A Wide-Range Linearly Tunable Optical Filter Using Lorentz Force

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***Abstract*—In this letter, we have proposed and demonstrated, for the first time, the application of low-voltage magnetic actuation to a tunable optical filter to achieve a wide linear tuning range. We have fabricated and tested three different types of spring structures: straight, corrugated, and meander types to optimize the proposed magnetic actuation for high linearity and low power consumption. From the fabricated actuator, we have acquired a wide linear tuning range over 200 nm in wavelength, which is the widest ever reported to the best of our knowledge. The fabricated tunable filter has demonstrated a maximum static power consumption of less than 25 μW for wavelength tuning up to 200 nm with an external magnetic field of 0.28 T.**

***Index Terms*—Electromagnetic forces, microelectromechanical (MEMS) devices, optical communications, optical components, tunable filters.**

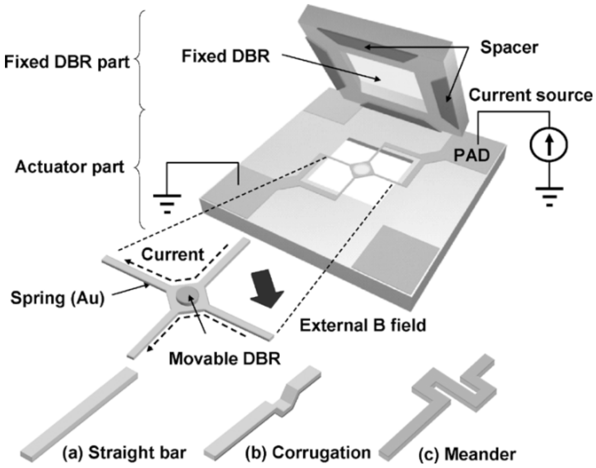

Fig. 1. Conceptual diagram of the proposed tunable optical filter using magnetic actuation and three types of springs tested for linear displacement: (a) straight bar; (b) corrugation; and (c) meander-type springs.

I. INTRODUCTION

RECENTLY, wavelength-division-multiplexing (WDM) networks have been widely deployed because of their high transmission capacity. In order to fully utilize the possible capacity given in a fiber, the number of wavelengths launched in a fiber has been continuously increased and this trend will continue in the coming years. With the invention of zero water-peak fiber like Corning's SMF-28e, the available bandwidth in a fiber for communication has reached over 400 nm, eliminating the blocking region near water-peak at 1400 nm in wavelength. It is anticipated that utilization of available bandwidth in a fiber will be accelerated in future optical communications. Consequently, it is required to develop optical components with a wide tuning range for emerging markets in high capacity WDM networks.

Recently, various microelectromechanical (MEMS) tunable optical filters have been reported [1]–[5]. Most of them have used electrostatic actuation [1]–[4], while a thermally tunable filter has been also reported [5]. Electrostatic actuation is adequate for low-power operation, but its tuning range is limited due to pull-in phenomenon and its actuation voltage is relatively high. Also, electrostatic actuation intrinsically has a nonlinear behavior. On the other hand, thermal actuation can achieve a wide tuning range but it consumes large power and its response time is slow.

In this letter, we propose a wide-range tunable optical filter using magnetic actuation for the first time. A simple magnetic actuator using Lorentz force has been designed and demonstrated without any complicated coils that have been employed in typical magnetic actuators. Because Lorentz force is bidirectional and relatively strong, we could achieve a wide tuning range with small power consumption using a strong external magnetic field. We could also achieve a high linearity by utilizing a Lorentz force which is linearly proportional to an applied current.

II. DESIGN AND FABRICATION

Fig. 1 illustrates the conceptual diagram of the proposed tunable filter. It consists of a Fabry–Pérot cavity with two dielectric distributed Bragg reflectors (DBRs) similar to other cavity-type MEMS tunable filters. One DBR is formed on the fixed DBR part and the other is located on the actuator part, as shown in Fig. 1. Two DBRs are separated by a spacer. However, in the figure, two parts are shown detached for visual comprehension. Since the actuator part consists of suspended conductor bridges, it receives Lorentz force directly by electrical current flowing through it in a magnetic field. Magnetic field is applied in plane with the actuator. Displacement of the actuated DBR changes a cavity length and so does a filtering wavelength. We have tested three different types of spring structures (straight, corrugated, and meander types) to optimize the actuator for high linearity and low power consumption, as shown in Fig. 1. Fig. 2 shows the cross-sectional view of the proposed filter structure.

Our initial target tuning range was 200 nm from 1400 to 1600 nm, the upper half of the required bandwidth for the coarse WDM (ITU-T G694.2) application. In this work, we target to achieve a resonant wavelength of 1600 nm at the initial actuator

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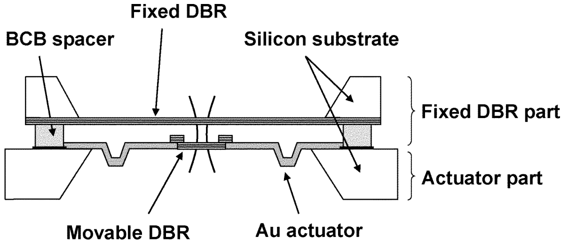


Fig. 2. Cross-sectional view of the proposed filter structure.

position. For 200-nm tuning range, we have determined a cavity length of 5.6 μm to use free spectral range between the seventh (1600 nm) and eighth mode (1400 nm). The required actuation range is 0.7 μm. If a mode number lower than seven is used, the cavity length as well as the required actuation range should be decreased accordingly. However, it is not desirable because full-width at half-maximum (FWHM) of the filter increases.

Fabrication processes are relatively simple. For the actuator part, corrugation pits of 10 μm in depth are defined by silicon anisotropic etching in KOH, first. Next, a gold film (1.3 μm) is sputtered and patterned by liftoff to form an actuator. Then, a DBR layer (2.5 μm) is deposited by plasma-enhanced chemical vapor deposition (PECVD) and patterned by reative ion etching. In order to demonstrate concept feasibility of magnetic actuation for wide range tuning, we have used simple 5.5 pairs of PECVD SiN_x–SiO_2 as a DBR. After that, the structure is released in KOH solution. For the fixed DBR part, DBR is deposited followed by spacer formation using BCB (Benzo–Cyclo–Butene). The thickness of the spacer is about 4 μm for 200-nm tuning range. The actual effective cavity length will be 5.6 μm as designed when penetration depth of DBR is included. Next, DBR membrane is released in KOH solution. Finally, the two processed wafers are bonded on a hot plate at 120 °C to form a cavity filter [6].

Fig. 3 shows the scanning electron microscope (SEM) photographs of the fabricated actuators with various spring types. Spring dimensions are indicated in the figure. The deposited DBRs and gold films have a minor tensile stress about 80 MPa, allowing the whole structures to stay flat, as shown in Fig. 3. The photograph of a completed tunable filter is shown in Fig. 3(f).

III. Measurement and Discussion

The static and dynamic behaviors of the fabricated actuator have been measured with Polytec's Laser Doppler Vibrometer. The magnetic field of 0.28 T was applied to the actuator using permanent magnets. Fig. 4 shows the measured mechanical displacement of the fabricated actuators. Actuators with corrugation and meander-type springs can be actuated linearly, while the one with straight bar springs shows poor linearity, as shown in Fig. 4. This comes from thermal expansion of the springs due to Joule-heating. Both structures with meander and corrugation springs have enough actuation range (>0.7 μm) to meet the requirement imposed for linear wide-tuning range over 200 nm. Over 3-μm linear displacement has been measured with meander-type springs, which is four times larger than target value. The tuning speed has been measured as 3 ms from transient response.

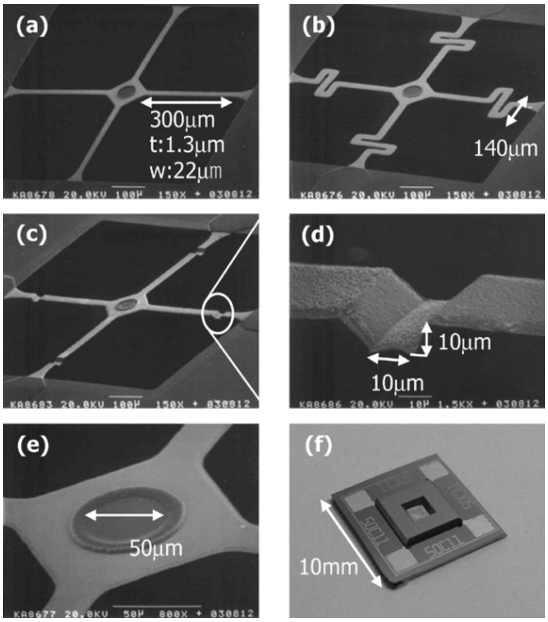


Fig. 3. SEM photographs of the fabricated actuators with (a) straight bar-type springs, (b) meander-type springs, and (c) corrugation-type springs; magnified SEM photographs of (d) corrugation pits and (e) a DBR membrane; and (f) optical photograph of the completed tunable filter after bonding.

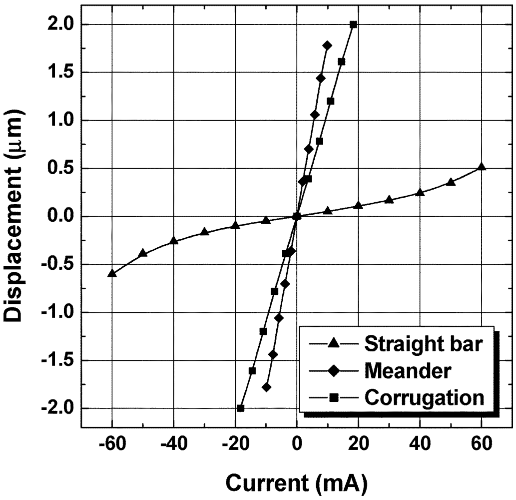
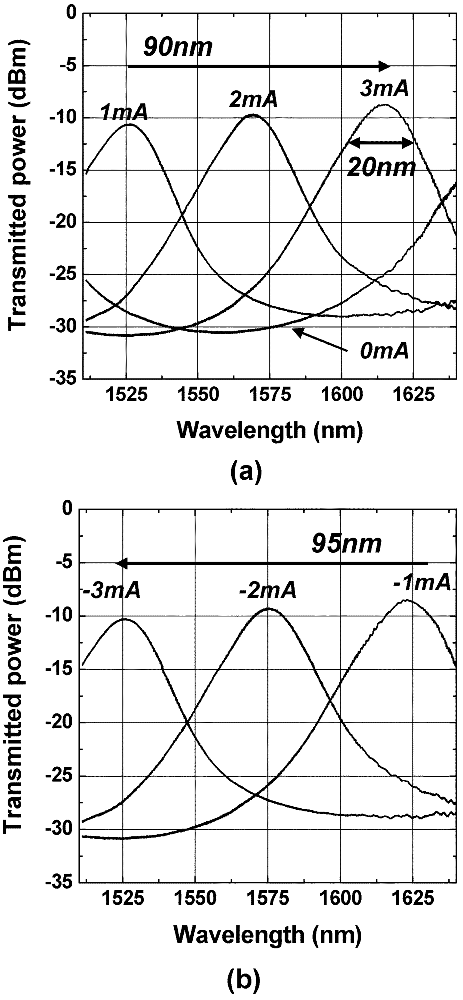


Fig. 4. Mechanical displacement of the fabricated tunable filter with three types of different springs.

Optical spectrum of the fabricated tunable filter has been measured in free space by a measurement setup with four lenses, a tunable laser source, and a detector module. Light from a tunable laser source is guided by an optical fiber and focused to the fabricated tunable filter by two objectives. The transmitted light is focused and coupled into an optical fiber and the guided light is detected by a power meter. The focused beam size was about 12 μm in diameter. Fig. 5 shows the tuning response of the fabricated filter with meander-type springs. Unfortunately, the tuning range of tunable laser source does not cover the whole tuning range; therefore, we have carried out the tuning measurement using two adjacent peaks. In Fig. 5(a), a higher mode peak was shifted by 45 nm/mA toward higher wavelength direction by increasing the current in the magnetic actuator. In Fig. 5(b), a lower mode peak was shifted by the same amount toward lower wavelength direction with negative current. Fig. 6 shows the theoretical and measured wavelength



(a)

(b)

Fig. 5. Measured bidirectional tuning response of the fabricated tunable filter with meander-type springs.

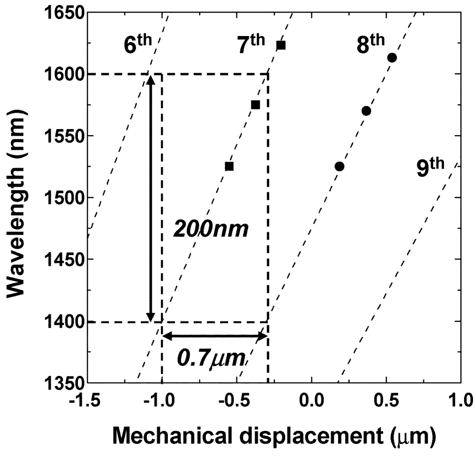


Fig. 6. Relationship between wavelength of several mode peaks and mechanical displacement of the fabricated tunable filter. (Dashed lines and dots represent calculation and measurement results, respectively.)

TABLE I

SUMMARY OF MEASURED PARAMETERS OF THE FABRICATED TUNABLE OPTICAL FILTER WITH MEANDER-TYPE SPRINGS

Cavity length (μm)	5.8
Max. reflectance	0.9
FSR (nm)	200
FWHM (nm)	20
Tuning range (nm)	> 200
Max. power consumption (μW)	< 24.3
Tuning speed (msec)	3

for several mode peaks as a function of mechanical displacement of the fabricated filter. As shown in the figure, the seventh mode can be tuned from 1600 to 1400 nm with the actuation from -0.3 to -1.0 μm. Since the measured actuation range is over ± 1.5 μm, as shown in Fig. 4, it is easily inferred that the fabricated filter can be bidirectionally and linearly tuned about 200 nm, which is the widest ever reported to the best of our knowledge. The maximum power consumption has been estimated as 24.3 μW. The effective cavity length has been estimated as 5.9 μm including DBR penetration depth and the measured FWHM is about 20 nm. This can be further improved by using other DBRs with higher reflectance. Measured filter characteristics are summarized in Table I.

IV. CONCLUSION

In this letter, we have proposed and demonstrated a wide range linearly tunable optical filter using magnetic actuation for the first time. A simple magnetic actuator using Lorentz force has been fabricated and successfully applied to a wide-range tunable optical filter. We have achieved more than 200-nm linear tuning range bidirectionally at low power consumption of less than 25 μW. The tuning efficiency is over 45 nm/mA and the measured FWHM is about 20 nm. The proposed tunable optical filter has successfully demonstrated its feasibility for wide linear tunability which will play an important role in the future WDM networks.

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