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Rayleigh backscattering based macrobending single mode fiber for distributed refractive index sensing

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ABSTRACT

A novel and compact distributed refractive index (RI) sensor based on Rayleigh backscattering and macrobending single mode fiber (SMF) is proposed and experimentally investigated. Our proposed sensor is simply fabricated by bending a piece of SMF to a radius of curvature in several millimeters. We detect the refractive index of the external medium surrounding the macrobending fiber, for the first time, by analyzing the Rayleigh backscattering signals recorded from optical frequency domain reflectometry. We measure the range of the RI from 1.3348 to 1.3557 using the proposed method. To verify the capability of the distributed sensing, we also use this sensor to detect multipoint RIs simultaneously. The RI measurement sensitivities are 2319.24 GHz/RIU (18.55 nm/RIU) and 2717.85 GHz/RIU (21.74 nm/RIU) with bending diameters of 12.2 mm and 11.3 mm, respectively. In addition, our macrobending fiber has its original buffer coating remaining intact, allowing the fiber to maintain optimal mechanical property and be suitable for more practical applications.

1. Introduction

Fiber optics refractive index (RI) sensors have been studied and proposed extensively for biomedical, chemical, industrial and environmental applications over the past decades [1], owing to their well-known advantages such as immunity to electromagnetic interference, compact size, light weight, potential low cost and the possibility of distributed sensing over a long distance [2–6]. Most of the optical fiber based RI sensors work in the principle of interaction of the evanescent field with the external medium. A number of optical fiber RI sensors have been proposed with different structures, such as a long period fiber grating (LPFG) [7,8], fiber Bragg gratings (FBG) [9], optical fiber surface plasmon resonance (SPR) [10], photonics crystal fiber based sensor [11], Fabry–Perot refractometer [12–14], thin core fiber based sensor [15], in-fiber Mach–Zehnder refractometer [16] or single-mode-multimode-single-mode (SMS) fiber [17–19].

In recent years, an interesting idea of designing an optical fiber based RI sensor is to simply bend a single mode fiber (SMF). This method has attracted considerable interests in RI measurement due to its easy fabrication and high sensitivity. For instance, Sun et al. developed a fiber taper-based modal interferometer with a microfiber bend [20]; a leaky mode interferometer of bend fiber was also presented by Zhang et al. [21]; Chen et al. proposed a RI sensor based on macrobending fiber Bragg grating [22]; Wang et al. introduced a RI sensor based on macrobending single mode fiber by measuring bend loss [23,24], and they also reported a Whispering Gallery mode based RI sensor, in which high loss fiber was used after removing the buffer coating and bent in the shape of ring [25]. Though some of these techniques can achieve very high RI sensitivity, the sensor fabricated by stripping the coating, polishing, etching, tapering or drilling makes the fiber more fragile [7–25]. Moreover, most of these methods are point sensors and difficult to realize distributed sensing or multiplexing based on their proposed interrogation methods, showing less interest in practical applications. In addition, the aforementioned RI sensors based on bending structures work in transmission mode, which may limit their practical applications. As such, designing a RI sensor based on bending structure with distributed sensing capability and reflection mode is highly needed.

The macrobending single mode fiber structure is sensitive to changes in refractive index of the external medium. Due to the macrobending of the fiber, the light travelling in the core will be partially coupled into the cladding and therefore generates multiple cladding modes with different orders. An interferogram will be formed due to multimodal interference. It has been approved

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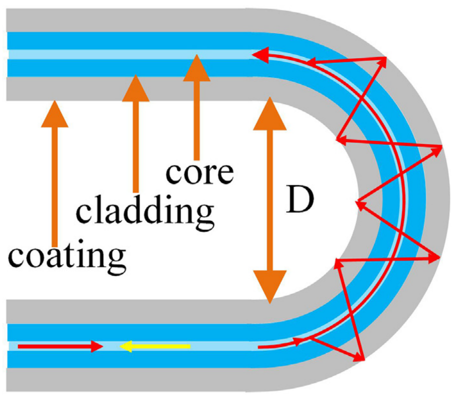

Fig. 1. Schematic diagram of a macrobending fiber consisting of core, cladding and coating. *D* is bending diameter of this structure.

that this interferogram can be used for ambient RI sensing [26]. Typically, the interferogram is acquired by a broadband source and optical spectrum analyzer, or a scanning laser with a photodetector. It would be difficult to realize distributed sensing based on these conventional interrogation methods. Inspired by the traditional Rayleigh scattering based distributed sensing technology, for the first time, we are considering to use Rayleigh backscattering to acquire the interferogram due to multimodal interference. Potentially, distributed RI sensing with macrobending structures can be achieved based on this method. Rayleigh backscattering is caused by random refractive index fluctuations along an optical fiber, and it can be modeled as a long, weak FBG with random periods [27]. The strain or temperature variation causes a local Rayleigh backscattering spectra (RBS) shift, which can be calculated using the cross-correlation between the measured RBS and a reference RBS [28]. When we combine the technologies of the macrobending single mode fiber and distributed sensing using an RBS shift, a Rayleigh backscattering based macrobending single mode fiber for distributed refractive index sensing can be developed.

In this paper, we propose and demonstrate a distributed refractive index sensing technology based on Rayleigh backscattering and macrobending single mode fiber. Our proposed sensor can be easily fabricated by bending a piece of SMF to a radius of curvature in several millimeters. We detect the refractive index of the external medium surrounding the macrobending fiber by measuring the RBS shift using optical frequency domain reflectometry (OFDR). In our experiment, we measure the range of the RI from 1.3348 to 1.3557 using the proposed method. We also use this sensor to detect multipoint RIs simultaneously to verify the capability of distributed sensing. In addition, our macrobending fiber has buffer coating remaining which helps to maintain the mechanical property of the sensor and makes it robust in practical applications.

2. Structure design and measurement principle

A schematic diagram of Rayleigh backscattering based macrobending single mode fiber is illustrated in Fig. 1. The structure of bending fiber is fabricated mechanically with a selected bending diameter. The buffer coating in the bend fiber remains intact to prevent it from breaking. Also, it has been proven that the RI variation of the external medium can be detected with the intact coating via our Rayleigh backscattering based method. The two ends of fiber after the bending part are fed through two microtubes with a length of 4 cm and inner diameter of 0.5 mm, respectively. We use 3 M industrial tape to hold both the microtubes and the fiber on a plastic plate with a length × width of 60 × 30 mm, so the bending structure can be fixed with a certain bending diameter. To verify the capability of multipoint RI sensing, we make the same structure at another position along this fiber with a different bending diameter. This easy-to-build and robust structure can be easily employed at any position along the whole fiber for distributed RI sensing.

When the light propagates along the straight SMF to the bending section as shown in Fig. 1, high order cladding modes confined in the optical fiber itself will be excited, where the light in the core will be coupled to the cladding therefore generates multiple cladding modes with different orders. As we know that the RI of the cladding is lower than the RI of the fiber core. If the RI of the external medium is lower than that of the coating, meanwhile the bending diameter is not too small, the radiated field of total internal reflection will not only occur at the core-cladding boundary but also the coating-surrounding boundary [22,25,29]. After the light travels through the bending section, the RI of the external medium modifies the coupling light, the light recoupled to the core mode will interfere with the remaining mode and generate interference fringes in the spectral domain, an interferogram will be formed due to multimodal interference, which causes a spectral shift in interferogram at this bending section [20,21,25,26]. The Rayleigh backscattering light will also be coupled in the bending section and experience multimodal interference, which could be used for RI measurement. The phase difference between the core and the cladding mode after propagating through the bending section of fiber can be written as $\Delta\Phi = \frac{2\pi}{\lambda}\left(n_{co,eff} - n_{cl,eff}\right)L = (2m+1)\pi$ [21,22], where $n_{co,eff}$ and $n_{cl,eff}$ are the effective RIs of fundamental core mode and cladding mode, respectively. L is the effective dsflength of bending section, λ is the wavelength. The central wavelength of the dip induced by the macrobending fiber structure can be described as $\lambda_m = \frac{2}{2m+1}\Delta n_{eff}\cdot L$, where $\Delta n_{eff} = n_{co,eff} - n_{cl,eff}$ is the effective RI difference between the core mode and cladding mode, m is an integer. When our bending structure is subjected to external RI perturbation, the Rayleigh backscattering spectra (RBS) shift is $\Delta\lambda = \frac{\delta n_{eff}}{\Delta n_{eff}}\lambda_m$, where δn_{eff} is the variation of Δn_{eff} caused by surrounding RI chage. Thus, RI of external medium can be detected and evaluated by measuring the RBS shift.

The Rayleigh backscattering originates from the random fluctuations in the index profile along the optical fiber and it can be modeled as a long, weak FBG with random periods [27]. The RI variation causes some modification in the local Rayleigh backscattering, which cause a shift in the Rayleigh backscattering spectra (RBS). We can detect the local spectral shift by cross-correlation to realize the RI measurement. The signal processing is similar to that of distributed temperature sensing based on the RBS shift in OFDR [28]. Our signal processing procedure for RI sensing in detail is as following:

a The reference and measurement signals with different RI values are acquired separately.
b The signals from the optical frequency domain are converted to the spatial domain by fast Fourier transform.
c A sliding window with a width of ΔX is used to select the local Rayleigh backscattering.
d To increase the frequency resolution, the local Rayleigh scattering signal in spatial domain after applying a window function is zero-padded.
e These selected local Rayleigh backscattering signals are converted back to the optical frequency domain by inverse fast Fourier transform.
f Cross-correlation is performed between the reference and the measured RBS to obtain the spectral shift. The cross-correlation peak is spectral shift of the local RBS, which reflects the RI variation of external medium.