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多芯光纤及其在弯曲传感中的应用

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摘　要:采用纤芯间距为38.78 μm的国产多芯光纤设计了一种光纤弯曲传感器.该多芯光纤弯曲传感器由长度为1 m的七芯光纤与单模光纤拼接制成,多芯光纤弯曲时,相邻的纤芯发生模式耦合.在传感器一侧,将宽带光注入到位于多芯光纤中心的纤芯,用光谱分析仪测量带有曲率信息的频谱,获得弯曲传感器的透射谱波长偏移与弯曲曲率半径的关系.结果表明:多芯光纤弯曲半径越小,弯曲曲率越大,串扰越明显.

关键词:光纤应用;光纤弯曲传感器;模式耦合;多芯光纤;弯曲传感
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Multi-core Fiber and Its Application for Bending Sensor

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Abstract: A fiber bending sensor was proposed based on a home-made multi-core optical fiber with seven inner cores where the distance between adjacent cores is about 38.78μm. For a section of bending multi-core fiber, mode coupling happens between adjacent cores, which provides a method to achieve bending sensing by measuring the transmission spectrum of the bending multi-core fiber. The multi-core fiber-based bending sensor is fabricated by splicing a seven-core fiber with a length of approximate 1 m to single mode fibers. When a broadband light is injected into the central core of the multi-core fiber on one side, the transmission spectrum with the information of bending curvature can be measured by an optical spectrum analyzer. The relationship between the wavelength shift of the transmission spectrum and the bending radius of the multi-core fiber-based bending sensor shows that the output spectrum of multi-core fiber under bending condition has much more obvious crosstalk phenomenon along with the bending curvature of multi-core fiber increasing.

Key words: Fiber optic applications; Fiber bending sensor; Mode couping; Multi－core optical fiber
OCIS Codes: 060.2310, 060.2370, 080.2740

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0 Introduction

Optical fibers[1] are playing a critically important role in current information society due to their applications as the cornerstone of the optical communications with huge transmission capacity. Fiber optics has been developed to promote the development of optical fiber industry. Since the end of last century, several novel types of optical fibers including Photonic Crystal Fiber (PCF)、double-clad fiber and so on has been developed, which further enlarge the applications (e. g. fiber sensors) of the optical fibers besides optical communications. In recent years, Multi-core fiber[2-4] has been proposed and demonstrated to reduce the fiber optic cable manufacturing cost and overcome the limit of cable size[2-3]. However, few reports can be found for the sensing application of the multi-core fibers.

In this paper, we introduce a multi-core fiber with 7 fiber cores, and a fiber bending sensor based on the multi-core fiber was also proposed. Mode coupling[5] between two fiber cores of the multi-core fiber appears when the multi-core fiber is bending and inference spectrum in the output port of the central fiber core of the multi-core fiber is observed when the broadband light is injected to the input port of the central fiber core. Bending sensing is achieved by measuring the inference spectrum from the multi-core fiber.

1 Multi-core fiber

The multi-core fiber used in our experiment was provided by Futong Group, whose sectional view is showed in Fig. 1(a). Fig. 1(b) is the microscpoe image of multi-core fiber which six cores are respectively located around the coeners of a regular hexagon with a central core inside. The multi-core fiber has a central core and other six side cores that are arranged in a quasi-hexagonal array. All the seven cores have the same diameter of 10. 31μm, which is bigger than the core of conventional communication single-mode optical fibers (d=8. 6μm). The distance between core-A and core-B ,namely core-to-core pitch ,is designed with 38. 78 μm (Λ=38. 78 μm). The index difference between each fiber core and the surrounded cladding ($n_{core}-n_{clad}$) is approximately 0. 0045 in Fig. 1. (c) and (d), there are respectively presented simulated mode profile of the power flow of the fundamental mode of core-A and core-B. No mode coupling happens between each core under natural condition. Each core typically has a radius of only a few micrometers and the diameter of the multi-core fiber without polymer covering outside is 125. 03 μm and the acrylate dual coating diameter is 250 μm. The loss of fiber at 1 301 nm、1 383 nm and 1 550 nm are about 0. 317 dB/km、0. 301 dB/km and 0. 320 dB/km, respectively.

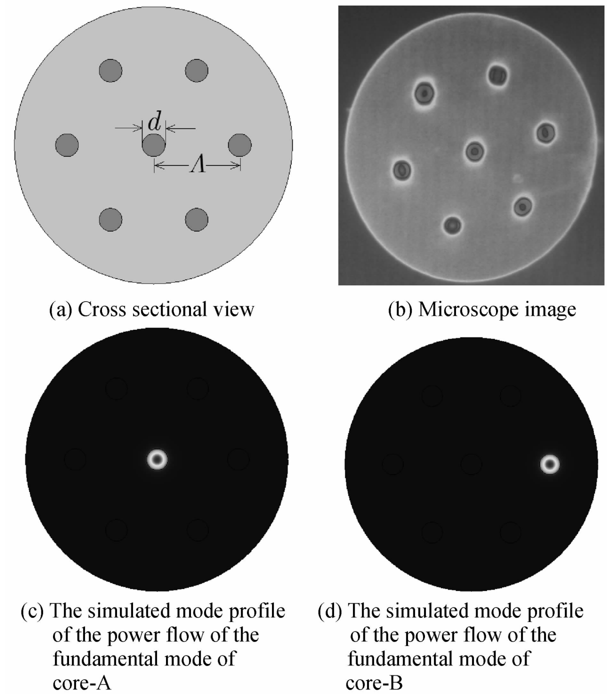


Fig. 1 The 7-core multi-core fiber

2 Bending sensing

Fig. 2 shows the experimental diagram for multi-core fiber′s application in bending sensing. As shown in Fig. 2, a broad light source which provides continuous wave broadband light whose wavelength ranges from 1 510 nm to 1 630 nm is utilized to inject light into the central fiber core of the multi-core fiber via a leading Single Mode Fiber (SMF). After removing optical fiber coatings, the multi-core fiber is spliced with single mode fiber with center alignment by arc fuison splicer (FSM-45PM-LDF). And we add heat-shrinkable tubings around the fusion place protecting them from breaking off. An Optical-Spectrum Analyzer (OSA) is used to analyse the relationship between the wavelength shift of the transmission spectrum and the bending curvature of the multi-core fiber-based bending sensor. The multi-core fiber used in our experiment is about 1m, and both ends are fusion spliced with SMF by matching the central fiber core to the SMF. The multi-core fiber is bended through intertwining a cylinder whose diameter can be artificially set. In our experiment, there are five different bending diameters for the multi - core fiber , namely , 14 mm,15 mm,

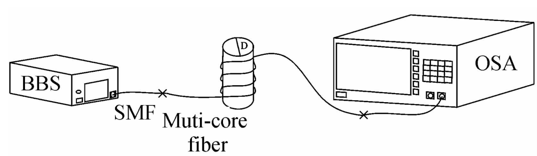
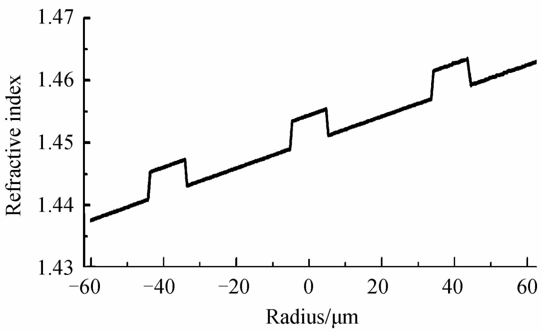


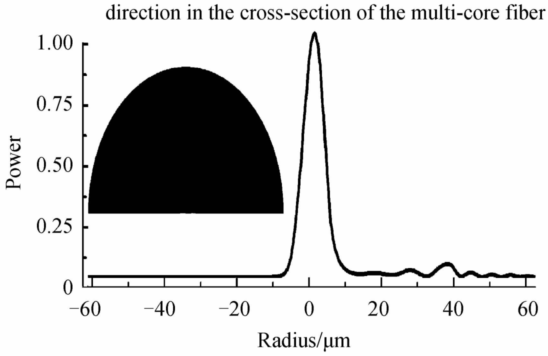
Fig. 2 Schematic diagram of the multi-core fiber based bending sensor

16 mm, 17 mm and 18 mm respectively. Bending curvatures are the reciprocals of those bending diameters, so smaller bending diameter means bigger bending curvature.

There are three fiber cores along the radial directional of the multi-core fiber. Each core has higher refractive index than the surrounded cladding silica. When fiber is bended, it would results in refractive index deformation in the radial directional of the multi-core fiber as the picture shows in Fig. 3 (a). We simulate the mode distribution of a bending multi-core fiber, with injected wavelength λ is 1 550 nm and cylinder diameter D=14 mm.



(a) Bend-induced refactive index distribution in radial direction in the cross-section of the multi-core fiber



(b) Mode distribution of a bending multi-core fiber

Fig. 3 Refactive index and mode distribution of a bending multi-core fiber

Since we splice SMF with multi-core fiber by matching the central cores, almost all light will propagates in the central fiber core (core-A) of multi-core fiber when the multi-core fiber is in the straight state. However, when the multi-core fiber is bending, the refractive index of the adjacent core (core-B) and the surrounded cladding silica between them become higher, leading to a mode coupling between the two fiber cores (core-A and core-B). The coupled-mode theory[6-8] illustrates the bending diameter dependence of crosstalk through introducing the index change caused by bending and twisting. According to the conventional coupled-mode theory[9,10], the output power on the output side of the fiber core-A and core-B of the multi-core fiber can be given by

$$P_1(z,\lambda)=\cos^2(S_z)+\cos^2(\eta)\sin^2(S_z) \tag{1}$$

and

$$P_2(z,\lambda)=\sin^2(\eta)\sin^2(S_z) \tag{2}$$

respectively. The maximum power transferred from the fiber core-A to the fiber core-B is

$$P_2|_{\max}=\sin^2(\eta) \tag{3}$$

which occurs at the coupling length $z=L_c=\pi/(2S)$. Note that we have

$$S=|n_e-n_o|\pi/\lambda \tag{4}$$

$$S=\sqrt{\delta^2+k^2} \tag{5}$$

$$\tan(\eta)=\delta/k \tag{6}$$

and

$$\delta=|n_a-n_b|\pi/\lambda \tag{7}$$

Where n_a and n_b are the effective index of the individual fiber core-A and the individual fiber core-B, respectively. When multi-core fiber is straight without strain, δ is equal to zero as the fiber core-A and the fiber core-B are symmetrical in the multi-core fiber.

As shown in Fig. 3 (a), the refractive index varies along the radial directional of the multi-core fiber under the bended condition, which provides the possibility for the mode coupling between the the fiber core-A to core-B [11-12]. We simulate the mode distribution of multi-core fibers when a bending diameter is 14 mm with an operation wavelength of 1 550 nm. Fig. 3(b) show that most part of the energy is concentrated in the core-A, and maximum power transferred from the fiber core-A to the fiber core-B with increasing bending curvature. According to the simulation, when the broadband polarized light is injected into the multi-core fiber, we can achieve bending sensing by measuring the wavelength shift of the output spectrum of the multi-core fiber with a fixed length.

The experimental results are shown in Fig. 4. After the broadband light is injected into the MFC, it will lose some power due to the bending loss of the multi-core fiber and the optical connection losses between single mode fiber and multi-core fiber. Obviously, bending losses rise up when the bending diameter being smaller. Besides, the fiber core is an ellipse rather than a standard circle, which makes that the output spectrum depends on the bending direction of the multi-core fiber. It is difficult for us to ensure that every bending can acquire the best interference condition in the experiments. There are existing five curves separately on behave of the sensor transmittted spectrum on the different bending diameters. As we can see in the Fig. 4, with the increasing of the bending curvature, much more power leaks outside which means the interference with outer cores becomes stronger.

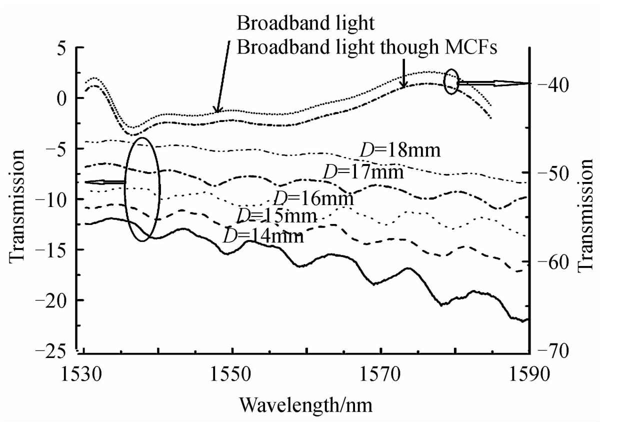


Fig. 4 Experimental results of output spectra of the multi-core fiber based sensor with the different bending diameters, respectively

4 Conclusion

In conclusion, we have proposed a 7-core multi-core fiber and experimentally demonstrated a bending sensor based on the multi-core fiber structure. Our experiment shows that the output spectrum of multi-core fiber under bending condition has much more obvious crosstalk phenomenon along with the bending curvature of multi-core fiber increasing. The multi-core fiber based bending sensor can be used for bending curvature measurement.

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