Analysis of a Novel MOEM Race Track Resontor based Vibration Sensor

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ABSTRACT

In this paper we analyze a novel Micro Opto Electro Mechanical Systems (MOEMS) race track resonator based vibration sensor. In this vibration sensor the straight portion of a race track resonator is located at the foot of the cantilever beam with proof mass. As the beam deflects due to vibration, stress induced refractive change in the waveguide located over the beam lead to the wavelength shift providing the measure of vibration. A wavelength shift of 3.19 pm/g in the range of 280 g for a cantilever beam of $1750\mu m \times 450m \times 20\mu m$ has been obtained. The maximum acceleration (breakdown) for these dimensions is 2900g when a safety factor of 2 is taken into account. Since the wavelength of operation is around 1.55μm hybrid integration of source and detector is possible on the same substrate. Also it is less amenable to noise as wavelength shift provides the sensor signal. This type of sensors can be used for aerospace application and other harsh environments with suitable design.

Keywords: MOEMS, vibration sensor, race track resonator

1. INTRODUCTION

MOEM devices and systems based on the principles of integrated optics and micromachining technology on silicon have immense potential for sensor applications.[1] Integrated optical sensors when linked by optical fibers can provide ready isolation from high voltages and can provide a high degree of immunity to EMI (Electromagnetic Interference). It has been reported that[2]in a two port ring resonator when the group velocity (v_g) is slow ($v_g << c$), there is enhancement of sensitivity of optical properties to the effective index changes in the ring. Which shows the ring resonator has potential for sensing application.

Most of the MOEM vibration sensors utilize the optical power transfer between the waveguide on the cantilever beam to the waveguide on the substrate due to vibrating force. Since the waveguide core sizes are small, the power variation is small. Hence the dynamic range is small. Intensity based sensors are more amenable to noise.

In this paper we propose and analyze a vibration sensor, which consists of cantilever beam attached to the straight portion of a race track resonator.

2. THEORY OF OPERATION

A ring resonator is simply a waveguide shaped into a ring structure as shown in Fig 1a and Fig.1.b.When an input electric field, E_i, is coupled to the ring waveguide through an external bus waveguide, a positive feedback is induced and the field inside the ring resonator, E_r, starts to build up. Coupling between the straight and the ring waveguide is achieved through the evanescent wave. Therefore, the gap and coupling length between them determine how much power is coupled from the straight waveguide to the ring waveguide and vise versa. The feedback mechanism is simply induced by the ring waveguide and therefore there is no need for any Bragg gratings, mirrors, or distributed feedback waveguides which are more difficult to fabricate. In such configuration, only certain wavelengths will be allowed to resonate inside the ring waveguide, thus frequency selectivity is obtained. A resonant mode will have a wavelength that satisfies

$$m\lambda_m = nL \tag{1}$$

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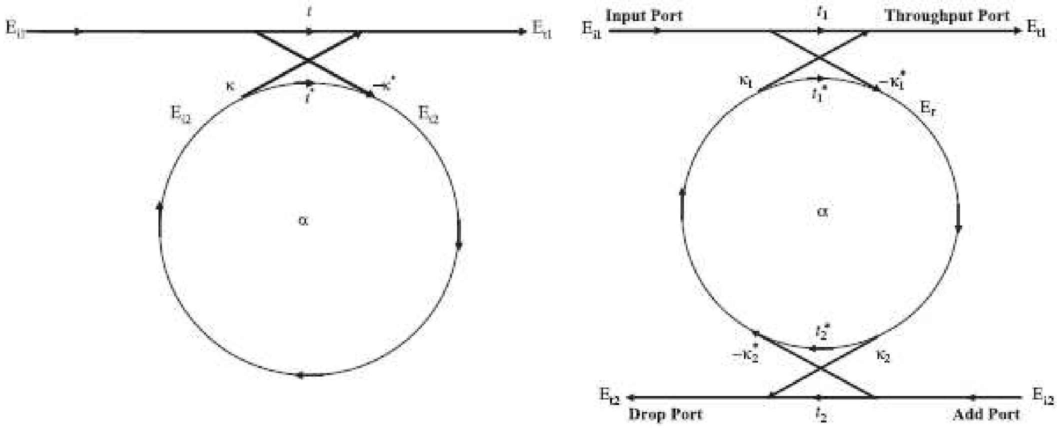

Fig.1.a Fig.1.b

Figure 1. Single Port and Two-port Ring Resonator

Here, the integer, m is the longitudinal mode number, $m\lambda_m$ is the resonant mode wavelength, n is the refractive index of the guiding material, and L is the circumference of the ring resonator. A race track resonators working principle is same as ring resonator except the change in geometry. For a vibration sensor since the length dimension is longer than the width in the mechanical structure (cantilever beam) of the vibration sensor, it is difficult to use the ring resonator. But race track resonator can effectively be used in this case.

3. OPTICAL MEMS VIBRATION SENSOR

As the cantilever beam deflects due to vibration, the stress induced refractive index change produces phase change in the waveguide located over the foot of the beam and hence the vibration is readout as resonant wavelength shift of the racetrack resonator. The design of the sensor involves the mechanical design of cantilever beam, racetrack resonator and opto-mechanical coupling for the sensor readout as wavelength shift.

3.1 Racetrack Resonator

The straight portion of the racetrack resonator is taken to be the width (b) of the cantilever beam as shown in Fig. 2.

The length of the curved path, for which the line joining the arc is same as width of the beam, is given by

$$L = 2r\sin^{-1}(\frac{b}{2r}) \tag{2}$$

where r is the radius of curvature of the arc. The arc and the straight waveguide are assumed to have continuity without sharp bends.

The total optical path length of the resonator is

$$L\text{op} = 2n_{\text{eff}}\{b + 2r\sin^{-1}\frac{b}{2r}\} \tag{3}$$

The FSR of this resonator is given by c/Lop. The resonance characteristic is determined by the total optical length dictated by the b, r and effective refractive index of the waveguide. The curved portion is taken as part of the circle of 1mm radius (since oxynitride waveguide can have at best 1mm bend radius without much loss[3]) with angle 0.454 rad such that the straight line joining the arc is 450 μm (the cantilever beam width). The FSR of this resonator is 111.5 GHz (893 pm).

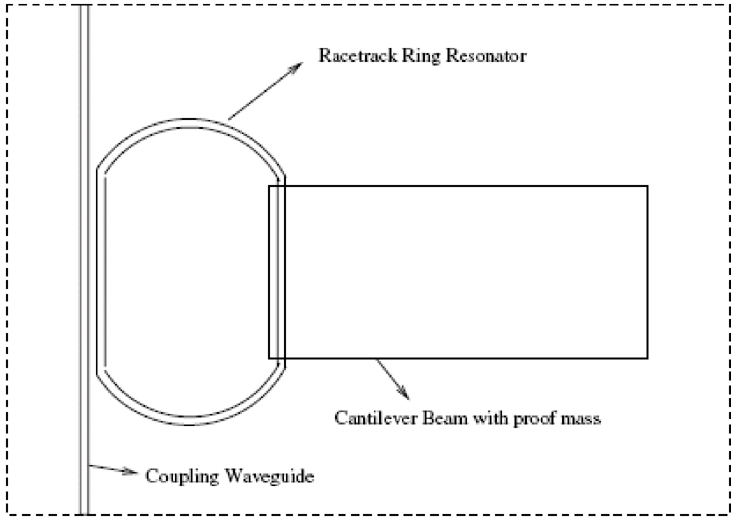

Figure 2. Schematic of the MOEMS vibration sensor with race track resonator

3.2 Mechanical Design and Opto-mechanical Coupling

The mechanical element in vibration sensor is a cantilever beam with length l_1 and a proof mass of sides l2 with thickness tw (wafer thickness). This can be modeled as a cantilever beam of length ($l = l_1 + l_2/2$) with proof mass m attached at the center of l_2 (valid for $l_2 \geq 10l_1$)[4] satisfying

$$m\frac{d^2\omega}{dt^2} + c\frac{d\omega}{dt} + k\omega = q \tag{4}$$

with spring constant $k = 3EI_1/l^3$ where $I_1 = bh^3/12$ is the moment of inertia of the beam. The fundamental frequency is given by

$$f = \frac{1}{2\pi}\sqrt{\frac{3EI_1}{m(l_1 + l_2/2)^3}} \tag{5}$$

The damping coefficient c and the fundamental frequency dictate the mechanical dimensions of the beam. Normalized damping coefficient ($\xi = c/2m\omega$) is adjusted to 0.7 to get maximum linearity. For $l_1 = 250\mu m, l_2 = 3000\mu m, b = 450\mu m, h = 20\mu m$, fundamental frequency is 410Hz and the required gap for $\xi = 0.7$ is $33\mu m$. The bending stress (in units of g) at the foot of the cantilever and on the top surface is now given by

$$\sigma_{yy} = \frac{mg(l_1 + l_2)/2}{6bh^2} \tag{6}$$

For beam with $l_2 = 3000\mu m$, the stress is 2.46 MPa/g. Since the fracture stress of the material (silicon) is 7GPa, maximum acceleration (breakdown) for these dimensions is 2900 g when a safety factor of 2 is taken into account. The change in refractive index of the waveguide located at the foot of the beam is given as earlier $\Delta n = C\sigma_{yy}$. Since the index change is uniform over the waveguide as the stress is constant across the width, the phase change in the waveguide in terms of beam parameters (in units of g) is given by $\Delta\phi = k_\phi g$, where

$$k_\phi = \frac{2\pi}{\lambda}\frac{\Delta n}{n_{eff}}C\frac{6m(l_1 + l_2/2)}{h_1^2} \tag{7}$$

Phase change is more for longer and thinner beam. For $l_2 = 3000\mu m$ and $h_1 = 20\mu m$, phase change is 22.4 mrad/g. The photoelastic tensor $C = 4.42 \times 10^{-12}$/Pa.

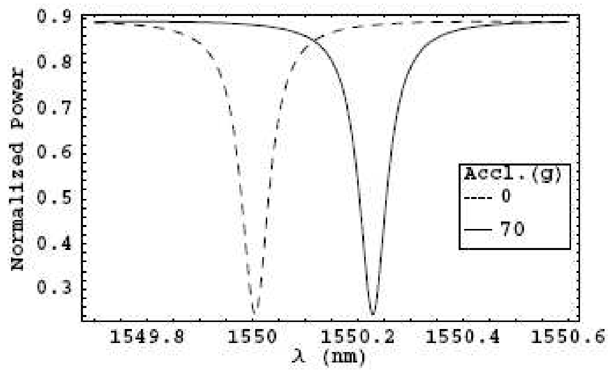

Figure 3. Wavelength shift with and without applied acceleration of 70g for optical MEMS vibration sensor

3.3 Sensor Readout

As in pressure sensor case, the phase change produces wavelength shift is $\Delta\lambda_{\text{shift}} = \Delta\lambda_{\text{FSR}}\Delta\phi(g)/(2\pi)$, where $\Delta\lambda_{\text{FSR}}$ is the FSR in terms of wavelength. The vibration amplitude in units of g is readout as this wavelength shift. For the chosen dimensions, wavelength shift of 3.19 pm/g occurs. Fig. 3 shows the wavelength shift for 70g vibration amplitude with respect to the original resonating wavelength. Since the FSR is 893 pm, upto 280g vibration amplitude with 410 Hz vibration frequency can be measured.

4. CONCLUSION

We have proposed and analyzed a novel MOEM vibration sensor with optical read out. A cantilever beam of length 250μm and width 450μm with a seismic mass is placed over the straight waveguide of a race track resonator. The FSR of resonator is 111.5GHz (893 pm) and the corresponding phase change is 22.5mrad/g. The dynamic range of race track resonator is doubled as compared to the Mach Zehnder Interferometer(MZI). MOEMS sensor of this kind provide better sensitivity as frequency measurements are made instead of intensity measurements.

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