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Study on the effect of carbon nanotube coating on the refractive index sensing sensitivity of fiber modal interferometer

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ABSTRACT

Refractive index sensing of liquid is important in the domain of chemistry and biology. Fiber optical sensors provide an excellent way to measure the refractive index due to their feasible integration to other fiber optics components, high sensitivity, small size, and distributed sensing. However, conventional optical sensors have different shortages. To find a practical way to measure the refractive index of liquid, this paper intended to combine Carbon Nanotube (CNT) with non-core fiber (NCF) to prepare a kind of modal interferometer sensor and to explore the effect of CNT coating on refractive index sensing properties of the modal interferometer. Firstly, a structure of single mode non-core single mode (SNS) fiber with a CNT film coating was proposed and simulated. The simulation results showed that the CNT coating could improve the refractive index sensitivity of the interferometer sensor. Then in the experiment part, the CNT solution was fabricated and deposited onto the NCF, and a refractive index sensing system was built to examine the property of the CNT-coated SNS interferometer sensor. During the experiment, the influence factors of sensitivity were summarized by testing the sensing performance under different conditions, and it was demonstrated that the CNT coating could improve the contrast of the interference spectrum, and also had the possibility to increase the refractive index sensitivity of the interferometer sensor.

1. Introduction

In recent years, refractive index sensing has been paid close attention. It has been proved that the refractive index acted a crucial role in the studies of different kinds of liquid. It can be used to analysis the contents of different materials like glucose, carbamide, and vitamin. Consequently, the sensing of refractive index becomes an important process in many biological and environmental applications [1]. Optical fiber sensors have been used widely in refractive index sensing, due to their incomparable merits such as anti-electric magnetic field interference, anti-corrosion, light weight, possibility of remote-distance sensing, and flexibility [2]. There are several technologies used in the optical fiber sensors like optical grating [3], surface plasmon resonance (SPR) [4], and fiber interferometer [5]. However, these methods also exist some shortages: the traditional optical grating technology is a widely-used method in optical fiber sensing, but its sensitivity cannot be assured; the SPR technology can provide high sensitivity while its cost is too high; the fiber interferometer sensor is low cost, but it has also a low sensitivity and is susceptible to the surroundings to be practically used [5]. By comparison, fiber modal interferometer sensor has its own unique advantages, such as low-cost, easy fabrication, and high stability. In recent years, studies of modal interference theory used in the domain of refractive index measurement experienced a rapid growth. In 2014, Rui Xiong and his group proposed an optical fiber sensor for measuring refractive index and temperature, which was based on modal interference theory, and its sensitivity of refractive index was −37.9322 nm/RIU [6]. In 2016, Chao Li and his group proposed an optical fiber sensor based on multipath Mach-Zehnder interferometer. This device consists of a segment of four-core fiber (FCF) spliced between two single mode fibers (SMFs), and its sensitivity to refractive index can reach 91.39 nm/RIU [7]. Among all these different kinds of sensors based on the theory of modal interference, it can be seen that

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traditional modal interferometer based sensors can hardly gain a high sensitivity. To improve their sensitivity, scientists attempt to change the basic structure of the sensors. For example, in 2011, Wu and his group eroded part of the fiber cladding and the core in a single-mode-multimode-single-mode structure, and they used this structure to measure liquid refractive index. The maximum sensitivity is 1815 nm/RIU [8]. In 2016, Jie Li and his group made an investigation on single taper-based all-solid photonic bandgap fiber modal interferometer. This special structure promoted the sensitivity of the sensor to 3512.36 nm/RIU [9]. Although they promote the sensitivity of the sensor to a whole new level, we have to admit that the structure of the sensor has been damaged. This may bring a series of stability problems when the sensor is used in practical environment.

In the recent years, there also has been an increasing interest of researching how a thin film deposited on the sensing element of an optical fiber will improve the sensitivity of the element. In 2004, M. Penza and his group experimentally proved that the carbon nanotubes (CNTs) can improve the refractive index sensitivity of optical sensor to a certain level [10]. In the year of 2015, Arafat Shabaneh and his group used CNT coated taper multi-mode optical fiber to measure the alcohol concentration. The sensitivity of the sensor reached 0.1441/vol% when the alcohol concentration ranged from 5% to 80% [11]. Among all these studies, CNT shows great potential as an active material in electronic and photonic devices due to its broad operating wavelength, good stability, and easy fabrication process [12–15].

Based on the above analyses, we proposed an assumption that the depositing of CNT on non-core fiber of a single mode non-core single mode (SNS) modal interferometer would improve the sensitivity of the sensing element, when it is used to measure the refractive index of ambient surroundings. In this paper, this assumption has been analyzed and examined in three aspects: theoretical analyzing, simulation and experiment. In the theoretical analyzing part, we concluded to a result that the evanescent field in the optical fiber will be enhanced by the high refractive index of CNT, thus intensifying the effect of the surroundings to the sensing element, which will extremely promote the sensitivity. In the simulation part, the SNS optical fiber structure was established in software. The impacts of the length and the CNT coating thickness of the NCF to the sensitivity of the sensing element was simulated and evaluated. In the experiment part, a SNS interferometer with the CNT coating on the NCF was fabricated and tested. The result showed that the depositing of CNT could improve the sensitivity of the optical fiber modal interferometer.

2. Theoretical analysis

The structure of the SNS modal interferometer is shown in Fig. 1.

The design of this sensing structure is based on the Multi-Mode Interference (MMI) theory. Since the core diameter, core length, and effective refractive index of the multi-mode fiber will all be changed by the changing of the surroundings, the multi-mode interference effect inside the fiber will also be influenced, which means that the output transmission spectrum will be drifted and the light energy will be altered [16]. In the sensing element, a short length of non-core fiber has been spliced between two SMFs. This structure provides two welding regions lying between the SMFs and the non-core fiber. The fundamental mode propagated from the SMF will be excited in this region because the NCF is not matched with the SMF [17–19]. The broadband optical signal created by the light source will firstly propagate through the SMF and be excited into multiple modes in the first welding region, including fundamental mode and cladding modes. Since the propagation parameters are different between the fundamental mode and the cladding mode, there will be a phase difference between the two different modes. The light will propagate along the NCF in different modes and finally recombine at the second welding region where the interference will happen. Than the coupling light will propagate into the output SMF. According to the evanescent field theory, the non-cladding structure of the NCF will guarantee the changes of the surrounding refractive index affecting the propagation of the light inside of the fiber directly, which means that the effective refractive index of the multiple modes will also be changed. The changes will make the light wave energy redistribute, which will cause a movement of the interference spectrum that can be monitored to deduce the changes of the surrounding refractive index.

Due to the difference of structure parameters between the NCF and the SMF, the fundamental mode of optical signal will be excited to a series of high-order modes LP_{0m}. Assuming the SMF and the NCF are jointed in a non-eccentricity state, only the LP_{0m} mode will be excited [20] because of its central symmetry. According to the continuity condition of electromagnetic field, the light field inputted from the SMF can be expressed as:

$$E(r,0) = \sum_{m=1}^{N} c_m F_m(r) \quad (1)$$

where N is the total number of modes existed in the NCF, c_m is the excitation coefficient of order m, $F_m(r)$ is the optical field of order m, respectively. c_m can be determined as:

$$c_m = \frac{\int_0^\infty E(r,0)F_m(r)rdr}{\int_0^\infty F_m(r)F_m(r)rdr} \quad (2)$$

while the light wave propagates for a distance of z, the optical field can be expressed as:

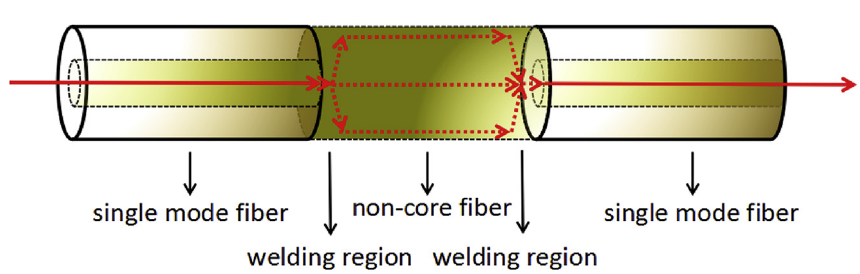

Fig. 1. Structure of the SNS modal interferometer.