Sensors and Actuators A 228 (2015) 62–68

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Cladless few mode fiber grating sensor for simultaneous refractive index and temperature measurement

Hang Zhou Yang[a], Muhammad Mahmood Ali[b], Md. Rajibul Islam[b], Kok-Sing Lim[b,c,*], Dinusha Serandi Gunawardena[b], Harith Ahmad[b,c]

[a] School of Physics, Northwest University, Xi'an, Shaanxi 710069, China
[b] Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia
[c] Department of Physics, Faculty of Science, University of Malaya, 50603 Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 9 December 2014
Received in revised form 15 February 2015
Accepted 2 March 2015
Available online 9 March 2015

Keywords:
Few mode fiber
Bragg gratings
Chemical etching
Refractive index sensing
Temperature sensing

ABSTRACT

In this work, we have demonstrated a cladless few-mode fiber grating sensor for simultaneous measurement of refractive index (RI) and temperature. The proposed sensor is fabricated from an etched few-mode Fiber Bragg Grating (FMFBG) that can support two Bragg wavelengths, in which the sensitivities for each Bragg wavelength to the changes of RI and temperature are different. A mode coupling theory is used to describe the sensing principle of the proposed sensor and the simulation result finding that an etched diameter of 14.1 μm can get the better performance for optimal the power confinement of etched FMFBG. Experimental results show that the proposed sensor has the RI sensitivities for both λ_{01} and λ_{11} are estimated to be 1.183 nm/RIU and 4.816 nm/RIU respectively, and temperature sensitivities for λ_{01} and λ_{11} are 9.62 ± 0.08 pm/°C and 9.52 ± 0.13 pm/°C respectively. With the assistance of 3×3 characteristic matrix, discrimination measurements of temperature and RI has been demonstrated and the deviations in RI and temperature measurements are $\pm 8 \times 10^{-4}$ RIU and ± 1 °C respectively.

1. Introduction

Since last few decades, optical fiber sensors such as fiber Bragg gratings (FBGs), long period gratings (LPGs), interferometers, surface profile scanners, leakage light based sensors etc., have proven their pivotal role as industrial sensors in physical, chemical and biological applications [1–8]. It is due to their tremendous advantages such as compact structures, single sensing element, linear response, good robustness, immune to electromagnetic (EM) interference and capability of simultaneous detection of more than one measurands such as chemical concentration of the solution based on refractive index, temperature and etc. [1,2]. Discriminative measurement for multiple measurands is achieved by exploiting the difference in the phase variations of different transverse modes in the fiber. With the aid of 2×2 characteristic matrix, accurate determination of each measurand can be demonstrated. Various types of structures using optical fibers have been proposed by different researchers for the achievement of simultaneous sensing of parameters. The continual development of these kinds of sensors have eventually led to the commercialization of various devices for the applications of measurement of blood glucose level and detection of glutamate, aspartame, sulfite, lactose and, ethanol in food and water products [3]. The biosensor and chemical sensor industry is holding a great promise for addressing the need for simple, fast, and continuous in situ monitoring techniques. Generally, most of the optical biosensors and chemical sensors are based on the detection of the fluorescence intensity or the measurement of the analyte RI.

In the sensing of liquid RI, a sensor comprises of a FBG was proposed for temperature and refractive index measurement in which a pair of incoherent waves from the FBG and the facet end due to Fresnel reflection are employed for sensing [9]. Similarly, many researchers have proposed other fiber optic based sensors like as tilted FBGs [10,11], LPGs [12], double cladding fibers (DCFs) [13] and interferometry based sensors as [14–17], for simultaneous sensing of temperature and refractive index. Meanwhile, several techniques have been proposed to improve the RI sensitivity of the normal FBG by accessing the evanescent field of the fundamental mode in the optical fiber, such as chemical etching. Iadicicco et al. [17] proposed an intriguing approach for simultaneous sensing of RI and temperature in which a portion of an FBG is etched to produce a Bragg wavelength that is sensitive to both changes of ambient refractive index and temperature of a solution whereas the

---

* Corresponding author at: Photonics Research Centre, University of Malaya, 50603 Kuala Lumpur, Malaysia. Tel.: +60 176040474.
E-mail addresses: kslim@um.edu.my, yanghz@nwu.edu.cn (K.-S. Lim).

http://dx.doi.org/10.1016/j.sna.2015.03.001
0924-4247/

unetched part of the FBG will provide a different Bragg wavelength that is only sensitive to ambient temperature change. Accurate measurements of refractive index can be attained via cancelation of temperature based on the data from both Bragg wavelengths. Considering the fact that the etched-core grating is sensitive to both temperature and RI, a temperature insensitive sensor based on partial cone-shaped FBG is proposed [18,19]. The constituent of temperature from the wavelength reading of the etched part of the FBG is eliminated based on the reading from the un-etched part of the FBG, which is insensitive to ambient RI change. In Ref. [18], sensitivities of 7.8×10^{-2} and 3.4×10^{-3} are reported in the range of 1.45 and 1.33, respectively and temperature sensitivity of 6.15×10^{-6}/°C and 5.66×10^{-6}/°C are achieved in the range of 15–50 °C. Similarly Yang et al. [20] proposed the same concept but with different structure, in which the FBG part of the fiber was chemically etched with tapered shape whereas the etched FBG has minimum etched diameter of 4.4 μm.

Qiu et al. had fabricated a few-mode grating in polymer optical fiber. Multiple Bragg wavelengths are observed from the grating. They share similar strain sensitivities but different temperature sensitivities for different orders of modes. These properties are exploited for discrimination measurement between temperature and strain [21]. This finding has inspired us to use FMFBG in our work on RI and temperature sensing. In this work, we proposed a cladless grating sensor for simultaneous RI and temperature sensing. The proposed sensor is fabricated by inscribing a grating into the core of two-mode few mode fiber (FMF). A chemical etching technique is performed to remove the cladding and to produce a grating sensor with an etched diameter of ~14.1 μm and two Bragg wavelengths. The device is mechanically more stable and easy to fabricate than the etching of normal FBG in single mode fiber (SMF). The etching diameter of 14.1 μm is based on the simulation result for optimal the power confinement of etched FMFBG.

On the other hand, the cross sensitivity between parameters in the simultaneous measurement is also considered. The negligence of this factor in simultaneous sensing may lead to imprecise measurement. Particularly in the case of single element sensor with multi-parameter sensing ability, the sensitivities of each parameter may be the functions of other parameters. For accurate discriminative measurement, cross sensitivity should be taken into measurement with the aid of 3 × 3 characteristic matrix [21]. Simulation on the proposed sensor is performed to identify the transverse mode of each Bragg wavelengths. The property of cross sensitivity between temperature and RI is investigated. Discrimination measurement using 3 × 3 characteristic matrix is also discussed and presented.

2. Operating principle and theoretical model

The fabrication begins with inscription of Bragg grating structure inside the core of an FMF. The FMFs used are germanosilicate fibers (OFS, Denmark) with a core diameter of 19.5 μm, RIs of cladding and core are 1.444 and 1.449 respectively which gives an NA of ~0.12. More than one reflection Bragg wavelengths are observed in the reflection spectrum of grating and the relationship between Bragg wavelength (λ_ν), effective index ($n_{eff,\nu}$) of each transverse mode (LP_ν) is given by

$$\lambda_\nu = 2n_{eff,\nu}\Lambda \tag{1}$$

where Λ is the grating period and $\nu \in \{01,11,02\}$.

Due to the asymmetric index profile in grating over the fiber core by the UV laser side illumination [22], intermodal couplings between the transverse modes are excited and new reflection wavelengths are produced. The amplitudes of the reflection peaks can be controlled by using core offset technique [23].

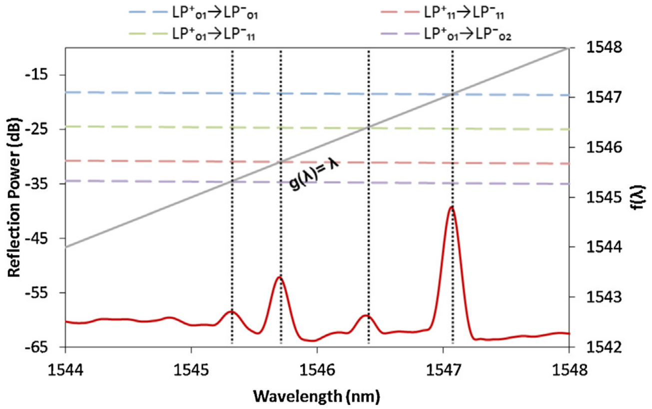

Fig. 1. Theoretical estimation of the Bragg wavelengths of the corresponding modes are given by the intersections between $f(\lambda) = [n_\mu(\lambda) + n_\nu(\lambda)]\Lambda$ and $g(\lambda) = \lambda$. The estimated wavelengths (vertical dotted lines) are in agreement with the reflection spectrum (experiment).

The relationship between the excited wavelength and the two corresponding transverse modes ($LP_\mu^+ \rightarrow LP_\nu^-$) is given by [24]:

$$\lambda_{\mu,\nu} = [n_{eff,\mu} + n_{eff,\nu}]\Lambda \tag{2}$$

where $\mu, \nu \in \{01, 11, 02\}$, $\mu \neq \nu$. Since the excited Bragg wavelength $\lambda_{\mu,\nu}$ is positioned exactly at the middle between λ_μ and λ_ν. Eq. (2) can be rewritten as

$$\lambda_{\mu,\nu} = \frac{(\lambda_\mu + \lambda_\nu)}{2} \tag{3}$$

From Fig. 1, it is described that the Bragg wavelength for each transverse mode can be theoretically estimated from the position of the intersection between the two functions, $f(\lambda)$ and $g(\lambda) = \lambda$, where $f(\lambda) = 2n_{eff,\mu}\Lambda$ for mode coupling of $LP_{01}^+ \rightarrow LP_{01}^-$ and $LP_{11}^+ \rightarrow LP_{11}^-$ whereas $f(\lambda) = [n_{eff,\mu} + n_{eff,\nu}]\Lambda$ is for intermodal coupling of $LP_{01}^+ \rightarrow LP_{11}^-$ and $LP_{01}^+ \rightarrow LP_{02}^-$ [22]. For the ease of explanation and presentation, the Bragg wavelengths which correspond to mode couplings of $LP_{01}^+ \rightarrow LP_{01}^-$ and $LP_{11}^+ \rightarrow LP_{11}^-$ are denoted as λ_{01} and λ_{11} for the rest of this article.

Cladless FMFBG sensor is fabricated from FMF through simple fabrication processes – UV grating inscription and chemical etching. KrF excimer laser and standard phase mask with period 1068.80 nm, were used to produce 2 cm long grating in the core of hydrogen loaded FMF. After the fabrication, FMFBGs were annealed in a hot oven at 80 °C for 10 h to remove the residue hydrogen.

After that, chemical etching was performed to remove the cladding of the fiber to enhance the evanescent wave of the core modes and to enable interaction between the core mode and ambient medium. Buffered Oxide Etchant (BOE) solution with the volume ratio of NH_4F solution (40% in water) and HF solution (48% in water) was prepared as the etchant. The etchant is covered with a thin layer silicon oil to prevent the evaporation of the etchant solution. After achieving the desired fiber shape, the FMFBG is rinsed with distilled water to remove the residual etchant. The microscope image of the etched FMFBG end is shown in Fig. 2(b). For the ease of understanding, an illustrative diagram of device structure is presented in Fig. 2(c) and experimental setup is given in Fig. 2(d). In the sensor calibration experiment, the broadband laser source from an erbium doped fiber amplifier (EDFA) is used to launch the light into a circulator before it enters the FMFBG which is placed in the solution. A digital hot plate is used to heat up the solution, which has a temperature resolution of 0.1 °C. Meanwhile, a thermocouple is placed as close as to the FMFBG to get the temperature information of the solution. The reflection spectrum of the FBG is analyzed by an optical spectrum analyzer (OSA) at the resolution of 0.01 nm.