A MZI Based Integrated Optical Accelerometer

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Abstract— We demonstrate an optical accelerometer based on geometrically asymmetric Mach-Zehnder interferometer which is proposed to be fabricated on a flexible substrate. The asymmetric MZI based device made by polymer waveguides and substrate to realize the elastic property with a double arms cantilever beam. The relation between the structure parameters and the sensitivity are analyzed. A prototype is fabricated and a detecting experiment scheme designed for this flexible optical accelerometer is proposed. Due to simplicity of the structure, the sensor is suitable for mass production.

1. INTRODUCTION

Accelerometers are the important inertial measurement devices which are widely adopted in guidance system, automation control system, vibration sensing, and impact detection. Various physical principles such as, capacitive [1], piezoelectric [2], piezoresistive [3], magneto-resistive, and optical effects [4, 6], have been utilized to design different types of accelerometers so far. Compared with accelerometers based on electromagnetic principles, the ones utilizing optical effects show several significant advantages. For example, they are immune to electromagnetic interference, electrically insulated, more sensitive, corrosion-resistant, and reliable in inflammable or explosive conditions. Conventional optical accelerometers realized by using fibers or other separated optical components as signal carrier units are of large size [7]. With the development of integrated optical technique, researches of accelerometers based on MOEMS (Micro-Opto-Electro-Mechanical-Systems) have attracted a lot of attention in past few years, as they have lower manufacturing cost, higher integration, lighter weight, and smaller size.

In this paper, we demonstrate an optical accelerometer based on geometrically asymmetric Mach-Zehnder interferometer which is proposed to be fabricated on a flexible substrate as shown in Fig. 1. The asymmetric MZI based device made by polymer waveguides and substrate to realize the elastic property with a double arms cantilever beam. When the acceleration to be measured exerts a force on the flexible beam, the long arm waveguide of the MZI experiences a strain which causes optic transmission phase to change due to strain-optic effect and the physical elongation of the waveguide. The device meters the acceleration through measuring the interference optic intensity of the light beams in the two arms. The relation between the structure parameters and the sensitivity are analyzed. We have fabricated a prototype utilizing a flexible substrate fabrication

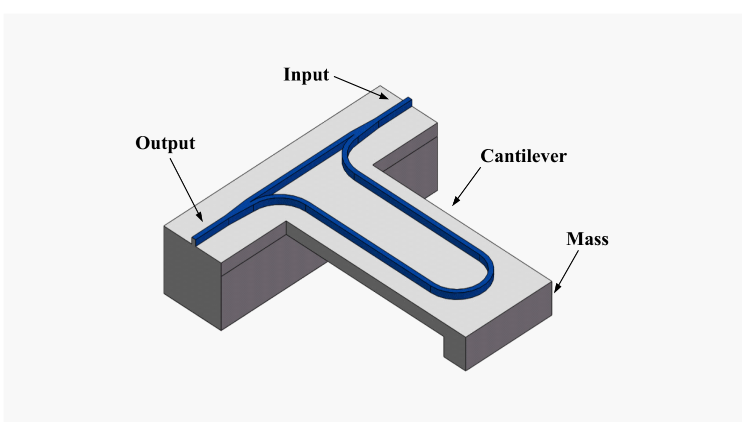


Figure 1: Schematic diagram of the proposed MZI based accelerometer fabricated on a flexible substrate.

scheme in our previous work [8]. Due to simplicity of the structure, the sensor is suitable for mass production.

2. THEORY OF THE MZI BASED ACCELEROMETER

Figure 2 shows the schematic picture for the structure of the proposed polymer MZI based accelerometer. The layout design for the device is shown in Fig. 2. The structure consists of two identical Y branches and two asymmetric arms. The length of the reference arm is $L_1 = 4R$, the bending radius is R, and the total length of the measuring arm is $L = 2\pi R + 2L_2 = VL_1$ where L_2 is the length of the straight waveguide in the measuring arm, and V is a numerical value larger than 1. Several S-bend waveguides are used in Y branches, their bend angles Φ are designed to be $1.1°$. For the purpose of studying the sensing characteristics of this accelerometer, it's necessary to deduce the Phase-Intensity relationship accurately.

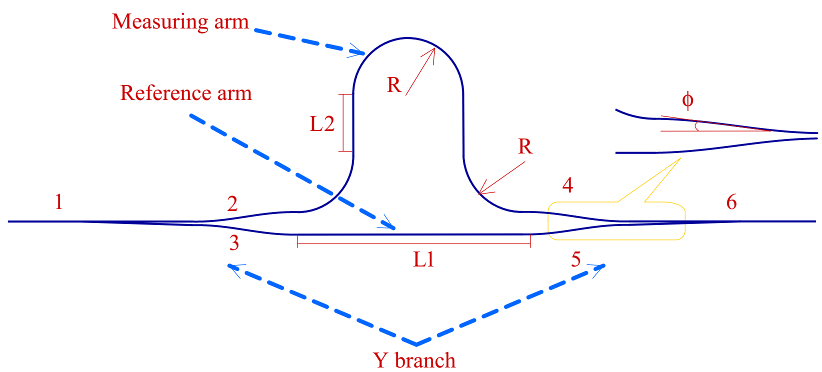


Figure 2: Schematic picture of the proposed MZI structure.

As is depicted is Fig. 2, light launched into the circuit at port 1, is split into the measuring and reference arms through the Y branch, and comes out from the port 6. The Y branch is geometrically symmetric so that we can ensure the half-half power split at port 2 and 3. The complex electric fields at different ports can be deduced as follows,

$$E_2 = E_3 = \frac{E_1}{\sqrt{2}} \tag{1}$$

$$E_4 = \exp\left(-\alpha V L_1 + i\varphi_{42}\right) E_2 \tag{2}$$

$$E_5 = \exp\left(-\alpha L_1 + i\varphi_{53}\right) E_3 \tag{3}$$

$$E_6 = \frac{E_4}{\sqrt{2}} + \frac{E_5}{\sqrt{2}} \tag{4}$$

where $\varphi_{42} = \beta V L_1 + \Delta\varphi_{42}$, and $\varphi_{53} = \beta L_1$ corresponding to the phase transfer operators through the measuring and reference arms respectively, $\Delta\varphi_{42}$ is the phase shift induced by the acceleration, and 2α is the propagation loss, $\beta = 2\pi n/\lambda$ is the mode propagation constant, n is the mode effective index, λ is the light wavelength in the vacuum. So the intensity of output signal can be written as

$$I_6 = \frac{I_1}{4} g_2 \left\{g_1 + g_3 \cos\left[\beta(V-1)L_1 + \Delta\varphi_{42}\right]\right\} \tag{5}$$

where $g_1 = 1 + \exp[-2\alpha(V-1)L_1]$, $g_2 = \exp(-2\alpha L_1)$, $g_3 = 2\exp[-\alpha(V-1)L_1]$. Thus, from the above expression, we can say that the output intensity will vary along with the variation of $\Delta\varphi_{42}$ caused by the force exerted on the flexible cantilever.

The sensitivity of the accelerometer is deduced as follows [10],

$$S = \frac{\partial(I_6)}{\partial(a)} = \frac{\partial(I_6)}{\partial(\Delta\varphi_{42})} \times \frac{\partial(\Delta\varphi_{42})}{\partial(a)} \tag{6}$$

$$\frac{\Delta\varphi_{42}}{\varphi_{42}} = \frac{\Delta n}{n} + \frac{\Delta L}{L} \tag{7}$$

In the above equation, $\Delta n/n$ is the phase variation due to the strain-optic effect, while $\Delta L/L$ stands for the change induced by the mechanical deformation. The force exerted on the mass is

$F = ma$, provided that, the acceleration is a. Then, the strain of the cantilever can be described as [9, 10],

$$\varepsilon(x) = \frac{6F(L_a - x)}{Ebt^2} \tag{8}$$

where ε is the strain experienced by the measuring arm, x is the position of the beam with respect to the fixed end. E is the Young's modulus of the substrate, and b, L_a and t are the width, length, and thickness of the device, respectively. We give $\Delta L = 2\int_0^{2R+L_2} \varepsilon(x)dx$ [10] and assume the value of $\Delta n(x)/n$ is $-0.11\varepsilon(x)$ [9, 10]. We can get that the shift in the transmission phase is given by

$$\Delta\varphi_{42} = ag_4 \left[L_a(2R + L_2) - 0.5 \times (2R + L_2)^2\right] \tag{9}$$

where $g_4 = 21.36\,\text{nm}/Ebt^2\lambda$, c is the speed of light in the vacuum, f is the frequency of the light signal. From (5), (6) and (9), the output intensity and sensitivity become

$$I_6 = \frac{I_1}{4} g_2 \left\{ g_1 + g_3 \cos\left[\beta(V-1)L_1 + ag_4 L_a (2R + L_2) - ag_4 0.5 \times (2R + L_2)^2\right]\right\} \tag{10}$$

$$S = \frac{\partial(I_6)}{\partial(a)} = \frac{\partial(I_6)}{\partial(\Delta\varphi_{42})} \times \frac{21.36nfm}{Ebt^2 c}\left[L_a (2R + L_2) - 0.5 \times (2R + L_2)^2\right] \tag{11}$$

The two expressions indicate that the sensitivity is proportional to the length of beam L_a, inversely proportional to b, t^2 and E. So the sensitivity can be tailored based upon the geometrical parameters and Young's modulus of the cantilever. We set the parameters of the accelerometer as follows. The light wavelength in the vacuum λ, the mode effective refractive index n, the amplitude coefficient of the waveguides α, radius of the bend waveguides and the length of the straight waveguide in the measuring arm R and L_2 are 1550 nm, 1.4533, 0.1, 0.25 cm, and 0.5 cm respectively. The Young's modulus E, mass of the proof mass m, and the size of the beam b, t are 0.087 N/μm^2, 15 g, 1.5 cm, and 0.05 cm respectively. Based upon these parameters, the relation between intensity and acceleration are shown in Fig. 3. It also indicates that the sensitivity and dynamic range can be easily tailored by applying different L_a.

3. FABRICATION AND EXPERIMENTAL DESIGN

In order to achieve flexible polymer substrate of our device, a special lift-off process is applied as described in our previous publication [8]. The post-off process in this work is based on the water-solubility of the polyvinyl alcohol (PVA). The schematic outline of the fabrication procedure is illustrated in Fig. 4. As a first step, we spin coated a layer of PVA, which can firmly adhere to both Si wafer and flexible polymer substrate, on a Si wafer. Then, the flexible polymer substrate

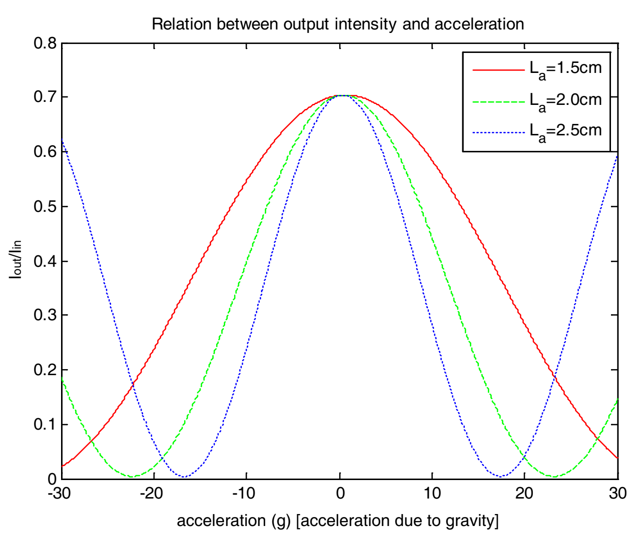


Figure 3: The relation between the acceleration and the output intensity with different values of length (L_a) of the beam.

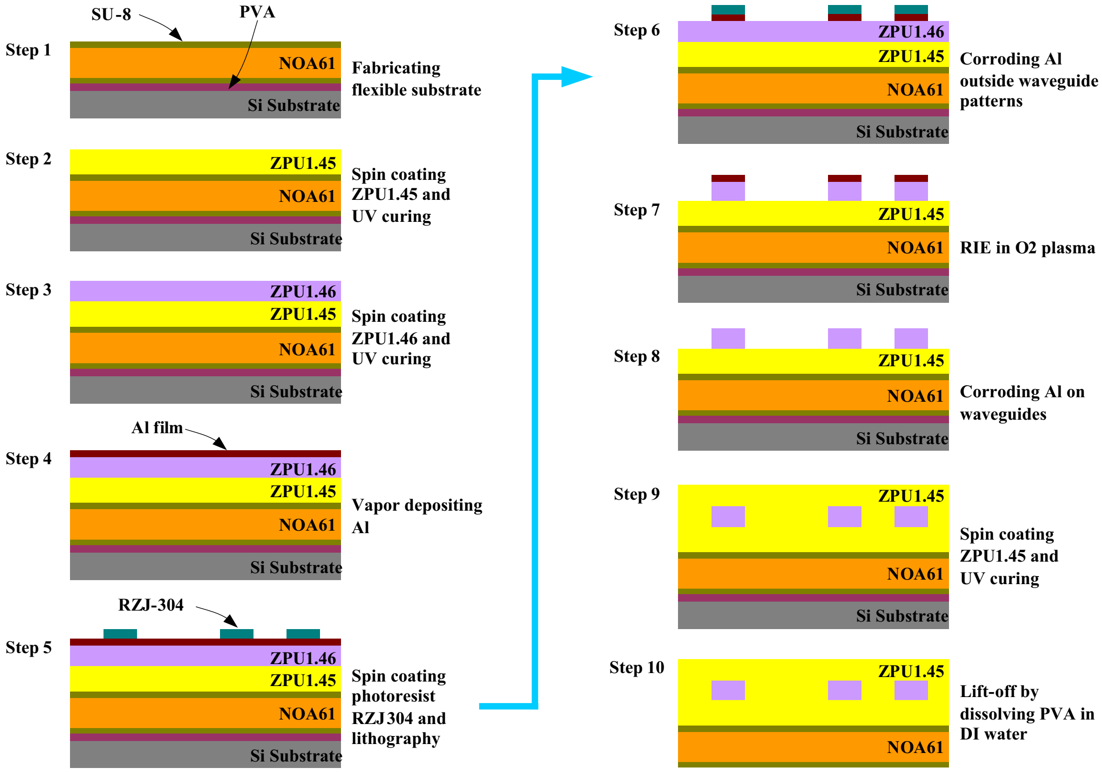
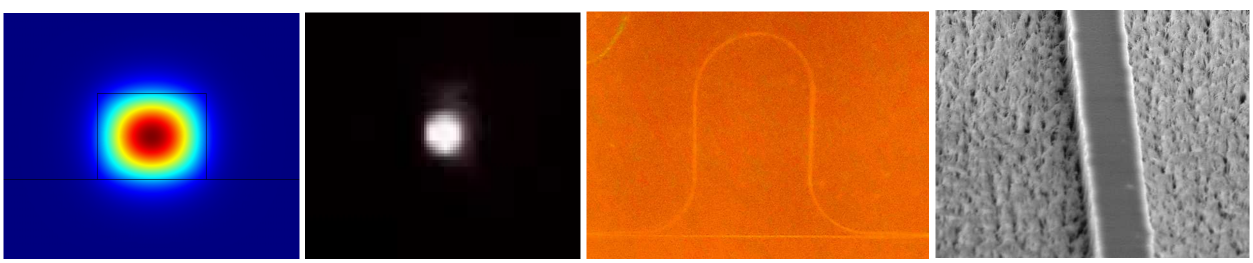


Figure 4: Fabrication procedure for the MZI based accelerometer.



(a) (b) (c) (d)

Figure 5: (a) The simulated intensity distribution of HE_{11} mode at 1550 nm. (b) Light spot captured by a infrared camera. (c) a photograph of a practical device. (d) The SEM image of a waveguide.

was fabricated on the PVA layer in the structure of two SU-8 layers sandwiching a layer of NOA61, thus tunable Young's modulus can achieved through changing the thickness of SU-8 and NOA61.

The device was designed and characterized for 1550 nm. After the flexible substrate was achieved, a 20 µm thick layer of ZPU1.45 with refractive index of 1.45 was spin-coated on the substrate as the lower cladding. Then the membrane was cured in a UV chamber for 2 minutes, followed by a hard bake process for 30 minutes at 160°C. After that, we spin coated a 5 µm film of another ZPU material (ZPU1.46) with refractive index of 1.46 as the core layer and cured it in UV chamber for 2 minutes too. A film of Al of 100 nm–300 nm is coated on it as the barrier layer by vapor deposition so that we can protect the wanted waveguides from being etched in the following RIE process. The MZI structures were then patterned on the layer by conventional photolithography using RZJ-304 photoresist. The photoresist pattern was then transferred to the core layer by corroding Al layer outside the waveguide patterns in the phosphoric acid solution and a reactive ion etching (RIE) in O_2 plasma in sequence. Then we corrode the Al on the waveguides. The cross dimension of the stripe waveguide is $7\,\mu\text{m} \times 5\,\mu\text{m}$ so that it only supports fundamental mode as shown in Figs. 5(a) and (b). Again, we spin coated and cured a film of ZPU1.45 as the upper cladding layer. The flexible device can be separated from the Si wafer by dissolving it in deionized water. A photograph of the final device and a Scanning Electron Microscope (SEM) image of a waveguide is shown in Figs. 5(c) and (d) respectively.

For the accelerometer experiment, we fix the end with input and output ports of the flexible device on the optic measuring platform, and a proof mass with moderate iron powder is attached at the other end. Both the input and output ports are pigtailed to single-mode optical fibers which are connected to a laser ($\lambda = 1550\,\text{nm}$) and an optical detector respectively. A micro electromagnet controlled by a tunable voltage source is put under the proof mass. Thus, we can effectively exert different force on the proof mass through adjusting the control voltage, that is, the equivalent acceleration can be controlled easily according to Newton's Second Law of Motion. Through detecting the signal of the optical detector on the condition of different acceleration, we can obtain the sensitivity characteristic of the device.

4. CONCLUSION

An MZI based optical accelerometer fabricated by flexible waveguide technique has been investigated. The relation between the output optical intensity and acceleration is deduced theoretically. The result shows that the sensitivity and dynamic range can be tuned by applying different dimension parameters. Meantime, the fabrication of the flexible device is exhibited and a viable test scheme is proposed. Owing to simplicity of the structure and fabrication process, such optical accelerometer is suitable for mass production in the future.

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