VARIABLE NANO-GRATING FOR TUNABLE FILTERS

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Abstract: This paper presented the design of subwavelength grating (i.e., nano-grating) for narrow-band and wide-band filter applications. The grating period can be tuned from 700 nm to 1140 nm by a rhombic-shaped thermal actuator array with a driving current of 2.7 mA, achieving a change of transmissivity by 13 dB due to the guided mode resonance. Wide-band of filtering can be obtained by use of another fixed-period grating to compensate the dispersion. Such grating design makes it practical to implement many tunable nano-optical devices.

Keywords: Microelectromechanical systems (MEMS), nano-optics, subwavelength grating, thermal actuator, tunable filter.

1. INTRODUCTION

The optical gratings has long been driven by the spectroscopic applications to go from large period to short period, and from fixed period to variable period as shown in Fig. 1. Compared with the conventional gratings whose period is much larger than the wavelength, subwavelength gratings have a period shorter than the wavelength, typically in the range of 100 nm – 1 μm (thus called nano-grating). The short period renders some special features such as form birefringence, local guided mode resonance between the grating lines and no diffraction light except for the 0th order [1, 2], making it attractive to many applications such as polarization switches, narrow-band filters, anti-reflection surface and broadband illumination [3-6].

However, most of the presented nano-gratings are fabricated on hard substrates and thus their periods are not tunable [3-6]. Some are fabricated by soft materials such PDMS [7] and elastomers [8], and the period can be changed slightly by mechanical strain or thermal expansion. However the tuning ratio is very limited. A recent work obtained remarkably 32% tuning ratio of grating period using soft electroactive polymer, but high voltage of 4.5 kV was used [9]. On the other hand, many MEMS tunable gratings have been developed, but the grating periods is larger than the wavelength (> 2λ) and the tuning ratio is only 0.2 – 2.5% [10-13]. These problems severely limit the applications of the gratings.

Based on these understanding, this paper aims at developing tunable nano-gratings using the MEMS actuators. The design and analysis will be presented in Section 2, followed by the experimental results in Section 3.

Fig. 1 Development of MEMS tunable grating as a result of pursuing short period and tunability.
2. DESIGN & ANALYSIS

2.1 Narrow-band tunable filter

The guided-mode resonance in the nanograting has been extensively studied for narrowband filters. Under certain condition, the incident light can be strongly coupled to the resonant mode inside the grating layer as illustrated in Fig. 1. The resonant condition can be expressed as \[ G = H + k_m \sin \alpha \]
(1)
where \( \alpha \) is the incident angle to the nano-grating, \( G \) is the grating vector, \( p \) is the grating period, \( H \) is the propagation constant in the grating layer, \( k_m = 2\pi/\lambda \) is the wavenumber, and \( \lambda \) is the wavelength. Eq. (1) provides a guideline for the choice of the parameters of wavelength, incident angle and grating period to reach the resonant. However, the actual power distribution can only be determined by the rigorous coupled wave analysis method [14].

The transmittance of the grating in response to the change of the grating period is plotted in Fig. 2 after normalization. With the gradual increase of grating period, the transmittance fluctuates in a high level (>0.8) before it suddenly drops to nearly 0. It then rises up to > 0.9, followed by a slow drop to low level. The sharp drop corresponds to the occurrence of the guided mode resonance inside the grating, and the narrow notch suggests a narrow filtering bandwidth. As a result, a narrow-band tunable filter can be obtained by varying the grating period. In the simulation, the parameters are the same with those of the experiment to be discussed later. The initial wavelength \( \lambda_0 = 1.55 \ \mu m \), the incident angle is 30 degrees. The grating has a period of 0.8 \( \mu m \) and a fill-factor of 0.57, the grating line is 3 \( \mu m \) high with a refractive index of 3.45.

2.2 Wide-band tunable filter

In many applications, it needs a wide pass-band (or stop-band), which the narrow-band filter cannot provide. According to the study above, the transmitted power is dependent on both the wavelength and the grating period. To obtain a wide band, the dependence on the wavelength must be alleviated while the guided mode resonance should also be unaffected. To solve this problem, another fixed-period grating is used to compensate the dispersion of the nano-grating as shown in Fig. 3. To avoid the confusion of the two gratings, the fixed-period grating is called compensator here.

The direct target of this design is, for a given incident angle \( \phi \), to have the diffraction angle \( \beta \) kept unchanged regardless of the incident wavelength. For a guided-mode-resonance filter, \( \beta \) should be 90 degrees. In this way, the resonant wavelength \( \lambda_n \) in the nano-grating for a given grating period \( p \) still corresponds to the resonant state and is actually filtered. However, other incident wavelength after passing through the compensator can also reach the resonant state since the wavelength difference is compensated. \( \lambda_n \) becomes the central filtering wavelength of the filter while the bandwidth of the filter is determined by the compensation effect. For a good compensation, the band can be very wide. By varying the nano-grating’s period, the central wavelength can be tuned while the bandwidth is kept almost unchanged. The compensation and tuning are the key ideas to obtain the wide-band tunable filter.

![Fig. 2 Simulated filtering property of transmission in response to the variation of grating period.](image)

![Fig. 3 Dispersion compensation scheme of the nano-grating using another fixed-period grating.](image)
The parameters are chosen to compensate the dispersion of both the nano-grating and the compensator. According to the general grating equation [12], the dispersion of the nano-grating is given by

\[ \frac{d\alpha}{d\lambda} = \frac{m}{p \cos \alpha} = \frac{1 + \sin \alpha}{\lambda \cos \alpha} \]  

(2)

while the compensator has the dispersion relation

\[ \frac{d\psi}{d\lambda} = \frac{m_1}{p_1 \cos \psi} = \frac{\sin \phi + \sin \psi}{\lambda \cos \psi} \]  

(3)

where \( \lambda \) is the wavelength, and \( m \) and \( p \) are the diffraction order and the grating period, respectively. \( \phi \) and \( \psi \) are the incident and diffracted angles in the compensator, and \( m_1 \) and \( p_1 \) are the diffraction order and period of the compensator.

Due to the geometrics \( \alpha = \theta_b + \psi \) (where \( \theta_b \) is the tilting angle of the compensator relative to the nano-grating), the compensation of dispersions requires \( d\alpha d\lambda = d\psi d\lambda \). As a result, it should satisfy

\[ \sin \phi = \frac{\cos \psi}{\cos \alpha} (1 + \sin \alpha) - \sin \psi \]  

(4)

Based on these equations, the parameters are \( m_1 = 1 \), \( p_1 = 1.79 \) \( \mu \)m, \( \phi = 21.45 \) degrees, \( \psi = 30 \) degrees, \( \theta_b = 0 \), \( \alpha = 30 \) degrees, and \( \beta = 30 \) degrees.

3. EXPERIMENTAL RESULTS

The nano-grating is fabricated by deep ion reactive etching on the silicon-on-insulator wafer, which has a 3-\( \mu \)m thick silicon layer sitting on a 1-\( \mu \)m oxide buffer layer on top of a silicon handling wafer. The overview of the nano-grating device and the close-up of the actuator array are shown in Fig. 4. To remove the oxide layer, wet release approach using diluted HF has to be employed since the structural layer is too thin to cause the notch effect for the dry release approach and it is also too fragile to use the backside open approach. The grating has 50 lines, each 400 nm

![Grating lines and Actuator arrays](a)

![Grating lines and Actuator arrays](b)

**Fig. 4** Scanning electron micrographs of the tunable nano-grating. (a) Overview, and (b) close-up of the actuator units.

![Displacement generated by a rhombic actuator unit in response to the driving current](c)

**Fig. 5** Displacement generated by a rhombic actuator unit in response to the driving current.

![Measured results of the grating reflectivities for \( \lambda = 1550 \) nm and 1620 nm in comparison to the simulation](d)

**Fig. 6** Measured results of the grating reflectivities for \( \lambda = 1550 \) nm and 1620 nm in comparison to the simulation.
wide and 60 µm long, separated by 300 nm. The initial grating period is 700 nm.

The grating lines are attached to a rhombic-shaped thermal actuator array developed recently [15] as shown in Fig. 4(b). By flowing the current through the side beams of each actuator unit, the thermal expansion of the beams push the grating lines apart uniformly. Fig. 5 shows the displacement relationship. The gratings do not move at low current (< 0.7 mA), then the displacement is increased linearly to 430 nm when the current rises to 2.7 mA. A tuning ratio of the grating period > 60% is obtained.

The transmissivity of the nano-grating is measured at 1550 nm and is compared with the simulation as shown in Fig. 6. The transmissivity varies with the grating period and reaches its minimum at $p = 780$ nm (about half of the designed wavelength 1550 nm). A difference of 13 dB is obtained. Therefore, a narrow-band filter is implemented. To test the wide-band filtering property, the compensator is employed. When the wavelength is changed to 1620 nm, the transmissivity curve is still close to the original one, demonstrating a wide-band filter.

5. CONCLUSIONS

This paper presents the design and experiment of tunable nano-grating for tunable filters. The deep-etched grating has an initial period of 700 nm and obtains a tuning ratio of > 60% in the grating period using a thermal actuator array. A dispersion compensation scheme is also presented to apply such grating to wide-band tunable filters.

REFERENCES