# Low-cost lateral force sensor based on a core-offset multimode fiber interferometer with intensity based interrogation technique

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## ABSTRACT

A novel lateral force sensor based on a core-offset multimode fiber interferometer with intensity-based interrogation technique is reported. An offset between the cores of the single-mode fiber and multimode fiber is made to produce high extinction ratio. When a lateral force is applied to a short section of the multimode fiber, the extinction ratio decreases with the interference phase almost unchanged. In addition to serving as a sensing head, the multimode fiber can also act as a filter to realize lateral force measurement by determining the power change from a power meter. Experimental results show that the power ratio change has a linear relationship with respect to the applied lateral force, and the resolution of the sensor configuration is about 0.01 N.

**Keywords:** Multimode fiber, lateral force, interrogator

## 1. INTRODUCTION

Optical fiber sensors are compact, light weight, resistant to electromagnetic interference, and they can be embedded into other structures. Many force sensors based on fiber Bragg gratings (FBGs), Mach-Zehnder interferometers (MZIs), and other techniques have been developed. An FBG is attractive for using as a lateral force sensor [1,2] because of its small size and its property of wavelength encoding. However, FBGs are fragile and expensive, and their sensitivity to lateral force is not high. Multimode fiber (MMF) sensors have also aroused intensive study because they are cost effective and easy to manufacture. Chemical [3], displacement [4] and curvature [5] sensing can be realized using MMFs. Moreover, many researches focus on the measurement of temperature and longitudinal strain [6-9] by employing different types of MMF. Recently, our group reported a novel lateral force sensor based on a core-offset MMF interferometer [10], which is temperature and phase independent.

On the other hand, there is considerable interest in developing methods which monitor parameters other than wavelength information provided by the sensor head, because spectral information is usually obtained by optical spectrum analyzers (OSAs) which are expensive and have slow scanning speed. Many passive and active interrogation methods have been developed, such as using linearly wavelength dependent devices [11], charge-coupled device interferometers [12], Fabry-Perot filter interrogators [13], etc.. By adopting suitable interrogators, the optical fiber sensor systems become more competitive and can be commercialized as the cost and complexity are reduced.

In this paper, we present an improved fiber sensor configuration that is feasible to measure lateral force using a core-offset MMF interferometer [10]. When a lateral force is applied to a short section of the MMF, the extinction ratio decreases accordingly. By measuring optical power variations instead of the spectrum change, lateral force measurement can be achieved with a low cost and high speed. In addition, the sensor head can be encapsulated into the temperature compensation material to meet practical application.

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## 2. EXPERIMENT SETUP AND OPTERATION PRINCIPLE

Figure 1 shows the experiment setup. Light from the tunable laser source was split by a 3-dB optical coupler (OC). In one path, power $P_2$ was directly measured by a power meter (PM2) as a reference to eliminate any power fluctuation from the optical source; in the other path, power $P_1$ was measured by another power meter (PM1) after passing through a section of MMF. The MMF was originally designed for dispersion compensation applications, with a large dispersion parameter of -270 ps/nm/km at 1550 nm and a cutoff wavelength of 1663 nm. The core/cladding diameter of the MMF is 1.9/115.7 μm. As shown in Fig. 1, the MMF was sandwiched between two single-mode fibers (SMFs) acting as an MZI based on intermodal interference, with an offset between the MMF core and the SMF core. The core offset was made to increase the extinction ratio of the interferometer [10], since the core-offset splicing is an effective method to control mode coupling [14].

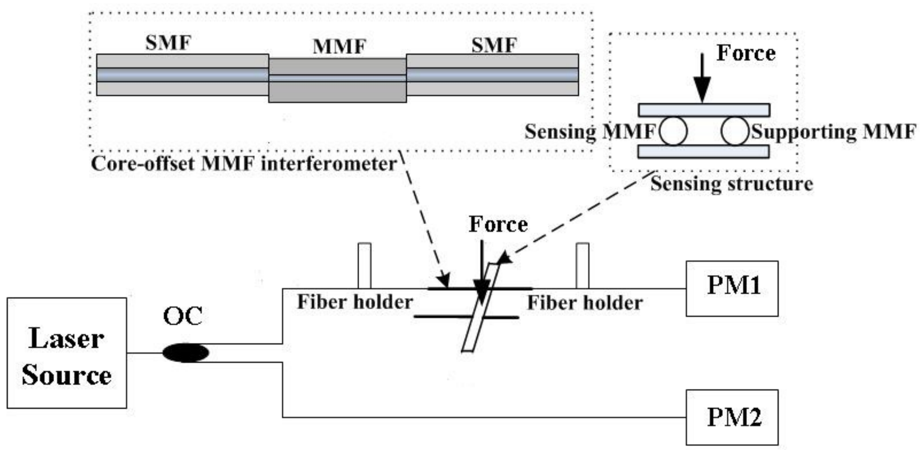


Fig. 1. Experiment setup. PM: Power meter; OC: Optical coupler

The spectra of the MMF interferometer and the laser source are shown in Fig. 2. The central wavelength of the laser source was tuned to 1544 nm, one of the peak transmission of the MMF spectrum. In order to investigate the types of interference modes, we fabricated several core-offset MMF interferometers and stripped the cladding layer of the MMF. There was no change on the transmission spectra after the interferometers were placed into the index match liquid. This confirmed that the interference modes are core modes. The MMF, or more strictly speaking the SMF-MMF-SMF structures, acts as an MZI based on intermodal interference. Many modes are excited when light is coupled into the MMF. Each of the modes has a different propagation constant. When they recouple in the SMF after passing through the MMF, the modes interfere. Each mode has experienced a different phase shift. If only two dominant modes are excited, the resultant interference fringe pattern is approximately sinusoidal with a uniform extinction ratio determined by the ratio of the intensities in the two modes (e.g., the best mode operation is to launch equal power in the two modes). If other higher order modes are excited, the interference fringe pattern will be modulated by their presence. The spectrum in Fig. 2 is rather uniform, confirming that only two modes primarily interfere in our case. The measured interference shown in Fig. 2 can be approximately expressed as

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos[\frac{2\pi\Delta n L}{\lambda}], \tag{1}$$

where $I_1$ and $I_2$ are the power distributed in the two interference modes, respectively, $\Delta n$ is the mode index difference of the two modes, and $\lambda$ is the wavelength of light in vacuum. The wavelength spacing $\Delta\lambda$ of the interfering spectrum is given by

$$\Delta\lambda \approx \frac{\lambda^2}{\Delta n L}. \tag{2}$$

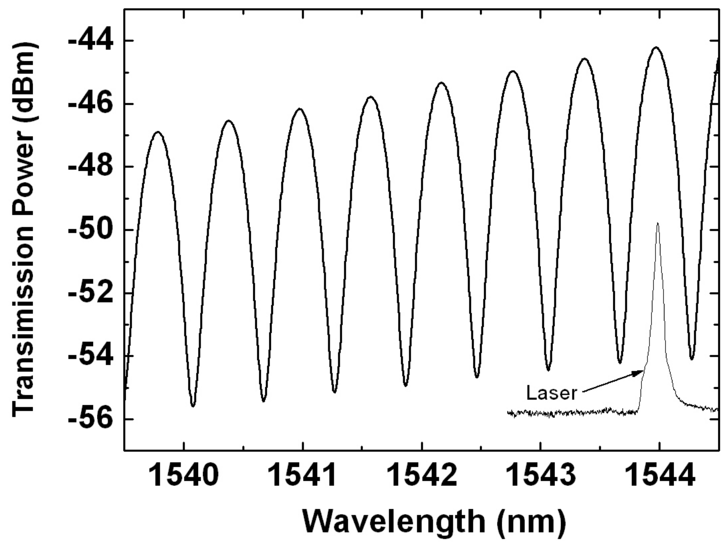


Fig. 2. Spectra of the MMF interferometer and the laser source.

It is clear that the wavelength spacing of the interfering spectrum is inversely proportional to both the mode index difference $\Delta n$ and the length of the MMF *L*. $\Delta\lambda$ is found to be about 0.57 nm from Fig. 2, and the length *L* of the MMF is about 22 cm in our experiment. Thus the mode index difference of the two interfering modes $\Delta n$ is estimated to be of the order of $10^{-2}$, which is at least 10 times larger than that of the MMFs used in [7-9]. In other words, our proposed sensor can be made at least 10 times smaller than the sensors of [7-9], provided that all the sensors have the same wavelength spacing. This feature indicates that the proposed MMF has the potential to be used as sensor heads to reduce the configuration size in practical applications.

From Eq. (1), the peak of the spectrum at 1544 nm can be described as

$$I_{\lambda=1554} = I_1\left(1+\sqrt{I_2/I_1}\right)^2, \tag{3}$$

determined by the power ratio of the two modes and the power of the fundamental mode. The lateral force applied to the MMF will lead to the deformation of the MMF, which must result in the power losses of all the modes. The higher-order mode will experience more power loss than the lower-order mode; hence the power ratio $I_2/I_1$ is reduced. Thus, the power $P_1$ measured by PM1 decreases when the lateral force is increased. In addition, the lateral force is applied to a short section of MMF producing negligible longitudinal strain, so that the phase of the interferometer remains almost constant [10]. These features make it possible to perform lateral force measurement by monitoring the power changes instead of the spectral variations.

## 3. EXPERIMENT AND DISCUSSIONS

As shown in Fig. 1, a core-offset MMF interferometer sensor with the MMF length of about 22 cm is fabricated. The extinction ratio reaches 9 dB, as shown in Fig. 2. A section of MMF identical to the sensing MMF is used as a supporting fiber. In order to avoid the rotation of the MMF, the interferometer is supported by two fiber holders placed on an optical table. Both the MMFs are fixed between two aluminum flakes with smooth surfaces. The width of the aluminum flake is about 1 cm. With increasing lateral forces applied to the MMF, the extinction ratio decreases, while the interference phase remains constant, as shown in Fig. 3. Since the maximum transmission power at 1544 nm also decreases, the power passed through the MMF is reduced, and the power measured by PM1 decreases. Thus, the MMF interferometer also serves as a filter.

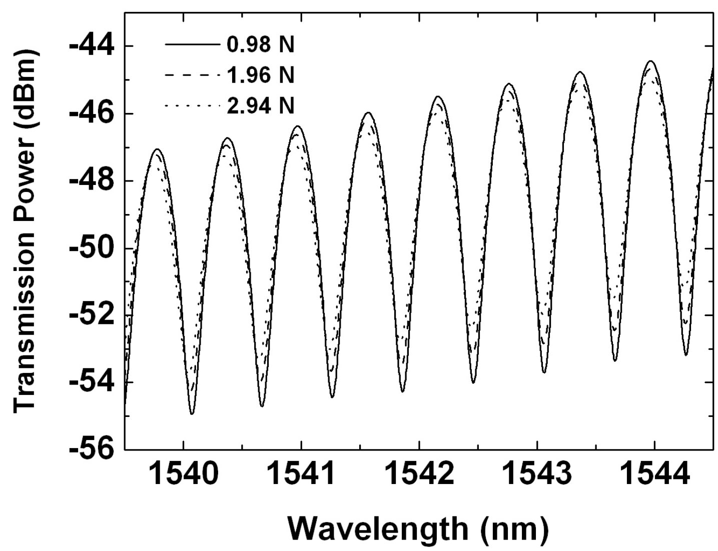


Fig. 3. Transmission spectra under different lateral forces.

Fig. 4 shows the change of the power ratio ($P_1/P_2$) as a function of the lateral force. $P_2$ was used as a reference to eliminate any power fluctuation from the optical source. The power ratio variation has a good linear relationship with respect to the applied lateral force. This is different from the result reported in Ref. [10], where the extinction ratio has a quadratic behavior with respect to the lateral force. In fact, the experiment data in Ref. [10] can also be fitted as a first-order exponential function within the operating range, but having a more complicated appearance. Thus, the linear relationship is reasonable in the present case where the MMF interferometer acts as a filter, because the power changes are measured in μw instead of the extinction ratio measured in dB [10].

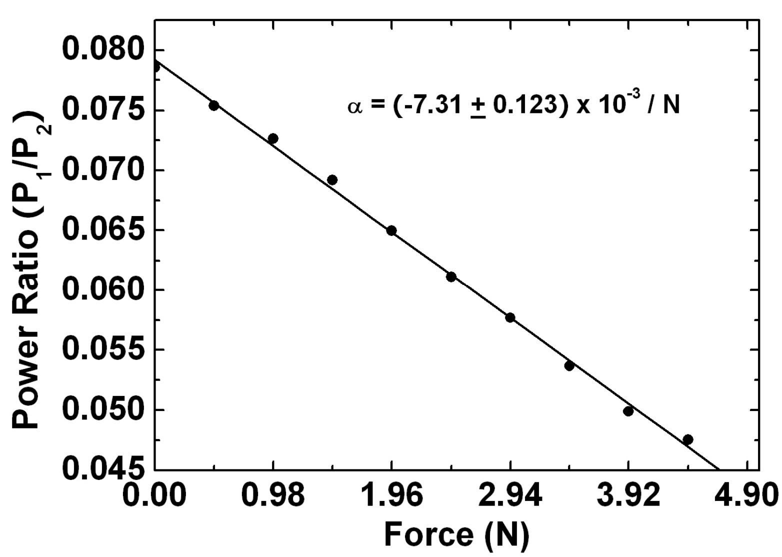


Fig. 4. Power ratio change as a function of applied lateral force.

In order to avoid breaking the MMF, the force is controlled in the range 0 ~ 4.5 N. This range can be increased by encapsulating the sensor head in materials with high Young's modulus for practical applications. Moreover, if there is an ambient temperature change, the spectrum of the interferometer has a red shift, which influences the sensing results. This problem may be overcome by encapsulating the sensing head in temperature compensation materials. In addition, the tunable laser source in our experiment can be changed to other simple sources to further reduce the cost. The resolution of the proposed sensor is about 0.01 N.

## 4. CONCLUSION

A lateral force sensor based on a core offset MMF interferometer is presented and demonstrated experimentally. The applied lateral force can be measured by monitoring power ratio changes instead of interference spectrum [10]. The proposed sensor has the advantages of simple structure and low cost. The resolution of the proposed sensor system is about 0.01 N.


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