Fiber Optic Pressure Sensor using Multimode Interference

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Abstract. Based on the theory of multimode interference (MMI) and self-image formation, we developed a novel intrinsic optical fiber pressure sensor. The sensing element consists of a section of multimode fiber (MMF) without cladding spliced between two single mode fibers (SMF). The MMI pressure sensor is based on the intensity changes that occur in the transmitted light when the effective refractive index of the MMF is changed. Basically, a thick layer of Polydimethylsiloxane (PDMS) is placed in direct contact with the MMF section, such that the contact area between the PDMS and the fiber will change proportionally with the applied pressure, which results in a variation of the transmitted light intensity. Using this configuration, a good correlation between the measured intensity variations and the applied pressure is obtained. The sensitivity of the sensor is 3 μV/psi, for a range of 0-60 psi, and the maximum resolution of our system is 0.25 psi. Good repeatability is also observed with a standard deviation of 0.0019. The key feature of the proposed pressure sensor is its low fabrication cost, since the cost of the MMF is minimal.

1. Introduction

Fiber-optic pressure sensor (FOPS) technology has progressed rapidly in the last decades [1], outperforming conventional pressure sensors. Currently, we can find different configuration of FOPS based primarily on Fabry-Peror resonators [2], fiber Bragg gratings[3], and microbending of single-mode fiber [4]. Recently, optical devices based on MMI effects combined with self-image conditions, have been developed in planar waveguide [5] and subsequently implemented in optical fiber devices under a single-mode – multimode – single-mode (SMS) fiber configuration. This configuration has been studied and developed to act as a novel optical device, showing excellent properties and ease of fabrication for optical sensing applications [6, 7, 8, 9, 10]. In SMS fiber structure, a multimode fiber (MMF) section is fusion spliced between two single-mode fiber (SMF) sections, and MMI effects will describe the behaviour of the input field within the MMF. In this work, we show the experimental results of a SMS fiber structure in FOPS technology applications. The proposed MMI pressure sensor is based on the intensity changes that occur in the light transmitted through the MMI sensor as the contact area between a polymer film and the MMF core is modified. The film is made
Polydimethilsiloxane (PDMS) and the MMF fiber is a special fiber that does not have clad, such that any contact between them alters the MMF fiber optical properties. The PDMS layer will move together with a pressure membrane in response to the applied pressure, and this results in a variation of the transmitted light intensity that is correlated to the applied pressure.

2. Principle of operation

The operating mechanism of the pressure sensor is based on the MMI effects combined with self-image phenomena occurring in a MMF section. In an optical fiber, MMI can be implemented using a SMS fiber structure by splicing a MMF section between two SMF sections. In this structure, the optical field emerging from the input SMF excites the modes supported by the MMF, and as they propagate along the MMF section the interference between them will give raise to the formation of images of the input field along the MMF axis. Power coupled to each mode is different and is highly dependent on the physical parameters of the MMF fiber, such as the diameter and the refractive index of core and cladding, this was shown in reference [10]. The input field profile is replicated due to constructive interference and self-images are found at periodic intervals at distances known as re-imaging distance and is given by [10],

\[ L = p \left( \frac{8n_c a^2}{\pi} \right), \quad \text{with } p = 0, 1, 2, ... \]  

where \( n_c \) and \( a \) are the refractive index and the core radius of the MMF respectively, \( k \) is the wavevector is free-space and the factor \( p \) denotes the periodic nature of the image along the fiber. As shown in equation (1), once we know the MMF fiber parameters, we can determine the length of the MMF that will give a self-image for a specific wavelength. This will correspond to maximum coupling from the input SMF to the output SMF. It is important to notice that if a different wavelength is used, the self-image for that wavelength will be at a different position and the coupled intensity will be lower. Therefore, when a broadband source is launched through the MMI device we obtain a pass-band filter response.

The key concept of our MMI sensor relies on the fact that when the effective refractive index of the MMF core is modified, the wavelength response is modified as well. In order to modify the MMF properties we use a special MMF know as No-Core fiber, which is basically a MMF without cladding, i.e. the clad is air. Therefore, when a polymer film makes contact with the MMF its effective refractive index is modified. The polymer film was made of Polydimethilsiloxane (PDMS) with a refractive index of approximately 1.42 at 1550 nm (based on curing conditions). This film is attached to an acrylic pressure membrane, and as the acrylic membrane bends due to the applied pressure the PDMS bends as well. As shown in figure 1, initially the PDMS layer makes contact with the No-Core fiber in a small area. However, as the pressure is gradually increased, the contact area between the PDMS and No-Core fiber will also increase. The contact area \( A \) shown in figure 1, as the PDMS layer covering the fiber is increased, is given by:

\[ A = 2L \cos^{-1} \left( 1 - \frac{h}{a} \right), \]
where $L$ is given by equation (1), $h$ is the vertical displacement of the PDMS layer and $a$ is the core radius of the No-Core MMF. When this contact area is enlarged, we should expect a variation in the wavelength response of the MMI pressure sensor, and this is what we measured to detect the applied pressure to the membrane. Such modification is mainly due to the fact that the effective index is being modified asymmetrically and when the modes are recombined to form the image, the intensity for each wavelength will be slightly different.

![Image](image_url)

**Figure 1.** a) PDMS layer covering the fiber and b) increment of contact area.

### 3. Experimental setup

The experimental setup is shown in figure 2. A nitrogen cylinder was used to apply pressure to the pressure chamber. Input pressure was controlled with an inlet control needle valve and measured by a conventional digital manometer at the system output. The testing system consisted of a tunable laser (HP lightwave Measurement Systems Company) with a wavelength range from 1460 to 1560 nm that was connected to one end of the MMI device, while the other end was connected to a photo-detector and a digital multimeter (DMM 2000 Keithley) with 1 µV resolution.
An acrylic membrane, with a thickness of 6mm, was sealed to the pressure chamber with diameter of 6 cm (figure 3). A 5 mm thick layer of PDMS, with a diameter of 3 cm, was attached to the pressure chamber membrane. This PDMS layer is put in contact with the sensitive element, which consists of a MMF section with a length of 14.10 mm (equation 1), fusion spliced between two single-mode fiber (SMF) sections by using a Fujikura 30S Arc fusion splicer. The fiber is kept straight to an aluminium disc and fixed with epoxy resin, taking care of not to cover the top of MMF section. We used a SMF-28 with a diameter of ~9 µm and refractive index of 1.4615, and a no-core MMF with a refractive index of 1.4615 and a diameter of 125 µm. The length of the multimode fiber (MMF) was 14.10 mm which is optimized to obtain the first self-image at a wavelength of 1510 nm.

**Figure 3.** Pressure testing cylinder and SMS fiber structure.

4. Experimental results.

Figure 4(a) shows the spectral response as a function of the applied pressure corresponding to a pressure range of 0-60 psi. Due to the low refractive index of the PDMS we should expect negligible attenuation of the transmitted spectrum. However, we can observe a slight intensity change for the first
5 psi of applied pressure. We believe that this change is due to the fact that the MMI fiber was not fully straight and there is a tiny change in curvature for the first 5 psi. After that, there is no significant change in intensity, but rather only a modification of the spectrum, as expected. The intensity variation at a wavelength of 1550 nm, corresponding to an increase of 5 psi is 0.15 mV (figure 4(b)), which is easily resolved with our multimeter.

![Figure 4](image1.png)

(a)  

(b)  

**Figure 4.** Overall spectral response at pressure range of 0 to 60 psi.

A non-uniform behaviour is observed over the spectral range, which was similar in all our tests. Therefore, instead of following changes to the full MMI response we track the intensity change at wavelengths of 1470, 1500, 1510, 1518 and 1550 nm, and the intensity as a function of applied pressure is plotted in figure 5.

![Figure 5](image2.png)

(a)  

(b)  

(c)  

(d)  

(e)  

**Figure 5.** Behaviour of spectral response in different wavelength.
We can observe that the response is highly dependent on the wavelength that we use to interrogate the MMI response. As an example, a decrease in the intensity in the first three wavelengths (figures 5 (a), (b), (c)) and the intensity remains unchanged in 1518 nm. This behaviour is opposite for a wavelength of 1550 nm. The higher sensitivity is on the longer wavelength side (figure 5). By fixed the laser wavelength at 1550 nm, the repeatability is measured and plotted in figure 6 corresponding to five different pressure measurements at different times. The response of every measurement overlaps perfectly with each other.

![Graph showing intensity vs wavelength and polynomial fit of degree 4th.](image)

**Figure 6.** Repeatability in five tests and polynomial fit of degree 4th.

The empirical relationship between the applied pressure and the output power may be expressed by the polynomial of degree 4th as is shown in figure 6,

\[ Y = a_0 + a_1x + a_2x^2 + a_3x^3 + a_4x^4 \]

where \( a_0 = 0.11447 \), \( a_1 = 0.0092 \), \( a_2 = -3.36605 \times 10^{-4} \), \( a_3 = 7.22908 \times 10^{-6} \), \( a_4 = -5.18566 \times 10^{-8} \). A monotonic variation in the sensor operation is observed. The standard deviation found was 0.0019 with a sensitivity of 3 µV/psi with a limit of resolution of 0.25 psi with our system.

5. Conclusions

A novel pressure sensor based on a MMI optical device is presented. We take advantage of a no-core MMF with a longer diameter in order to increment the sensitivity of the sensor. A high repeatability in the sensor operation under this simple configuration are found. Other characteristics of the SMS fiber structure are its ease of fabrication and low cost due to the inexpensive instrumentation used. The sensitivity of the proposed sensor was of 3 µV/psi for a range of 0-60 psi, and the maximum resolution of our system was of 0.25 psi. A high repeatability during the different measurements was observed with a standard deviation of 0.0019. The key feature of the proposed pressure sensor is its low fabrication cost, since the cost of the MMF is minimal.
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