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Resonant-Wavelength Tuning of a Pitch-Variable 1-D Photonic Crystal Filter at Telecom Frequencies

Yoshiaki Kanamori, Naoki Matsuyama, and Kazuhiro Hane

***Abstract*—We propose pitch-variable guided resonance filters for continuous resonant-wavelength tuning at telecom frequencies. Since the optical response is affected by not only the grating period but also the filling factor, in consideration of these parameters, the filter is designed to be tuned smoothly to a selective wavelength by using comb-drive actuators. The grating with the initial period of 860 nm is fabricated with high accuracy. When the grating is expanded, the resonant wavelength shifts to longer wavelength continuously as expected by the calculation.**

***Index Terms*—Microelectromechanical devices, optical device fabrication, optical gratings, tunable filters.**

I. Introduction

LATELY, photonic crystal (PC) slabs have been drawing considerable attention because of the promise of light confinement in a small area of integrated optical circuits. In a conventional PC waveguide, a light wave is confined in an in-plane guided-mode without any coupling to external radiations [1]. On the other hand, the PC slab can also interact with external radiations through a guided resonance (GR) in the structure. When period of the PC slab satisfies a GR condition caused by coupling between an incident light and a resonant mode inside the PC layer, the PC works as a high efficiency band-stop filter at the resonant wavelength, which is called a GR filter [2]–[6]. One-dimensional (1-D) GR filters with both narrow and broad bandwidths have already been investigated for telecom applications because of their advanced and widespread status [4]–[6]. Most of the GR filters fabricated have static optical characteristics.

Microelectromechanical systems (MEMS) are the promising mechanisms for introducing variable functions into PC devices. Although pitch-variable GR filters with high diffraction efficiency attract a lot of attention, there are only a few experimental reports because of the fabrication difficulty of self-supported GR grating structures. We have fabricated a pitch-variable GR filter with a MEMS actuator at visible frequencies [7]. However, the diffraction efficiency obtained was low because an incident light was absorbed by Si used as the grating beams at visible frequencies. More recently, Zhang *et al.* have reported a fabrication of a variable subwavelength-grating filter [8]. Since the optical characteristics were measured only at two wavelengths and a change in groove width arising from a pitch variation is not considered, the analog tunability of the resonant wavelength was not clear. An analog tunable grating has advantages for the telecom applications, since it is difficult for a digital tunable grating to tune any wavelength among a lot of channels into telecom bandwidth.

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The authors are with the Department of Nanomechanics, Tohoku University, Sendai 980-8579, Japan (e-mail: kanamori@hane.mech.tohoku.ac.jp).

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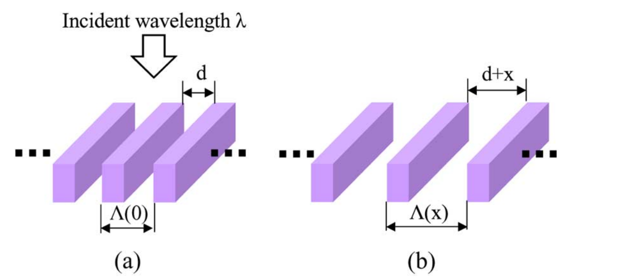
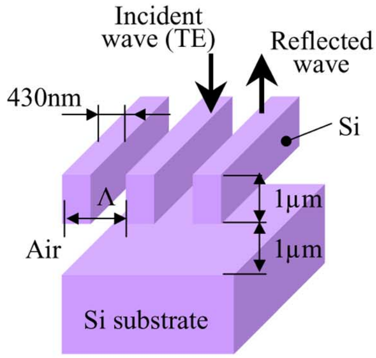


Fig. 1. Conceptual diagram of tunable wavelength-selective filters based on pitch-variable GR filters at (a) the initial state and (b) the expanding state. The d, Λ, and x show the initial groove width, the grating period, and the pitch variation, respectively.

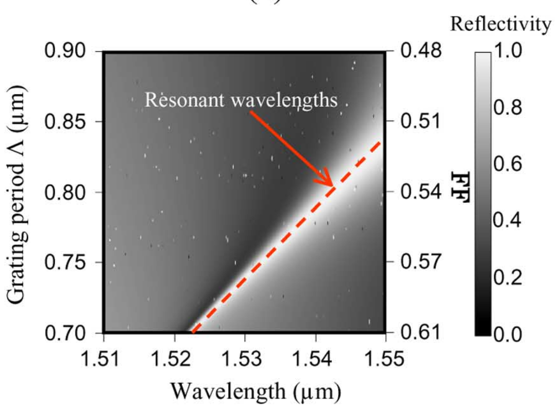
In this letter, we fabricate pitch-variable GR filters for analog resonant-wavelength tuning at telecom frequencies. A Si is used as a grating beam to obtain high diffraction efficiency because it does not absorb a light at telecom frequencies. Since the optical response is affected by not only a grating period and incident wavelengths but also a groove width, in consideration of these parameters, the filter is designed to be tuned continuously to a selective wavelength using comb-drive actuators. The thickness of the actuators is 1 μm, which is thinner than the 5 and 3 μm reported in [7] and [8], respectively, making the fabrication easy and achieving high integrity with various PC devices [9], [10].

II. Principle

Fig. 1 shows the conceptual diagram of analog-modulated wavelength-selective filters based on pitch-variable GR filters. When the grating is placed at the initial state with the period $\Lambda(0)$ as shown in Fig. 1(a), approximately 100% of incident light at certain resonant wavelengths is reflected caused by a strong coupling to a resonant mode inside the grating layer. When the grating structure is mechanically expanded as shown in Fig. 1(b), the grating period is changed from $\Lambda(0)$ to $\Lambda(x)$ by broadening the groove width from d to $d+x$, while the beam width of the grating is not changed. Therefore, the filling factor (FF), which is a ratio of the fixed beam width to the grating period, is also changed with the change in the grating period. Since the optical response is affected by not only the grating period but also the FF, in consideration of these parameters, the tunable filter can be realized.



(a)



(b)

Fig. 2. Optical design. (a) Calculation model and (b) the reflectivity as functions of the incident wavelength and the grating period.

III. Design

Reflectivity of the GR filter as shown in Fig. 2(a) has been calculated using rigorous coupled-wave analysis (RCWA), which yields accurate results using Maxwell's equations in the frequency domain [11]. The orders of the Fourier coefficients used in the calculation are between −20th and +20th. Incident light is assumed to irradiate along the direction normal to the substrate surface under transverse-electric (TE) polarization. TE polarization refers to the state in which the electric field of the plane wave is parallel to the grating groove. The refractive index of the Si used in the calculation is 3.48. The dimension of the structure has been designed to obtain the resonant wavelength around 1.55 μm in consideration of our fabrication skill. A Si grating with the period of Λ, the beam width of 430 nm, and the thickness of 1 μm is placed over a Si substrate with an air gap of 1 μm. It is possible to design a narrow bandwidth filter with different grating parameters, although the fabrication is challenging. Fig. 2(b) shows the calculated reflectivity as functions of the incident wavelength and the grating period. The FF, which is the ratio of fixed beam width (430 nm) to the Λ, is also indicated on a secondary vertical axis. The change of the FF makes a guided mode property vary, which causes resonant wavelength shift. Since it is difficult for the mechanical pitch-variable grating structure to control the grating period and the FF independently, the optical design becomes complicated. As shown in Fig. 2(b), the reasonable optical response, in which the resonant wavelength is shifted in a linear manner at telecom wavelengths with the pitch variation, is found out. The dotted line shows the center of the resonant wavelength. As can be seen, the reflectivity of approximately 100% is obtained around the line caused by the GR, although the reflectivity of the Si flat surface is approximately 30%. By controlling the grating period using comb-drive actuators, the selective wavelength can be tuned continuously.

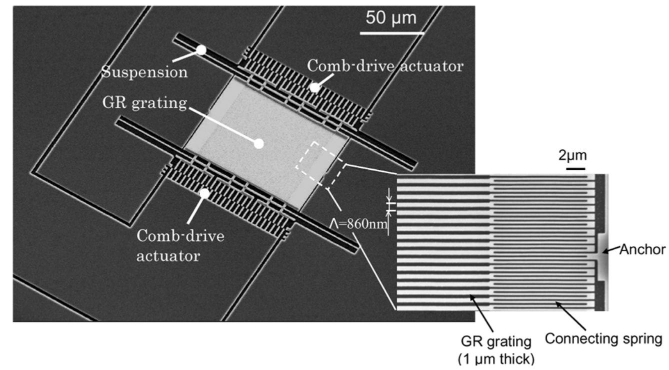


Fig. 3. SEM pictures of the fabricated GR filter.

IV. Fabrication

In the fabrication, a silicon-on-insulator (SOI) substrate with a 1-μm-thick Si device layer and a 1-μm-thick buried oxide layer on a 200-μm-thick Si substrate was used. The filter pattern was drawn by electron beam lithography. To etch vertically the Si device layer, a three-step etching technique using fast atom beam and inductive coupled plasma reactive ion etching machines was carried out. Finally, sacrificial-layer etching of the buried oxide layer was carried out using a hydrofluoric acid (HF) gas.

Fig. 3 shows scanning electron microscope (SEM) pictures of the fabricated GR filter. The filter mainly consists of a GR grating with an 860-nm grating period, connecting springs, and opposed comb-drive actuators on a substrate. These materials are crystalline Si. The GR grating and the connecting spring are self-supported structures and the each beam of the GR grating is connected next to each other by the connecting spring as shown in an inset of Fig. 3. The width, length, and thickness of the connecting spring are 200 nm, 10 μm, and 1 μm, respectively. The opposed comb-drive actuators are connected to the GR grating. By expanding the GR grating with the comb-drive actuators, the grating period can be changed. The GR filter is fabricated with high accuracy.

Surface roughness and warp on the GR grating cause optical scattering and loss. We measured the roughness on the grating surface. Then, low warp and small roughness with the maximum height of 2.75 nm were obtained.

V. Results and Discussion

To measure the changing of the grating period, the pitch-variable operation was performed in an SEM chamber. The magnified views of the grating and connecting spring parts at the initial and expanding states are shown in Fig. 4(a) and (b), respectively. By applying a voltage of 50 V to the comb-drive actuators, the grating period is changed from 860 to 875 nm.

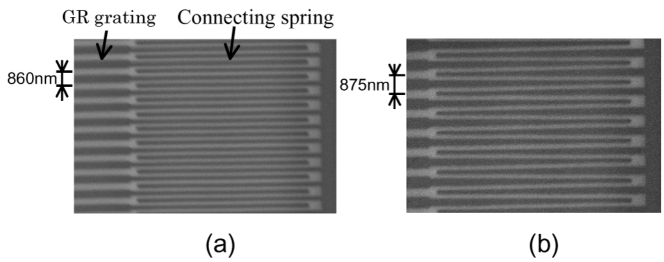


Fig. 4. Variation of the grating period performed in an SEM chamber. (a) The initial state and (b) the expanding state at the applied voltage of 50 V.

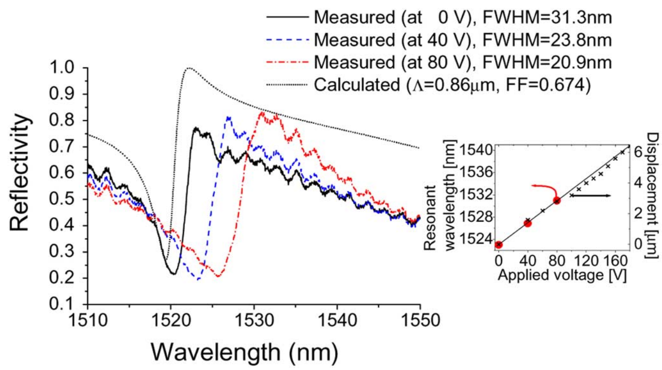


Fig. 5. Reflectivity as a function of the incident wavelength. Inset shows the resonant wavelength and the displacement of actuator as a function of the applied voltage.

From the optical microscope observation, we measured the displacement of the actuator at the applied voltage of 220 V and then the tuning ratio of the grating period was obtained to be 10%. The actuator driven at low voltage can be fabricated by increasing the suspension length or the number of actuation comb finger pairs or decreasing the suspension width [12].

Fig. 5 shows the measured reflectivity as a function of the incident wavelength at the applied voltages of 0, 40, and 80 V. TE-polarized laser light is incident from the normal direction to the substrate surface. The calculated reflectivity at the grating period of 0.86 μm and the FF of 0.674, which were estimated from SEM observation, is also shown in Fig. 5. When the GR grating is expanded by applying voltage from 0 to 80 V, the wavelength at the peak reflectivity shifts to a longer wavelength smoothly from 1523 to 1531 nm. The peak reflectivity of 83.7% and the bandwidth [full-width at half-maximum (FWHM)] of 20.9 nm are obtained at the applied voltage of 80 V. As can be seen in Fig. 5, the measured spectrum responses show the same tendency as calculated values. We consider that the discrepancy between the measured and calculated values is mainly caused by the surface roughness at the etching process. The saw-tooth responses in the long-wavelength regions are caused by optical interferences at both surfaces of the Si substrate, which are not considered in the RCWA calculations. The narrow bandwidth can be obtained by suppressing the reflectivity at the wavelengths around the resonant wavelength by etching out the Si substrate underneath the GR grating area for making a through hole, because the light reflected from the Si substrate makes the sidelobe reflectivity increase [13]. The inset in Fig. 5 shows the resonant wavelength as a function of voltage applied to the actuator. The displacement of actuator is also superimposed. As is expected from Fig. 2(b), in which the resonant wavelength is shifted in a linear manner with the pitch variation, the actuator moves in proportion to the applied voltage.

VI. Conclusion

We proposed pitch-variable GR filters for analog tuning at telecom frequencies. The optical design was carried out using RCWA by taking into account a change in the FF. The filter with an initial grating period of 860 nm was fabricated with high accuracy using an SOI substrate. Maximum reflectivity of approximately 80% was achieved. When the GR grating was expanded, the wavelength at the peak reflectivity shifted to longer wavelengths smoothly as expected by the calculation. The bandwidth of the fabricated filter was broad for telecommunication usage. The narrow bandwidth can be obtained by making a through hole underneath the GR grating area for suppressing the sidelobe reflectivity.

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