized as below: the resonance wavelength λ_C of 1580.6 nm, the corresponding bandwidth $\Delta\lambda$ of 0.92 nm, the maximum transmission efficiency T_{max} at sideband of 0.94, and the sideband width (λ_2 -λ_1) at $0.9T_{max}$ of 415 nm. According to the above simulation, the relative bandwidth $\Delta\lambda/\lambda_C$ = 0.0582% and the relative spectral range $(\lambda_2 -\lambda_1)/\lambda_C$ = 26.3% can be calculated for the proposed GMR filter under the normal incident wave with TE polarization. Its Q-factor is 1718. The deviation between the measured and simulated results may cause by the structural variation in fabrication and the divergence of incident beam in measurement. As shown in figure 3(b), the rectangular profile of shallow grating is not easy to control during the etching process and become an asymmetrically trapezoid-shaped one. The filling factor would be varied due to the asymmetrically trapezoid-shaped profile. The spectral response of a narrow-band GMR filter is sensitive to the incident angle of the input beam. The spectral response under an oblique incidence of 0.25° corresponding to the normal incidence is measured and illustrated in figure 5(b).

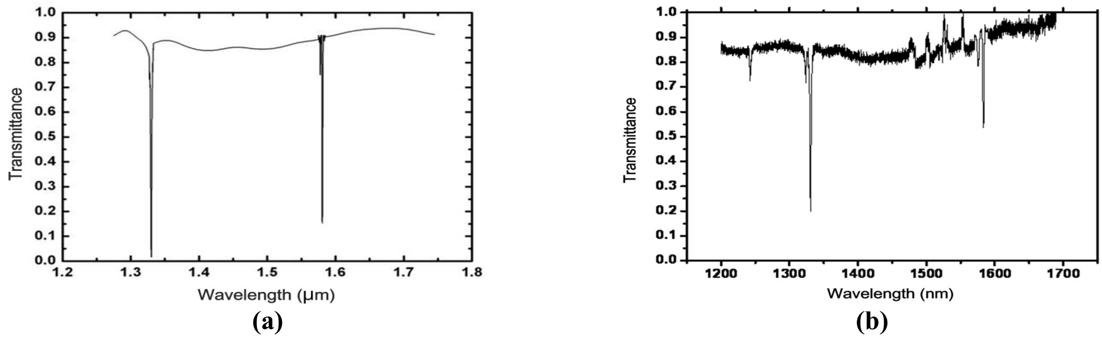


Figure 5. Measurement result for the transmission spectrum of proposed GMR filter. (a) The incident wave is at normal incidence. (b) The incident wave has an oblique incidence of 0.25°.

CONCLUSIONS

In this paper, a bandstop filter with a narrow relative bandwidth of 0.0582% and with a wide relative spectral range of sideband up to 26.3% is experimentally demonstrated by a two layer of suspended-membrane-type GMR structure based on silicon. The excellent performance of the proposed GMR filter with a penalty of the transmission loss at sideband of around 1 dB is achieved by using the weakly modulated grating with a depth less than the quarter-wave thickness. The higher-order guided mode resonating in the waveguide layer plays a role to reduce the resonant bandwidth. Therefore, the concept of the higher-order guided mode resonating in the waveguide layer can greatly simplify the layer number of GMR filter. In order to widen and flatten the sideband off resonance by using a single cladding layer with the quarter-wave thickness, removing the substrate from the GMR filter is an effective approach.

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