ABSTRACT

This paper presents a Nano-opto-mechanical actuator, which is driven by optical radiation force. The actuator consists of two waveguides, two identical ring resonators, and an actuator with Bragg reflector. Light is injected into the waveguides and coupled to the Bragg reflector via the ring resonator. The actuator is displaced by the optical force. The achieved maximum displacement of the actuator is 500.2 nm with the optical power up to 200 mW. The optical actuator has merits of high resolution (2.501 nm/mW), approximately perfect linear displacement and contact-free optical drive, which results in potential applications such as precise distance control, tunable laser, and weak force detection.

KEYWORDS

Nano-opto-mechanical Systems (NOMS), optical force, actuators

INTRODUCTION

With the recent development of nano-sized deep reactive ion etching and micromachining technologies, Nano-opto-mechanical systems (NOMS) presents the potential for various highly sensitive sensor applications. Compared with conventional optical MEMS, NOMS has many advantages such as nano-sized, higher sensitivity, and higher resolution in trapping and controlling polarized microparticles [1 – 3].

Most traditional actuators are driven by electrostatic actuators such as comb drive [4 – 6], or piezoelectricity [7 – 10] and thermal expansion [11]. However, these driven sources cause the conventional actuators with large size, high power consuming, and slow start-up speed. To overcome these drawbacks, it is possible to employ optical-driven actuation with the development of the nano-sensor and nano-actuator. Optical force plays an important role in the NOMS, especially after the discovery of attractive and repulsive optical force [12]. The structures of zipper [13], disk [14], and narrow waveguides [15] allow the application of optical force in optical-mechanical actuation and transduction.

In this paper, an optical force driven actuator in NOMS is presented. It combines the ring resonator with the Bragg reflector configuration. The optical force moves the Bragg reflector forward due to the reflection of photons. The optical force generated in the Bragg reflector is theoretically analyzed. Subsequently, the designed actuator is fabricated and experimented to investigate its stability and resolution.

DESIGN AND THEORETICAL ANALYSIS

Figure 1(a) shows the structure of the actuator, which consists of two waveguides, two identical ring resonators, four suspended folded-beams and an actuator with Bragg reflector. The input light is coupled through the waveguides to the central actuator with the Bragg reflector via the two ring resonators. The free-standing actuator is suspended by four folded-beams and can be pushed forward via the radiation force introduced by the ring resonators. The Bragg reflector reflects the light coupled from the ring resonators, and thus enlarges the momentum exchange between the photons and the actuator. Fig. 1(b) is the zoomed view of the Bragg reflector.
When the wavelength of the input light coincides with the resonant wavelength of the two ring resonators, most of the light is transferred to the port 1 and reflected to port 2 and rings as shown in Fig. 2(a). Fig. 2(a) shows the electric field distribution of the actuator.

The coupling coefficient ($\kappa$) between a straight waveguide and a ring with radius $R$ is expressed as [16]

$$\kappa = \frac{\alpha \varepsilon_0 \cos(k_{\text{w1}} - 2\pi R)}{2\sqrt{P_e P_w (\alpha_{\text{w1}}^2 + \alpha_w^2)}} \left[ \frac{\alpha_w}{\alpha_{\text{w1}}} \exp\left[\alpha_{\text{w1}}(w_2 - 2s_0)\right] \right]$$

$$\times \left[ \alpha_w \cos(k_{\text{w1}} \alpha_{\text{w1}}) \sinh(\alpha_{\text{w1}} \alpha_{\text{w2}}) \right]$$

$$+ k_{\text{w1}} \sin(k_{\text{w1}} \alpha_{\text{w1}}) \cosh(\alpha_{\text{w1}} \alpha_{\text{w2}})$$

where $\alpha$ is the circular frequency and $\varepsilon_0$ is the permittivity of free space. $k_{\text{w1}} = \sqrt{n_{\text{w1}}^2 k^2 - \beta_i^2}$ are the transverse propagation constants in the core of the straight waveguide ($i = w$) and the ring ($i = r$), respectively. $\beta$ is the propagation constant.

The widths of waveguide and ring are $w_{\text{w1}}$ and $w_r$, respectively. Their refractive indices are $n_{\text{w1}}$ and $n_r$. The surrounding cladding of index is $n_0$ (Fig. 2(b)).

$$P_i = \frac{\beta_i}{2\omega \varepsilon_0} \left( w_1 + 1 \alpha_i \right)$$

is the mode power and

$$\alpha_w = \sqrt{\beta_w^2 - n_0^2 k^2}$$

is the decay constant in the cladding of the straight waveguide. $2s_0$ is the smallest separation between the waveguides.

Due to the existence of the Bragg grating, the light is reflected to port 2 and the rings. The electric field distribution is proportional to the density of the photons. The density of the photons reaches its maximum near the edge of the Bragg reflector (mirror) within the actuator, which means most of the momentum exchange between the photons and the actuators occurs within this region. The electric field distribution of the Bragg reflector is shown in Fig. 2(c). The intensity of the electric field decreasing from the port 2 to port 1, which is the result of the reflection of Bragg reflector.

Based on the Maxwell stress tensor equation, the optical force $F_{\text{Optical}}$ in the direction along the actuator path is expressed as

$$F = \int_C \left( \frac{\varepsilon_0}{2} \left( E \cdot \hat{n} \right) \left( \nabla \times E \right) \cdot \hat{t} - \frac{\mu_0}{2} \left( B \cdot \hat{n} \right) \left( \nabla \times B \right) \cdot \hat{t} \right) dl$$

(2)

where $E$ is the electric field, $H$ is the magnetic field, $\hat{n}$ is the outward normal vector, and $C$ is the contour path along the surface of the actuator. Eq. (2) can be simplified as

$$F = \int_C \left( \frac{\varepsilon_0}{2} \left( E_i \cdot \hat{n} \right) \left( \nabla \times E_i \right) \cdot \hat{t} + \frac{\mu_0}{2} \left( B_i \cdot \hat{n} \right) \left( \nabla \times B_i \right) \cdot \hat{t} \right) dl$$

(3)

where $E_i$ and $H_i$ are the electric field and magnetic field along the $i$ ($i = x, y, z$) direction, $\delta_{ij}$ is Kronecker’s delta. The power $P$ is given by

$$P = \int_C \frac{1}{\varepsilon_0} \text{Re} \left( E \cdot H^* \right) dl$$

(4)

Therefore, the optical force is proportional to the square of electric and magnetic field’s amplitude, which are proportional to the input power. Fig. 3 illustrates the optical force change due to the input power. The optical force increases from 0 nN to 60.4 nN, when the input power changes from 0 mW to 200 mW. The optical force is linearly proportional to the input power with the rate of 0.302 nN/mW.

The total displacement of the actuator is calculated by the Finite Element Method. The displacement ($X$) of the
Bragg reflector actuated by the optical force \( (F_{\text{optical}}) \) is given as \[ F_{\text{optical}} = K_{\text{sys}} X \] \[ (5) \]

where \( K_{\text{sys}} \) is the effective spring constant of the folded-beam, and is expressed as \[ K_{\text{sys}} = 4Eh\left(\frac{b}{L}\right)^3 \] \[ (6) \]

where \( E \) is the Young’s modulus, \( b, L, h \) are the width, the length and the thickness of each folded-beam, respectively. Fig. 4 shows the FEM simulation of the actuator displacement for \( P = 200 \) mW, and \( E = 168.5 \) GPa. In this design, the refractive index \( n_{\text{Si}} \) is 3.493, \( b = 0.45 \) µm, \( h = 0.22 \) µm, and \( L = 30 \) µm. Based on the simulation results, the maximum displacement is 500.2 nm when the input power is 200 mW.

**FABRICATION AND EXPERIMENTS**

Figure 5(a) shows the SEM of the actuator (before release process), which is fabricated on a silicon-on-insulator wafer with the footprint of 3 mm × 2.8 mm. Fig. 5(b) shows the gap between the waveguide and the ring resonator. The gaps between the actuator and the ring resonator are 200 nm. The width and thickness of the ring resonators and the waveguide part of the actuator are 450 nm and 220 nm, respectively. The top layer is a hard mask.

Figure 6 shows the experimental results (black square) and the simulation result (black line) of the actuator displacement with different input optical powers. The optical force is modulated by the power of the input light. The displacement is measured by another waveguide, which is coupled with the left port of the actuator. The displacement of the actuator is linearly proportional to the input optical power and the resolution of the actuator is
measured as 2.501 nm/mW. The displacement range is from 0 nm to 500.2 nm when the input power is from 0 mW to 200 mw.

CONCLUSIONS
A NOMS actuator driven by optical force has been designed, fabricated and tested. The actuator consists of two waveguides, two identical ring resonators, and an actuator with Bragg reflector. Light is injected into the waveguides and coupled to the Bragg reflector via the ring resonator. The actuator is displaced by the optical force. The optical force actuator shows high resolution (2.501 nm/mW) and linear displacement to the input optical power, which leads to its potential applications on precise distance control, small mass measurement and contact free actuator.

REFERENCES

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