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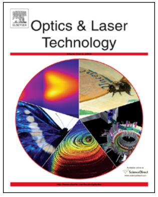

Highly sensitive curvature sensor based on single-mode fiber using core-offset splicing

Lili Mao [a,b], Ping Lu [a,b,*], Zefeng Lao [c], Deming Liu [a,b], Jiangshan Zhang [d]

[a] *National Engineering Laboratory for Next Generation Internet Access System, Huazhong University of Science & Technology (HUST), Wuhan, China*
[b] *College of Optical and Electronic Information, HUST, 1037 Luoyu Road, Wuhan 430074, China*
[c] *College of Electrical and Electronic Engineering, HUST, 1037 Luoyu Road, Wuhan 430074, China*
[d] *College of Electronics and Information Engineering, HUST, 1037 Luoyu Road, Wuhan, 430074, China*

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ABSTRACT

A highly sensitive curvature sensor based on core-offset splicing is proposed and demonstrated. The whole fabrication process is quite simple and the sensor head is cost effective. Measurement results show that it has a high sensitivity of -22.947 nm/m^{-1} in the range from 0.35312 m^{-1} to 2.8127 m^{-1}. Temperature sensitivity of 77.6 pm/°C within the range of 20–80 °C has also been achieved, which implies the possibility for measurement of temperature. High sensitivity and low-cost make it a preferable candidate for small curvature sensing with high resolution in practical applications.

1. Introduction

In line Mach–Zehnder interferometers (MZI) have attracted great research interest for their compact structures, easy fabrication and low cost. An in-line Mach–Zehnder inteferometer can be formed by introducing a mode-splitter and a mode-combiner to realize the coupling and recoupling of core mode and cladding modes. They have been widely used for measurement of various parameters, such as refractive index, temperature, etc. [1]. Most curvature sensors based on in-line MZIs are fabricated by splicing different kinds of fibers, for instance, a multimode fiber (MMF) between two sections of single mode fibers (SMF) [2], or splicing two silica fibers into a photonic crystal fiber (PCF) [3,4], or a polarization maintaining fiber (PMF) [5]. Gong proposed the SMS structure for curvature sensing and the maximum sensitivity of the structure is about -10.38 nm/m for a range between 0.25 m^{-1} and 0.5 m^{-1} [2]. The core-offset PMPCF proposed by Dong et al. for curvature measurement has a sensitivity of 2.826 nm/cm [6].

Some MZIs are developed through special fabrication such as concatenating two tapers [7], but it has low precision due to the visibility demodulation. The structure which employs special fibers (such as two-core fiber) can obtain a high sensitivity, from 0 m^{-1} to 0.27 m^{-1} [8]. Frazão reported a highly birefringent PCF with two asymmetric hole regions for curvature measurement [9].

Several types of curvature sensors based on fiber grating have also been presented. Frazão proposed a Mach–Zehnder interferometer combined with a multimode fiber and a long-period grating [10]. A MMF with a fiber Bragg grating (FBG) [11] and a core-offset FBG [12] were also proposed. These configurations based on FBG or LPG normally require expensive ultraviolet light laser source, phase mask and sophisticated fabrication technology. Recently, a novel bending vector sensor employing lateral-offset and up-taper has also been demonstrated [13].

In this paper, we propose a highly sensitive curvature sensor fabricated by simply core-offset splicing in a relatively large range suitable for small curvature measurement occasions. Such an in-line MZI sensor can be used to measure curvature by observing its wavelength shift. It is fabricated by splicing two attenuators together, such similar core-offset structure has originally been reported for refractive index sensing [14]. However, their design has major limitations: low distinction ratio (a maximum contrast ratio about 9 dB). Here we exploit the core-offset attenuators for curvature measurement and offer a solution for obtaining good interference spectra with core-offset structure in this paper. We pushing up the maximum contrast ratio to a value larger than 20 dB. The fabrication process of our sensor is quite simple and cost effective, and the mechanical strength can also be maintained. The in-line MZI exhibits a high curvature sensitivity of -22.947 nm/m from 0.35312 m^{-1} to 2.8127 m^{-1}. Which is two times higher than that of the SMS-based interferometer [2] (10.38 nm/m^{-1}) and also higher than that of SMSMS-based interferometer [15] (14.4 nm/m, offset+up taper based(11.987 nm/m) interferometer [13].

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[*] Corresponding author. Tel./fax: +86 27 87556188.
E-mail address: pluriver@mail.hust.edu.cn (P. Lu).

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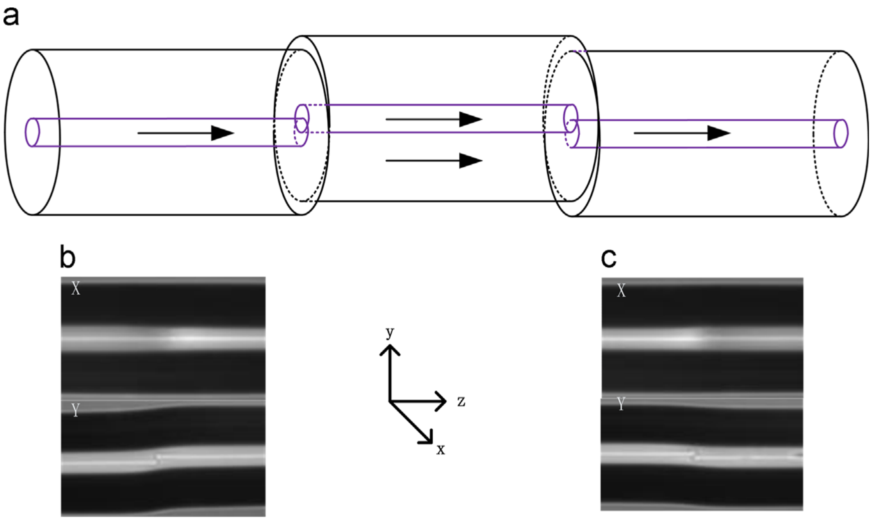

Fig. 1. (a) Structure of the curvature sensor based on core-offset splicing. (b) Splicing image of the first core-offset point (both *x* orientation and *y* orientation). (c) Splicing image of the second core-offset point (both *x* and *y* orientation).

2. Principle and sensor fabrication

The core-offset structure is fabricated by offset splicing a section of SMF between two SMFs, as depicted in Fig. 1(a). The fiber axis is defined as *z*-axis in the subsequent description. Fig. 1 (b) and (c) shows the images of the two offset splicing points. The fiber used in the experiment was fabricated by Yangtze Optical Fiber and Cable Company Ltd, which has a core and cladding diameters of 9.2 μm and 125 μm, respectively.

At the first offset splicing point, light from the transmission fiber is partially coupled into the cladding of the middle section fiber. Cladding mode is then recoupled into the core at the second offset splicing point. The reflection of uncovered SMF core at the core-cladding interface is so weak for the small refractive index difference between core and cladding and then can be ignored [16]. Due to the phase difference of the cladding mode and the core mode, a typical MZI is obtained. The total phase difference can be written as:

$$\phi = 2\pi(n_{eff}^{co}L_{co} - n_{eff}^{cl}L_{cl})/\lambda \tag{1}$$

where $n_{eff}^{co}, n_{eff}^{cl}$ is the effective refractive index of the core mode and the cladding mode respectively. L_{co}, L_{cl} is the propagating length of the core mode and the cladding mode respectively. When the phase difference satisfies $\phi=(2m+1)\pi$, where m is the interference order, a transmission dip appears at:

$$\lambda_m = 2(n_{eff}^{co}L_{co} - n_{eff}^{cl}L_{cl})/(2m+1) \tag{2}$$

When the curvature is applied on the MZI along $-y$ axis, the cladding mode will experience a longer transmission path than the core mode, namely L_{co} decreases and L_{cl} increases. It can be known that when a fiber bends, the effective refractive index for the region close to the inner side of fiber axis decreases, while it increases for the region close to outer side [13]. If a $-y$ axis bending is applied, the optical path difference will decrease, and as a result a blue shift will be observed on the dip wavelength.

We make the first offset splicing point with a commercial fusion splicer (FSM-60S) under a customized mode in the splicer menu, to make sure the offset in *y* axis and keep alignment in *x* direction, as shown in Fig. 1(b). Since the relative offset direction between the two points would greatly affects the fringe visibility of the interference pattern [14], the splicing of the second offset point is carried out under the monitoring of OSA (this may be a crucial point for obtaining high contrast ratio) by a manual operation for obtaining a good interference pattern.

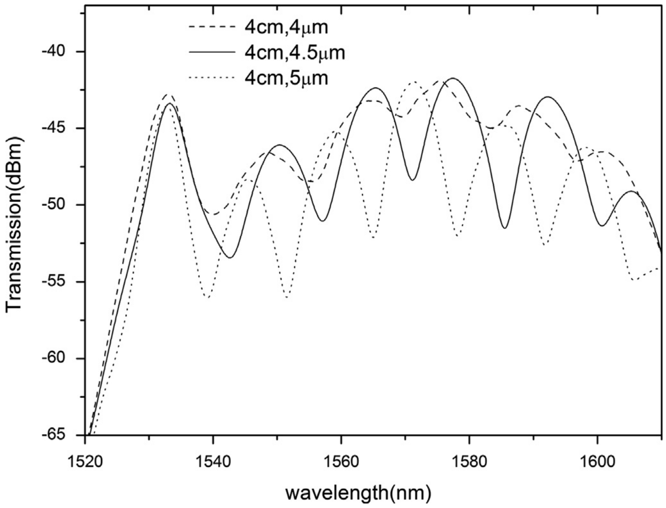

Fig. 2. Transmission spectra of MZIs with length of 4 cm exploiting different offset attenuators.

To analyze the dependence of interference on the offset parameter, same lengths of interferometers with different offset attenuators were fabricated. The transmission spectra of the MZIs are shown in Fig. 2, different offset values effect the interference pattern, MZIs with offset 5 μm can get the maximum contrast ratio, but endure large loss. The extinction ration and transmission loss of is the smallest for MZIs with offset 4 μm. So there is a trade-off between offset and insertion loss. Here we choose the offset value of the first point as 4.5 μm.

Following, the length of middle fiber should be appropriate, if too long, the cladding mode experience large loss, and the contrast ratio could also be degraded, as can be seen from the dotted line in Fig. 3 (5 cm, 5 μm). If too short, the free spectra range (FSR) will be large, so as the measurement range, but there should be at least two attenuation dips in the range of our broad–band optical source. We have made numerous samples, at last we choose a optimum length of about 15.9 mm for curvature measurement.

For verifying the presentation above, a batch of MZIs consisting of two attenuators with 5 μm offset value were fabricated with different lengths ranging from 3 cm to 5 cm, the transmission