Stress test and analysis based on SMS fiber structure with high sensitivity

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Abstract: Single mode-multimode-single mode (SMS) sensor is widely used for parameters measurement, such as bending, displacement, temperature, strain, refractive index, etc. Generally, SMS sensor has advantages of simple structure, low cost and easy layout, therefore it has become a research hotspot in recent years. In this paper, the multimode fiber with large core is used for manufacturing SMS structure with high sensitivity. Firstly, the multimode fiber with core/cladding diameters of 105/125 μm has access to the system by means of single mode optical fiber. Secondly, SMS device structure is manufactured by welding the eccentric shaft of multimode optical fiber. Afterwards, mode interference effect and spectral response characteristics of the structure of single mode-multimode-single mode optical fiber are analyzed theoretically. Finally, with the help of a wide spectrum light source and a spectrum analyzer, the transmission spectra characteristics of SMS optical fiber with strain is tested. By observing the curve that the wave changes with stress, the sensitivity is calculated and it is consistent with theoretical value .

Key words: SMS optical fiber structure; optical spectrum analyzer (OSA); amplified spontaneous emission; stress test

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0 Introduction

Optical fiber sensors had been developed rapidly in the past years as a new type of sensor. Not only it has many excellent characteristics of the fiber, but also frequency of the photon is much higher than radio (microwave) as an information carrier for information exchange and transmission, therefore, it has become one of the fastest growing international high-tech applications in recent years. After that, a single mode-multimode-single mode (SMS) optical fiber structure, which integrates the advantages of single-mode and multimode structrues with spectral filtering and sensing characteristics, has attracted widespread attention. Since the optical fiber sensing system with SMS structure uses single-mode fiber for signal transmission, which greatly reduces the transmission loss. By making use of the selective transmission of SMS fiber structure, the series interference to micro-bending sensors can be controlled effectively. The researchers found that SMS transmission spectrum is very sensitive to the change of multimode fiber length. Observing the change of SMS transmission spectrum to detect small variation in displacement is the sensing mechanism of SMS-based strain sensor. As early as 2000s, Mehta A, et al. proposed displacement sensor based on reflective SMS structure, which perceives the small displacement change[1] by monitoring the wavelength of the SMS reflection spectrum structure . Subsequently, based on this theory, Ribeiro R M, et al. analyzed the response of SMS optical fiber structure transmission spectra with longitudinal strain detailed[2]. In 2004, Mohammed W S, et al. made detailed theoretical derivation with

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the coaxial welding of different patterns of coupling coefficients of SMS mode, the image points of inside and outside conditions of multimode optical fiber[3]. In 2006, LI En-bang, et al. used higher-order mode interference to construct a reflective SMS fiber structure for high temperature measurements[4]. In 2007, LI En-bang used opposite polarity of SMS fiber structure for temperature and strain response and achieved a temperature compensation by reasonable sealing[5-6]. In addition, a number of research institutions at home and abroad have devoted themself to research on the SMS fiber sensor by combining different types of multimode optical fiber structures or SMS fiber structure with other optical devices to improve sensor sensitivity and efficiency[7]. In 2009, ZHANG Jian-zhong, et al. used multimode fiber (MMF) to construct Fizeau cavity for temperature and strain measurement simultaneously[8-9]. Silva S, who used SMS fiber structure to achieve independent bending sensor for temperature and strain measurement[10]. In 2010, Frazao O, et al. done a refractive index research on SMS structure[11]. In 2011, WU Qiang, et al. utilized a special fiber bragg grating (FBG) structure in SMS and used wavelength demodulation scheme to construct a new refractive index sensor with the range of refractive index from 1.324 to 1.439[12] and the experimental measured refractive index sensitivity as high as 7.33 nm/RIU.

This paper proposes a simple, low-cost and new optical sensing unit for strain measurement, which is composed of an off-axis welding SMS fiber structure. To acquire the information of sensing unit with a broadband light source, an optical spectrum analyzer (OSA) is used to obtain the required spectrum by observing the growth peak spectra in two particular locations corresponding to the wavelength drift strain demodulation.

1 Theoretical analysis

Experimental system is shown in Fig. 1. The off-axis optical fiber structure can be fused with SMS through the following steps. Firstly, fiber cleaver is used to cut multimode fiber (MMF) and a input standard single-mode fiber (SMF-28) end surface. Then both are placed in fiber welding machine. After manually adjusting the position of multi-mode fiber and single-mode fiber until the vertical offset of two fibers is less then 6 $\mu\varepsilon$, arc discharge starts and the splice after discharge is shown in Fig. 1. Finally, the other end of the multimode optical fibe is welded with output single mode fiber. The diameters of multimode fiber core/cladding are 105/125 μm with refractive indexes of 1.465 5/1.446 2, and multimode fiber length is 10 cm or so. The incident light source is a broadband light source with spectral range of 1 520—1 610 nm. Output single-mode optical fiber and OSA are connected for signal acquisition and demodulation.

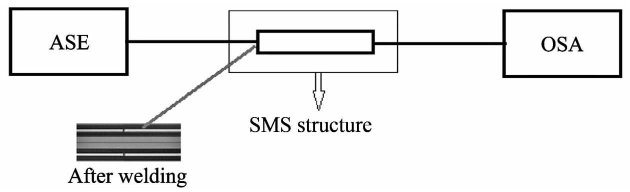

Fig. 1 Experiment table

When multimode fiber suffers from stress in length, changes will occur, leading to variation in SMS transmission spectrum. Stress-induced deformation is divided into longitudinal strain and lateral strain, that is, in the cross-section direction and transmission direction of fiber. In this paper, we discuss the influence of longitudinal strain on SMS output line. Only considering interference of adjacent modes, when the extreme value occurs between two neighboring modes[13], the wavelength can be expressed by

$$\lambda=\frac{16n_{\text{core}}a^{2N}}{(m-n)[2(m+n)-1]L_{\text{MMF}}} \quad (m>n), \quad (1)$$

where n_{core} means core refractive index of the multimode fiber, a represents multimode fiber core diameter, and L is length of multimode fiber. At a certain temperature, change of SMS fiber output spectrum depends on length of MMF. When SMS is subjected to radial stress, MMF length L will have small change, ΔL, called micro-strain. In this case, the output lines will be affected. Assuming that the temperature is constant[14], the amount of change in output wavelength can be expressed by

$$\frac{\Delta\lambda}{\lambda}=\left[\frac{1}{n_{\text{core}}}\Delta n_{\text{core}}+\frac{2}{a}\Delta a-\frac{1}{L}\Delta L\right]_T, \quad (2)$$

where λ represents wavelength, n_{core} means multimode fiber core refractive index, d is the core diameter of the multimode fiber, L is the length of multimode fiber, and T represents a temperature.

By deduction, if the optical fiber is only affected by the axial stress ε[15], there is

$$\frac{\Delta n_{core}}{n_{core}}=-\frac{n_{core}^{2}}{2}[P_{12}-\nu(P_{11}+P_{12})]\varepsilon=-P_{e}\varepsilon, \quad (3)$$

where P_{11} *and* P_{12} are elastic-optic coefficients, P_e is valid elastic-optic coefficient and ν is Poisson coefficient. $\Delta L/L=\varepsilon$ and $\Delta a/2=-\nu\varepsilon$, therefore, the above equation can be rewritten as

$$\frac{\Delta\lambda}{\lambda}=-(1+2\nu+P_{e})\varepsilon. \quad (4)$$

For ordinary optical fibers, $\nu=0.17$ and $P_e=0.22$.

As can be seen from the above equation, similar to the temperature characteristics, when longitudinal stress is applied to SMS, SMS transmission spectrum wavelength will drift. Through observation, the spectral line linearly decreases in a monotone with the increase of longitudinal strain.

2 Experiment and analysis

According to Ref. [16], there are several growth peaks of SMS transmission spectrum. After the exclusion of broad spectrum light source, the transmission spectrum is shown in Fig. 2.

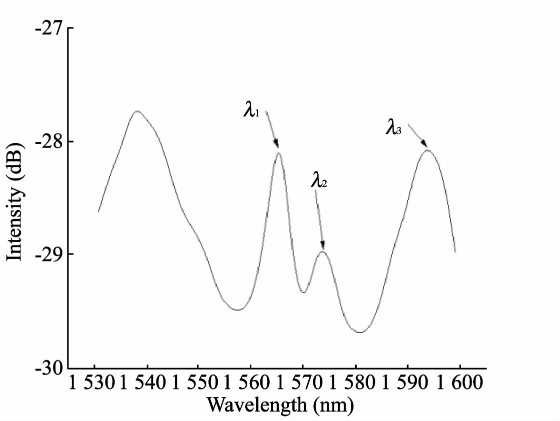

Fig. 2 Transmission spectrum of SMS structure without stress

It can be seen that there are some obvious growth peaks such as λ_1, λ_2 and λ_3. Because of the growth peak wavelength corresponding to λ_3 is instable, we only observe the change in wavelength. When the multimode fiber is applied to external stress, wavelength λ_1 and λ_2 corresponding to the two growth peaks will drift because multimode fiber size and effective refractive index change with the stress, which causes change of optical distance of multimode optical fiber transmission mode, resulting in change of multimode interference position and drift of growth peak.

Firstly, we test the sensor with the change of stress. SMS structure is put up in the micro-displacement stage and three to five cells are rotated each time (stretching 30−50 μm), transmission spectra under different stress values are shown in Fig. 3. It can be seen from Fig. 3, under the same stress, different growth peak wavelength drifts are obviously different: the first growth peak wavelength shift is larger than the second; when the external stress exceeds 275 με (assuming fiber move 1 to 5 μm by strain), the shape of the transmission spectrum has dramatic change, beyond the measurable range.

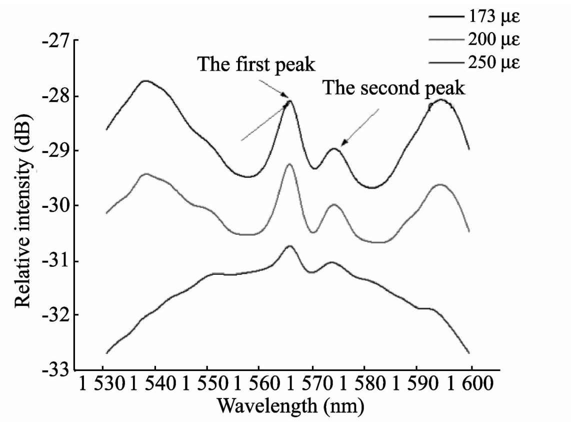

Fig. 3 SMS transmission spectra under different stress

Figs. 4 and 5 numerically reflect the changes of two growth peak wavelengths λ_1 and λ_2 with stress. By linear fitting, the sensitivities are −42.15 and −72.61 pm/με, respectively. The latter is more than 1.5 times the former, and the sensitivity corresponding to λ_1 is one of the larger values of the multimode optical fiber sensor. After linear fitting according to the measured value, it can be found that deviation level of measured value and fitted value is standard deviation of the difference between the measured value and the fitted value of 0.055 7 and 0.078 6. The value obtained by experiment is −42.15 pm/με and the value theoretically calculated is −40.78 pm/με. Both are relatively close. Therefore it is believed at this time, the interference patterns of LP_{13} and LP_{14} play a major role and the contribution of other modes is relatively poor. The other strain sensitivity is larger than the theoretical value of −72.61 pm/με, which results from the interaction of these five modes.

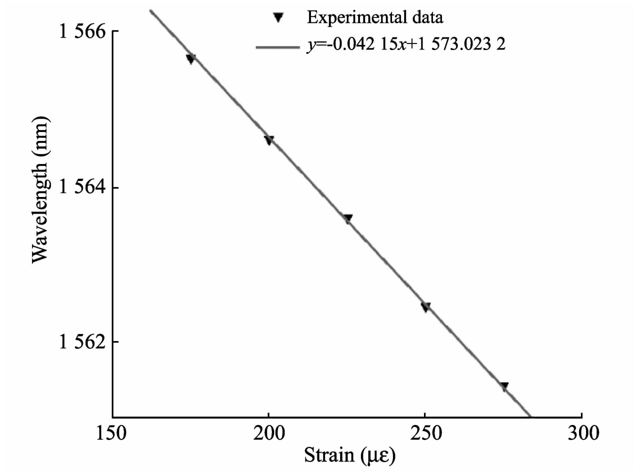

Fig. 4 Relation of λ_1 and strain

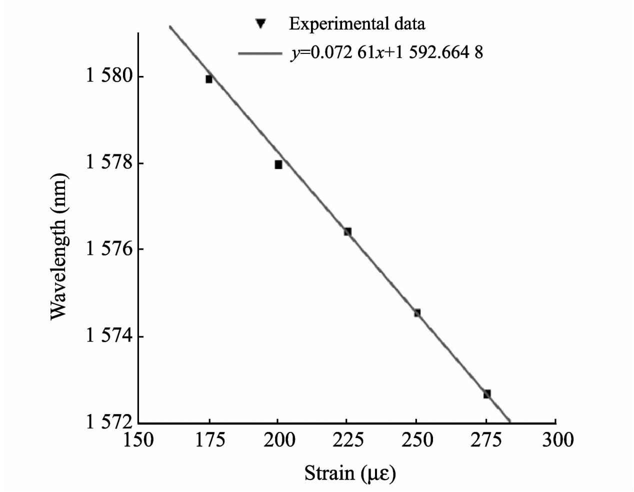

Fig. 5 Relation of λ_2 and strain

To prove such a phenomenon from arbitrary multimode and off-axis SMS fiber, the sensing properties of off-axis multimode fiber are tested. With fiber length of 8 cm and the same experimental environment and methods as above, when stress is applied to the sensor, growth peaks λ_1 and λ_2 generate corresponding response with applied stress. Under the same change of micro-strain, the drift of growth peak 2 is significantly larger than that of the growth peak 1. By fitting the data, it can be concluded that the two sensitivity values are relatively close because the off-axis of the latter is relatively smaller and less high-order mode leads to less energy.

3 Conclusion

In this paper, we design a new optical fiber sensor for measuring stress. Experimental test and verification are conducted. Using off-axis welding SMS optical fiber structure, based on the fact that the responses of two growth peaks to the stress are different, stress measurement is carried out. The sensor has the advantages of simple structure, portablity, anti-electromagnetic interference, etc. thus it is expected to have wide applications in national security visit and structure inspection. However, since multimode fiber selected is slightly longer, the result is not very satisfactory, which needs to be improved.

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基于 SMS 光纤结构高灵敏度应力测试与分析

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摘　要： SMS 传感器结构简单、成本低廉、易于铺设，被广泛的应用于弯曲、位移、温度、应变、折射率等参量的测量，近年来成为研究的热点。本论文利用大芯径多模光纤制作 SMS 结构以实现高灵敏度的光纤传感结构。首先，将纤芯/包层直径为 105/125 微米的多模光纤通过单模光纤接入光纤系统，实现 SMS 光纤结构，通过对多模光纤进行偏轴熔接的手段制作 SMS 器件结构；然后对单模-多模-单模光纤结构的模式干涉效应和光谱响应特性进行理论分析；最后，借助宽谱光源和光谱分析仪测试了单模-多模-单模光纤结构随应力变化的透射光谱特性，通过对波峰随着应力改变而发生变化的曲线的观察，计算出其灵敏度，发现实验值与理论值基本吻合。

关键词： SMS 光纤结构；光谱仪；宽谱光；应力测试

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