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Study of fiber laser micro-nano sensor based on colloidal crystal[*]

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A fiber laser micro-nano sensor based on colloidal crystal structure is proposed in this paper. The fiber laser has stable frequency and narrow linewidth. It is realized by using an unpumped erbium-doped fiber (EDF) as the saturable absorber. The saturable absorber possesses the shape of taper. The laser threshold can be effectively reduced by the tapered saturable absorber. The tapered fiber coated with colloidal crystal as sensing unit is studied. The concentration of ethanol can be obtained from the detection of the output laser wavelength. It can be extensively used in chemical, medical and biological detections.

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Fiber optic sensors[1,2] have been a very attractive technology, which attract broad attention. Due to their overwhelming advantages, such as compactness, light weight, high sensitivity, high corrosion resistance, immunity to electromagnetic interference, and the ease of multiplexing, fiber optic sensors, especially fiber Bragg grating (FBG) sensors, have made great development and progress in both scientific fields and industrial productions[3-5]. The light source of most fiber optic sensors is usually the broadband source, for instance, light-emitting diode, super luminescent diode and amplified spontaneous emission light source. Its relatively low power and weak coherence both restrict the development of high precise measurement to some extent.

Fiber lasers have been widely used in optical fiber communication systems for a long time, but fiber laser-based sensors are still not so common[6]. Compared with the broadband sources mentioned above, fiber laser source has much more advantages at the aspect of high sensitivity, long distance transmission and high signal to noise ratio. However, frequency stabilization of the output laser is a tough issue and key factor for fiber laser sensing. Generally, there are three different ways to obtain a single frequency fiber laser. The first one is fiber ring laser[7], in which intracavity filters and optical isolators are needed, so it is complex and expensive. The second one is short linear cavity fiber laser, including distributed Bragg reflector (DBR) fiber lasers and distributed feedback (DFB) fiber lasers[8,9]. The short linear fiber cavity is not easy to consider both the pumping efficiency and the output power. And the last one is the saturable absorber (SA) proposal[10,11]. Introducing unpumped active optical fiber in laser cavity, a narrow linewidth fiber laser would be obtained. Compared with the other two methods, the fiber laser obtained by the last one has striking features, such as low cost, narrow linewidth and stable frequency. Although the sensors based on FBG, surface plasmon resonance (SPR), multimode fibers and photonic crystal fiber have been extensively investigated, some of them are limited in the measurement of aqueous medium with low refractive index, which cannot meet the requirements for most chemical and biological applications. In this paper, a stable laser with narrow linewidth is realized by introducing an unpumped erbium-doped fiber (EDF) as SA which is characterized by tapered shape. Meanwhile, combining with a self-assembled polystyrene sphere (PS) colloidal crystal[12], the tapered section used as sensor unit is studied. The experimental results show that the output laser wavelength fluctuation can be maintained within 2 pm. And the fiber laser can be successfully used to measure the concentration of ethanol. It also may be

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used in chemical, medical and biological detections.

The proposed structure of the narrow linewidth fiber laser sensing system is shown in Fig.1. The setup includes a common EDF with length of 16 m, which is pumped using a laser diode operating at 976 nm. The linear cavity contains an FBG with reflectivity of 94.325% at reflective wavelength of 1550 nm and a 2×2 3 dB coupler. The two output ports of the coupler are spliced together to form a high reflective mirror. The reflectivity and transmittance can be denoted by[13]

$$R = 4k(1-k)\,, \tag{1}$$

$$T = (1-2k)^2\,, \tag{2}$$

where k is the power coupling coefficient of the coupler. Considering k is not strictly equal to 0.5, the reflectivity is not 100%, which means that a little light comes out of the transmission end, forming the laser output. But the wavelength of the output laser is not stable enough as shown in Fig.2 marked as “No SA”. For this reason, this configuration is not appropriate to act as a sensor.

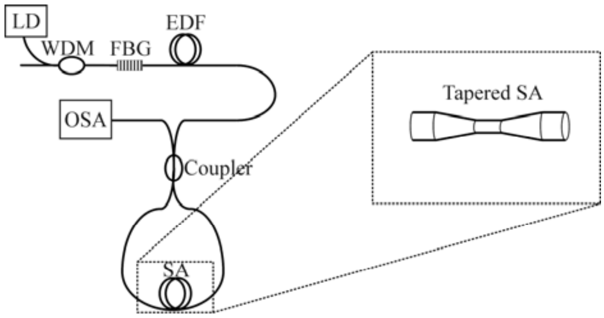

Fig.1 Schematic diagram of the proposed narrow linewidth fiber laser sensing system

Frequency stability is important for fiber laser based sensing. To solve the problem, a section of unpumped active optical fiber used as SA is spliced between two output ports of the coupler. When counter-propagating light waves are launched into the SA, the spatial hole burning effect will occur[12,13]. The two light waves interfere at the place of SA, giving rise to the strongest interference of a certain longitudinal mode. In other words, such a wavelength in the bright fringes of the interference pattern has the smallest absorption, while the oscillation of the other longitudinal modes is suppressed, finally forming the single mode operation. The effect is similar to inserting an amplitude Bragg grating, so a very narrow reflection bandwidth is generated. The length of SA can effectively affect the wavelength stability. As shown in Fig.2, when 2 m-long SA is used, the wavelength fluctuation is much stronger than that of No SA. And the wavelength becomes relatively stable again as 5 m-long SA is adopted. However, the longer the SA used, the larger the pumping energy needed. It tends to result in a power-wasting and high-cost configuration, which is contrary to the tendency of innovative applications and sustainable developments.

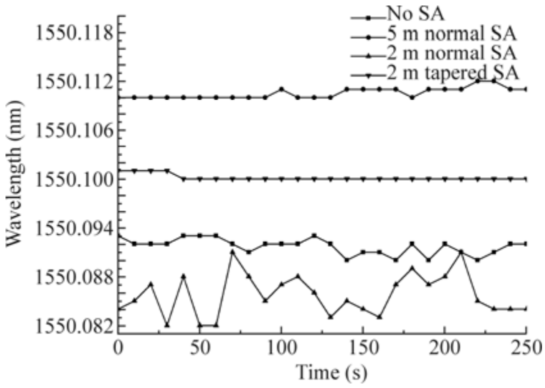

Fig.2 Stability of output laser under different lengths of SA

A simple but effective method is used to solve the problem mentioned above. A taper-shaped SA is fabricated via fusion splicer. Two ends of the fiber fixed on the fiber holder are stretched, and the middle region is heated by arc from the two electrodes inside the fusion splicer. Under appropriate arc power, arc duration and stretching distance, the holding fiber is stretched to a waist diameter of 50 μm and with the taper length of 16 mm. When the fiber is tapered, not only the fundamental mode but also several other propagating modes including cladding modes are excited. The intermodal beat among these cladding modes results in a comb-like filter which only allows certain longitudinal modes to pass through it[16]. Together with the spatial hole burning effect of the umpumped EDF, SA with shorter length is needed but a fiber laser output with narrow linewidth and stable frequency can be realized, as shown in Fig.2. The tapered fiber supports a portion of power propagating in the evanescent wave, which allows the strong light coupling between the fiber and the surrounding environment. Then a high-sensitivity fiber sensor goes into effect.

The effective refractive index of the colloidal crystal in certain environment can be expressed as[17]

$$n_{\mathrm{eff}} = n_{\mathrm{PS}} \cdot f_{\mathrm{PS}} + n_{\mathrm{environment}} \cdot f_{\mathrm{environment}}\,, \tag{3}$$

where n_{PS} and $n_{\mathrm{environment}}$ are the refractive indices of the PS spheres and the situated environment of fiber, and f_{PS} and $f_{\mathrm{environment}}$ are the volume fractions occupied by silica spheres and environment in the structure, which are generally taken as 74% and 26%, respectively, for a face-centered cubic (FCC) lattice. If the refractive index of environment is relatively small, the effective refractive index of the sensing unit is still big enough. Therefore, it is not limited to measure aqueous medium with low refractive index, and its application fields are extended. The fabrication process of colloidal crystal coated on fiber is briefly stated as follows. The tapered EDF is placed in an aluminum gutter on which the two ends of tapered fiber are fixed. The colloidal solution is prepared with 1.5% polystyrene microspheres with diameter of 760 nm in water/ethanol mixture with volume ratio of 1:4. The temperature is kept at 50 °C during the growth process of colloidal crystal. Colloidal crystals are formed after 4–5 h. In this paper, the colloidal crystal coated SA sensing unit is applied to measure the concentration of ethanol. The fiber optic sensing experimental results are depicted in Fig.3. The colloidal crystal coated SA sensing unit is sensitive to the surrounding environment. Different ethanol concentrations are corresponding to different refractive indices. It can be seen that the output laser wavelength varies with the change of ethanol concentration. Furthermore, the wavelength exhibits a red shift as the concentration of ethanol increases, which is consistent with the theoretical calculation[18]. The wavelength fluctuation is less than 3 pm, but its frequency variation rate is larger than that of the measurement in air. The volatilization of ethanol may be a considerable reason.

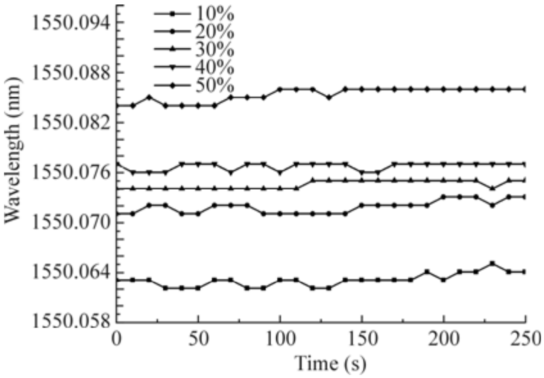

Fig.3 Measured results of output laser wavelength of the SA sensing unit coated with colloidal crystal immersed in ethanol solution with different concentrations

In conclusion, a fiber laser sensor based on colloidal crystal is introduced and demonstrated. The output wavelength is stable and possesses a fluctuation of 2 pm. The sensing unit is composed of a section of unpumped active fiber. It possesses the shape of taper and is coated with colloidal crystal. The results show that the concentration of ethanol can be measured. It is possible to further improve the sensitivity of the sensor by optimizing the parameters of the tapered fiber and the colloidal crystal. The proposed device has great potential applications in measuring or monitoring the refractive index and concentration, especially in the chemical and biological sensing fields.

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