Study of a novel pressure sensor based on optical microring resonator*

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We propose a novel pressure sensor based on the combination of the ring resonator with two straight waveguides and a two-end fixed beam. The principle of this device is acquiring the system static pressure by monitoring the changes in the transmission wavelength shift of the ring resonator with double waveguides. The numerical results show that the sensitivity of the system is up to 49.3 pm/kPa while the pressure range is 0—300 kPa. The thickness of the fixed beam is an important factor which impacts the sensitivity of the system. This device can provide support for fabricating high sensitivity and low cost micro pressure sensors.

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In recent years, pressure measurements have considerable applications in aviation, automobile, industrial automation, human health monitoring and so on. Compared with the conventional electronic pressure sensors, the optical pressure sensors[1-3] have a series of advantages, such as good stability, immunity to electromagnetic interference, compactness and easy to integrate. At present, the optical pressure sensors contain fiber pressure sensor[4] and fiber Bragg grating pressure sensor[5]. In general, the fiber pressure sensor needs to combine with an M-Z interferometer by monitoring the shift of the interference fringe to get the pressure. But the volume of this kind of fiber pressure sensor is too huge, and the reference arm is easily disturbed by the environment. To improve the sensitivity of fiber pressure sensors, scholars presented the fiber Bragg grating of F-P interferometer to measure pressure[6,7]. Liaohe oil field in China has already used the system combined with F-P interferometer for site testing[8].

Currently, the theory and application researches of large volume optical pressure sensors have become systematic. These years, the investigations of micro/nano-level pressure sensors have attracted much attention. Among the usual optical devices, the microring resonators have the properties of flexible design and integration. They can also be applied in the fields of biochemical sensing, temperature sensing, acceleration sensing and so on[9-11]. The American professor BipinBhola[12,13] has studied pressure sensing and accelerating sensing by using the polymer microring resonator, respectively. The measured sensitivity of the acceleration sensor is 31 pm/g. The Turkish professor Isa Kiyat[14] proposed and analyzed a novel displacement sensor based on race-track microring resonator. Wuyu[15] firstly fabricated a novel accelerometer by fixing the fiber micro-loop resonator on the cantilever beam. Moreover, this double cantilevers beam structure could improve the sensitivity of the system.

This paper presents a novel pressure sensor by combining a fixed beam and a double-channel microring resonator. The microring resonator serves as the sensitive element, and the sensing properties of the fixed beam pressure sensor based on microring resonator by spectrum shift measurement are analyzed. We obtain the transmission spectra at different pressures through the numerical simulations. And we study how the different structure parameters affect the system sensitivity. The research results will provide an effective way for fabricating high sensitivity integrated pressure sensors.

Fig.1 shows the schematic diagram of the two-end fixed beam. The structure characteristics based on a fixed beam and two-straight-waveguide-coupled single microring are put forward. We carry out the theoretical derivation of the sensing principle of the novel pressure sensor. If the fixed beam is under pressure, the shape of the fixed beam will be distorted.

The stress on the fixed beam can be expressed as[16]:

$$\delta(x)=\frac{3FL_1}{Ebh^2}(\frac{2x}{L_1}-1)\,, \tag{1}$$

where x is the distance of the fixed beam with respect to

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the end of the fixed beam, L_1 is the distance of the mass with respect to the end of the fixed beam, F is the static pressure, and b and h are the width and thickness of the fixed beam, respectively. The fixed beam has the greatest strain when $x= L_1/2$:

$$\varepsilon=\frac{3FL_1}{Ebh^2}\ . \tag{2}$$

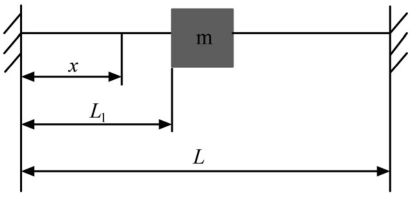


Fig.1 Structure of the two-end fixed beam

When the light wave satisfies the resonant condition, the resonance occurs in the microring resonator as shown in Fig.2(b). The resonant wavelength of the microring resonator is:

$$\lambda=\frac{n_{\mathrm{eff}}L}{N}\ , \tag{3}$$

where λ, L and n_{eff} represent the resonant wavelength, perimeter and effective refractive index of the microring resonator, respectively. N is an arbitrary integer (N=1, 2, 3···).

If an external pressure is added on the fixed beam, the perimeter of the ring will be changed. And due to the elasto-optical effect, the effective refractive index of the microring resonator is also changed[17]:

$$\frac{\Delta\lambda}{\lambda}=\frac{\Delta L_{\mathrm{m}}}{L_{\mathrm{m}}}+\frac{\Delta n_{\mathrm{eff}}}{n_{\mathrm{eff}}}\ , \tag{4}$$

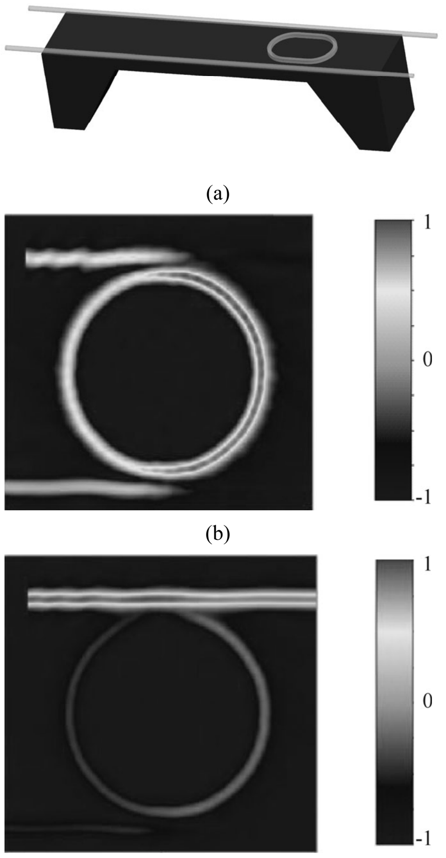
where $\Delta\lambda$, ΔL_{m} and Δn_{eff} represent the variations of resonant wavelength, perimeter and effective refractive index of the microring resonator, respectively. The relationships between variations of the perimeter and the effective refractive index of the microring resonator and the strain added on the fixed beam are:

$$\frac{\Delta L}{L}=\frac{\varepsilon(1-v)}{2}\ , \tag{5}$$

$$\frac{\Delta n}{n}=\frac{-n_{\mathrm{eff}}\times\varepsilon}{2}(p_{11}-2\times v\times p_{12})\ , \tag{6}$$

where v is the Poisson ratio of the fixed beam, and p_{11} and p_{12} are the elasto-elastic coefficients.

In this paper, we present a pressure sensor model which is combined with the mechanical fixed beam and two-straight-waveguide-coupled single microring (Fig.2(a)). Because of the distortion of the fixed beam and the elasto-optical effect, the resonant mode of the resonator will be changed. Then the transmission properties of the microring resonator will be changed, so we can measure the pressure by monitoring the shift of the output transmission wavelength of the microring resonator. Fig.2(b) and (c) show the optical field distributions without and with the pressure added on the fixed beam by finite difference time domain (FDTD) method[18], respectively. The microring resonator with double waveguides has two outputs which are used to test whether the sensor works normally or not, so that the sensitivity of the sensor can be improved.



(a)

(b)

(c)

Fig.2 (a) Structure of the pressure sensor; (b) Field distribution of the ring resonator on the fixed beam without pressure; (c) Field distribution of the ring resonator on the fixed beam with pressure

Based on the theory analysis mentioned above, we complete the simulation of this pressure sensor by using MATLAB. The major system parameters are as follows: the wavelength ranges from 1528 nm to 1544 nm, the diameter of the microring resonator is 20 μm, the length, width and thickness of the fixed beam are 1.2 cm, 100 μm and 30 μm, respectively, the index is 3.45, p_{11} is 0.137, p_{12} is 0.302, the material of the fixed beam is monocrystal silicon, v is 0.278, and E is 1.9×10^9. Fig.3 shows the transmission spectra of the pressure sensor while the pressure is 0−300 kPa. We find that the shape of the transmission curve and the 3-dB bandwidth are not changed, and only the resonant wavelength shifts to the right. Fig.4 shows the resonant wavelength as a function of the pressure, which is a basically linear relationship. The system sensitivity is about 47.9 pm/kPa when the pressure is 0—300 kPa, which is obtained by regression, and the relation between the resonant wavelength and pressure can be described as follows:

$$\lambda = 4.79\times10^{-5}P+1.529 \quad . \tag{7}$$

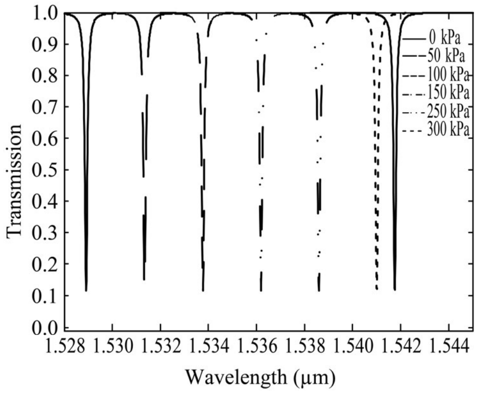


Fig.3 Transmission spectra of the pressure sensor at different pressures

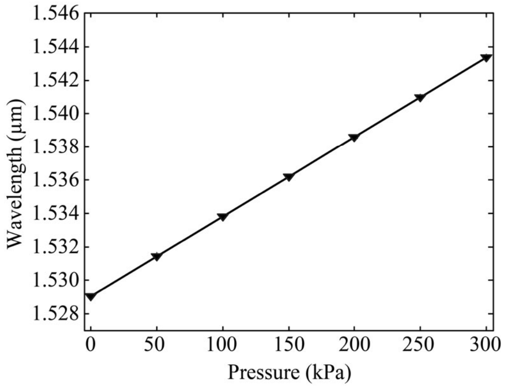


Fig.4 Relationship between resonant wavelength and pressure

It is noted that the structure parameters of the fixed beam affect the main properties of the pressure sensor. Fig.5 gives the relation between the resonant wavelength and pressure with different thicknesses of the fixed beam.

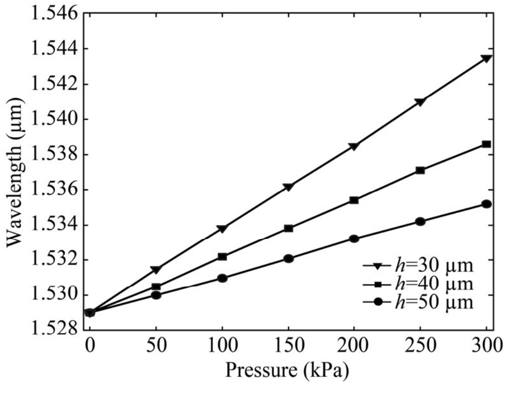


Fig.5 Relationship between resonant wavelength and pressure with different thicknesses of the fixed beam

The system sensitivity can be up to 47.9 pm/kPa, 32.3 pm/kPa and 20.8 pm/kPa as the length of the fixed beam is 1.2 cm, width of the fixed beam is 100 μm and the thicknesses of the fixed beam are 30 μm, 40 μm and 50 μm, respectively. Hence, the thickness of the fixed beam is an important factor which affects the system sensitivity. The relatively thin fixed beam is good for system sensitivity when the fixed beam satisfies the strain limitation.

In this paper, we propose a novel optical pressure sensor based on the combination of the ring resonator with double waveguides and a two-end fixed beam. The double outputs of the microring resonator can be measured to test whether the sensor works normally, and improve the system sensitivity. We can obtain the pressure by monitoring output transmission spectrum of the system, and the sensitivity of the sensor can reach 47.7 pm/kPa. The results of numerical analysis show that the relatively thin fixed beam can enhance the system sensitivity when the fixed beam satisfies the strain limitation.

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