Femtosecond laser fabricated all-multicore-fiber parallel Fabry-Perot interferometers for dual-parameter sensing

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Abstract: We demonstrate all-multicore-fiber parallel Fabry-Perot interferometers (FPIs) with individually variable cavity length of 26-61μm by femtosecond laser selective micro-machining and fiber fusion splicing, leading to the successful mitigation of cross-sensitivity arising in dual-parameter sensing.
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1. Introduction

All-fiber Fabry-Perot interferometer (FPI) has been comprehensively investigated for its convenience on various physical parameters measurement, such as temperature and strain [1,2], pressure [3], refractive index [4], owing to its advantages of miniature size, linear response, high sensitivity, and all-fiber in-line configuration. In order to simultaneously realize dual/multiple physical parameters sensing, various FPI based fiber optical sensors have been proposed, including multiple-cavity cascaded structure and FPI cascaded with fiber Bragg grating (FBG) structure, which utilize different response of FPI cavity or FBG to realize the dual-parameter sensing. Several multiple-cavity structures fabricated by the cascaded air cavity and fiber material cavity in the fiber axial direction, have been demonstrated by hybrid fiber fusion splicing [1,2] and laser induced air-hole structure [4]. However, the corresponding interferometric spectrum requires additional signal processing to recover response of each cavity, and expensive specialty fiber like photonic crystal fiber or hollow core fiber are used. Although FPI cascaded with an FBG can realize a discriminative measurement [3,5,6], such dual-parameter sensing solution requires an optical spectrum analyzer (OSA) with wide wavelength range or two separated OSAs for resolving both the FPI and FBG response, leading to high implementation cost. More importantly, both cascaded FPI structure are spatially separated along the fiber axial direction, which weaken the spatial measurement accuracy and bring the cross-sensitivity headache for the dual-parameter sensing. Furthermore, as for multiple-parameter sensing, current FPI cascaded structures are insufficient to provide enough scalability. Consequently, more cascaded structures are indispensable, leading to a complicated configuration and further reduction of the spatial measurement accuracy.

In this submission, effective parallel FPIs at same axial position of multicore fiber with good spatial measurement accuracy are demonstrated by femtosecond laser selective micro-machining and fiber fusion splicing. By controlling the micro-hole location and fiber fusion splicing parameters, FPI with variable cavity lengths from 16μm to 61μm can be fabricated on the arbitrary core of multicore fiber, resulting in parallel FPIs structure. Finally, parallel FPIs with different responses are simultaneously fabricated on two cores of seven-core fiber, leading to different responses for both temperature and strain sensing. As a result, the cross-sensitivity between them can be successfully mitigated. Moreover, by managing micro-holes diameters, FPIs with variable cavity length are possible to be fabricated in individual core of multicore fiber, which is promising to realize a multiple-parameter discriminative sensing in harsh environment.

2. Fabrication of parallel FPIs

Our experiment setup of femtosecond laser enabled micro-holes selectively drilling has been described in details [7]. The cladding of used seven-core fiber is 150μm, and the spacing between two adjacent cores is 42μm, as shown in Fig. 1(a). Each core with a diameter of 9μm is surrounded by a low refractive index trench. By using an image processing algorithm, location of each core can be precisely locked. The parallel FPIs fabrication process is described as follows. First, with a pulse energy of ~2.5μJ and a pulse duration time of T=1s, two micro-holes are drilled on the different cores of a cleaved seven-core fiber facet, as shown in Fig. 1(a)-(d). Then, seven-core fiber with micro-holes is spliced with another seven-core fiber without micro-holes by a fiber fusion splicer (Fujikura, 100P+). Due to the suddenly heating of the micro-holes, two micro-holes rapidly expand to an elliptically hollow sphere, as show in Fig. 1(e)-(h). During the parallel FPIs fabrication, we investigate the influence of parallel micro-holes location and fiber splice duration time on the fabricated parallel FPIs cavities. All parallel micro-holes, as shown in Fig. 1(a)-(d), are fabricated under conditions of the same laser pulse energy and pulse duration time. Then, parallel micro-holes on Fig. 1(a) and Fig. 1(b) experience a fusion duration time of 1s, while micro-holes on Fig. 1(c) experiences a fusion duration time 1.2s. We experimentally identify that, the increase of fusion splicing time is helpful to enlarge the cavity length of fabricated parallel FPIs. However, for parallel micro-holes with centrally symmetrical distribution in Fig. 1(a)-(c), the cavity length at parallel FPIs is almost same, due to almost the same arc-discharge distribution. Therefore, in order to fabricate parallel FPIs with different cavity length, the parallel micro-holes are fabricated on core 1 and core 2 to bring a different arc-discharge distribution along fiber radial direction, and the fusion duration time is set to 1.5s. Finally, parallel FPIs with different cavity length are simultaneously fabricated, as shown in Fig. 1(h). The micro-hole at the core 1 experiences a relatively small arc discharge, resulting in a small FPI with a cavity length of 26μm. While for the micro-hole on the core 2, large arc discharge results in an FPI with a cavity length of 61μm. Then, the sensing characteristics of parallel FPIs with different cavity length can be investigated.

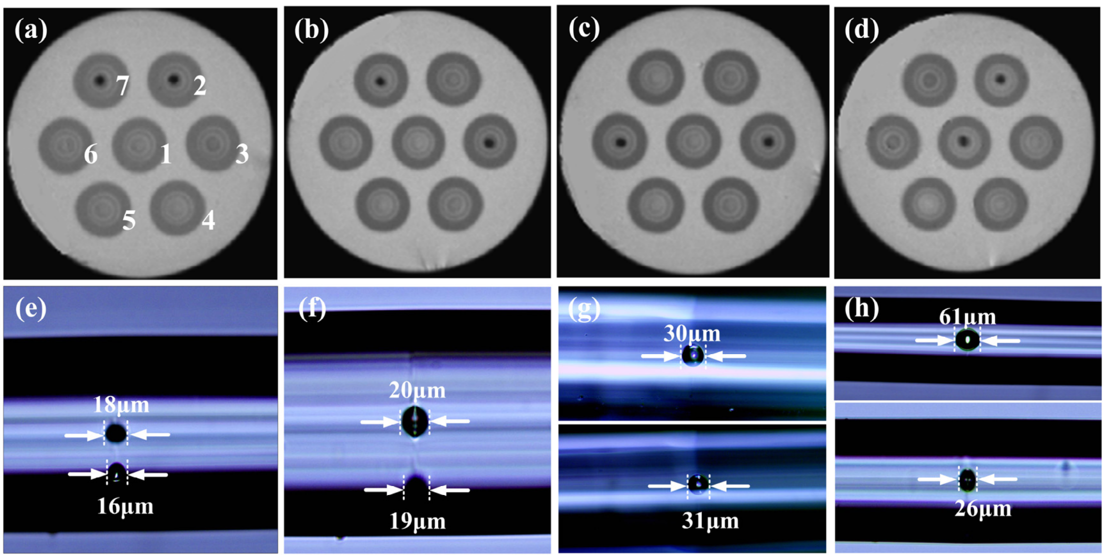

Fig. 1. (a)-(d) End view of four kinds of parallel micro-holes arrangements on the cleaved seven-core fiber facet. (e)-(h) Optical microscopic image of the fabricated parallel FPIs.

3. Experimental results of dual-parameter sensing

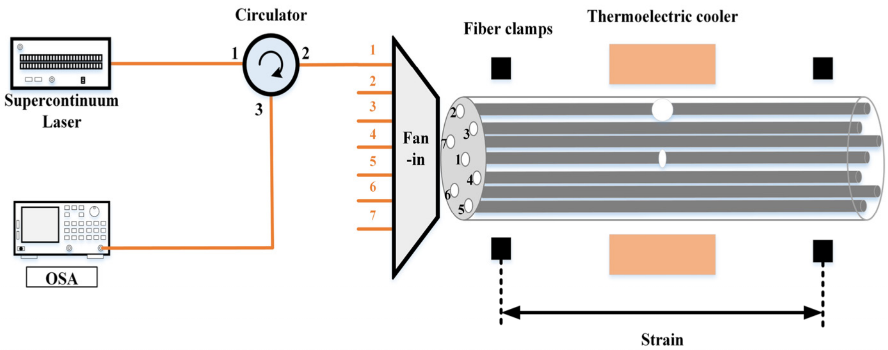

Fig. 2. Experiment setup for both temperature and strain simultaneous measurement.

Figure 2 shows the experimental setup of both temperature and strain simultaneous sensing by using the parallel FPIs fabricated in seven-core fiber. Light from the supercontinuum source covering the wavelength from 600nm to 1700nm goes through a circulator and introduce into single specific core of seven-core fiber with the help of the self-developed Fan-in device. Then, light is reflected by the micro-cavity of FPI, leading to the generation of an interference pattern recorded by OSA. By connecting the second port of the circulator with either 1 or 2 port of Fan-in device, parallel FPIs spectrum on core 1 and core 2 can be recorded. The responses of parallel FPIs reflection spectrum are shown in Fig. 3(a), and the dip wavelength A and B of each FPI reflection spectrum are monitored for the purpose of simultaneous measurement of both temperature and strain. Two ends of seven-core fiber are fixed by the fiber clamp, and seven-core fiber having parallel FPIs is placed on the thermoelectric cooler (TEC) with a resolution of 0.1°C to carry out the temperature measurement. When the strain is 0με, the temperature of TEC is increased from 20°C to 80°C with a step of 10°C, the wavelength shifts of two FPIs with respect to the temperature are shown in Fig. 3(b). Both FPIs possess a relative lower temperature sensitivity, due to the extremely low thermo-optic coefficient of silica with the air cavity. The temperature sensitivity of the core 1 is about 0.74pm/°C, while FPI at the core 2 possess a temperature sensitivity of 1.37pm/°C. As for the strain measurement of the parallel FPIs, two ends of seven-core fiber are fixed on the translation stage when the surrounding temperature is fixed at 30°C by the TEC. The strain is varied from 0με to 1000με with a step of 200με. The wavelength shifts of two FPIs with respect to the strain are shown in Fig. 3(c), respectively. FPI in the core 1 possess a strain sensitivity of 8.3pm/με, while the FPI in the core 2 has a strain sensitivity of 3.7pm/με.

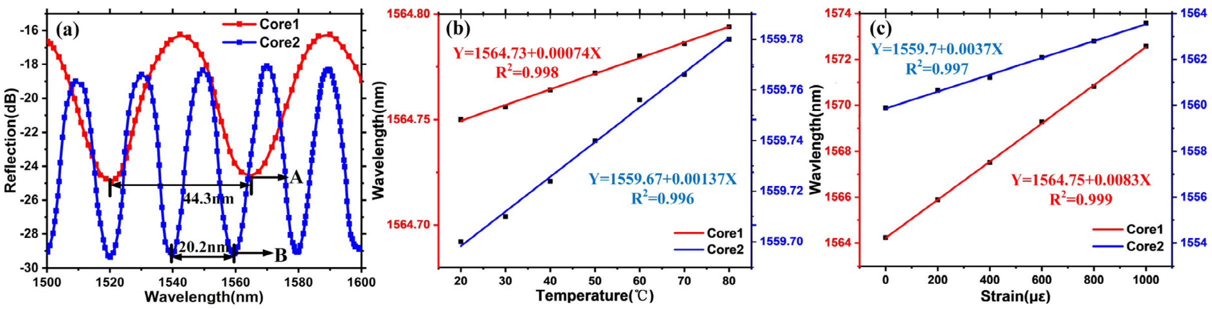

Fig. 3. (a). Optical spectral of the parallel FPIs. (b) Temperature and (c) strain response of the dip wavelength at the reflection spectrum of parallel FPIs

Due to the totally different sensitivity of the parallel FPIs towards the temperature and strain. A discriminative sensing of the temperature and strain can be realized by establishing a matrix equation, as shown in Eq. (1) [8]:

$$\begin{pmatrix} \Delta\varepsilon \\ \Delta T \end{pmatrix} = \begin{pmatrix} C_\varepsilon^1 & C_T^1 \\ C_\varepsilon^2 & C_T^2 \end{pmatrix} \begin{pmatrix} \Delta\lambda_{core1} \\ \Delta\lambda_{core2} \end{pmatrix} = \begin{pmatrix} 8.3 & 0.74 \\ 3.7 & 1.37 \end{pmatrix} \begin{pmatrix} \Delta\lambda_{core1} \\ \Delta\lambda_{core2} \end{pmatrix} \tag{1}$$

where C_ε^1 and C_ε^2 are the strain sensitivity, C_T^1 and C_T^2 are the temperature sensitivity of the FPIs at the core 1 and core 2, respectively.

4. Conclusion

We have successfully fabricated parallel FPIs on the seven-core fiber by femtosecond laser selective micro-machining and fiber fusion splicing. By controlling the micro-holes position and fusion splicing time, parallel FPIs with different cavity length can be fabricated, and discriminative measurement of both temperature and strain becomes possible, due to the different responses of parallel FPIs at different core. It is expected that, more parallel FPIs with different cavity lengths can be fabricated at individual core of multicore-fiber, and discriminative multiple-parameter sensing is promising under the harsh environment.

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