Optics & Laser Technology 84 (2016) 59–63

Contents lists available at ScienceDirect

Optics & Laser Technology

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

Full length article

Liquid level sensor based on fiber ring laser with single-mode-offset coreless-single-mode fiber structure

Zixiao Wang*, Zhongwei Tan, Rui Xing, Linjun Liang, Yanhui Qi, Shuisheng Jian

Key Laboratory of All Optical Network and Advanced Telecommunication Network of Ministry of Education, Institute of Lightwave Technology, Beijing Jiaotong University, Beijing 100044, China

ARTICLE INFO

Article history:
Received 25 January 2016
Received in revised form
29 March 2016
Accepted 6 May 2016

Keywords:
Fiber laser sensor
Offset fusion
Multimode interference
Liquid level

ABSTRACT

A novel reflective liquid level sensor based on single-mode-offset coreless-single-mode (SOCS) fiber structure is proposed and experimentally demonstrated. Theory analyses and experimental results indicate that offset fusion can remarkably enhance the sensitivity of sensor. Ending-reflecting structure makes the sensor compact and easy to deploy. Meanwhile, we propose a laser sensing system, and the SOCS structure is used as sensing head and laser filter simultaneously. Experimental results show that laser spectra with high optical signal-to-noise ratio (-30 dB) and narrow 3-dB bandwidth (<0.15 nm) are achieved. Various liquids with different indices are used for liquid level sensing, besides, the refractive index sensitivity is also investigated. In measurement range, the sensing system presents steady laser output.

1. Introduction

Liquid level sensors have been widely used in industrial application. Conventional liquid level sensors are mainly based on electrical and mechanical techniques, which unsuitable for conductive, combustible and explosive environments. Fiber optical sensors have been widely studied for the advantage of lightweight, small size, high sensitivity and immunity to electromagnetic interference [1–3]. Fiber liquid level sensors have high sensitivity, which are suitable for chemical industry and bioengineering application.

So far, fiber optical liquid level sensors are mainly based on fiber Bragg grating (FBG)/tilted fiber Bragg grating (TFBG) [4–6] or Long Period Grating (LPG) [7,8]. Liquid level sensors based on fiber Fabry-Perot interferometer (FPI) [9] are also reported. Sensors based on fiber grating have high sensitivity, but typically, the length of TFBG is limited by phase mask plate, and LPGs are fragile. In addition, the demand of fabrication of fiber grating is higher, which will increase the cost. Therefore, multimode-interference (MMI) fiber sensors are promising due to the low cost, easy to fabricate, and qualified for various physical quantity detection. MMI-based fiber sensors can be various, one of the most typical configurations is single-mode-multimode-single-mode (SMS) structure. Usually, the multimode fibers (MMFs) in SMS structures are coreless fibers, thus, these fiber sensors are also known as single-mode-coreless-single-mode (SCS) structures [10–13]. The coreless fiber is a special MMF, whose cladding is the air. Therefore, the mode field of coreless fiber extend out of the fiber and SCS fiber sensors are sensitive to the surrounding. Typically, the 3-dB bandwidth of the interference spectrum of MMI fiber structure is quite wide [13–15]. Using narrow-band sweeping light source like tunable laser can improve the spectrum characteristic [16], but a better scheme is laser sensors based on MMI, because fiber laser is much cheaper and simpler than tunable laser. By combining laser sensor and MMI device, optical signal-to-noise ratio (OSNR) of output spectrum is higher, while the 3-dB bandwidth is narrower. So the laser sensors based on MMI sensing structure are suitable for high sensitivity and long-distance sensing [10,17].

In this paper, an all-fiber ring cavity laser sensor based on single-mode-offset coreless-single-mode (SOCS) is proposed and applied for liquid level measurement with different refractive index (RI). In the sensing system, SOCS fiber structure acts as sensing head and laser filter simultaneously. Compared with the previous research [18], the sensing head contains a section of few-mode elliptical multilayer-core fiber (EMCF). Producing EMCF has many involved processes, and the cost of EMCF is also high. Besides, a polarization maintain fiber fusion splicer is required when fusing the EMCF. But in this paper, the proposed structure only consists of two sections of single mode fiber (SMF) and a section of coreless fiber, the materials of the sensor are more common, and a general commercial fiber fusion splicer is qualified for the fabrication. As a result, the cost of the sensor is lower. Thanks to the offset fusion, the sensitivity of sensor is improved; laser sensing system also

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* Corresponding author.
E-mail address: 14111011@bjtu.edu.cn (Z. Wang).

http://dx.doi.org/10.1016/j.optlastec.2016.05.001
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provides higher optical power, higher OSNR and narrower 3 dB bandwidth. Besides, unlike most of the offset structure fiber sensors who are transmission type [15,17,19–21], our sensor is reflecting type, which makes it easy to deploy and suitable for liquid level detection.

2. Principle

The schematic diagram of the proposed SOCS fiber structure is shown in Fig. 1, a section of coreless fiber is spliced between two sections of standard SMF. One of the SMFs is lead-in/out fiber, the other is sensing fiber, which has a thick silver film (reflectance is 99.5%) at the tip-end-face. There is a transverse offset between lead-in/out SMF and coreless fiber (Point A in Fig. 1), and the sensing SMF is fused coaxially with the coreless fiber (Point B in Fig. 1). Since fiber coatings would absorb cladding modes and reduce the sensitivity of sensor, coatings of the coreless fiber and the sensing SMF are both removed.

To detect the change of surrounding liquid level or liquid refractive index, cladding modes in the sensing SMF should be excited. Here, the offset-fusing coreless fiber is used to excite cladding modes in the sensing SMF. Since higher order modes (HOMs) are usually more sensitive to surrounding environment [2], the sensitivity of sensor will be improved if higher order cladding modes in sensing SMF are excited.

We assume the field in the lead-in SMF is Gaussian beam. For coreless fiber, the incident field can be described as [21]:

$$E_1(r,\theta)=E_0\exp\left[-\frac{r^2+\Delta r^2-2r\Delta r\ \cos(\theta-\theta_0)}{w_s^2}\right] \tag{1}$$

where Δr and θ_0 are the offset parameters, and w_s is the spot size of Gaussian beam.

To analyze the field in offset fusing structure, the mode expansion method is used [21,22]. The transverse components of electric field can be expanded as:

$$E_1(r,\theta)=\sum_m\sum_n c_{m,n}^{(CLF)}\Psi^{(m,n)}(r)\exp(im\theta) \tag{2}$$

where $\Psi^{(m,n)}$ is the field distribution of eigenmode in coreless fiber, m is the angular order, n is the mode number with the same angular order, and $c_{m,n}^{(CLF)}$ is the coefficient of eigenmode.

According to orthogonality relations [22], $c_{m,n}^{(CLF)}$ can be calculated:

$$c_{m,n}^{(CLF)}=\iint E_1(r,\theta)\Psi^{(m,n)*}(r,\theta)rdrd\theta/\iint|\Psi^{(m,n)}(r,\theta)|^2rdrd\theta \tag{3}$$

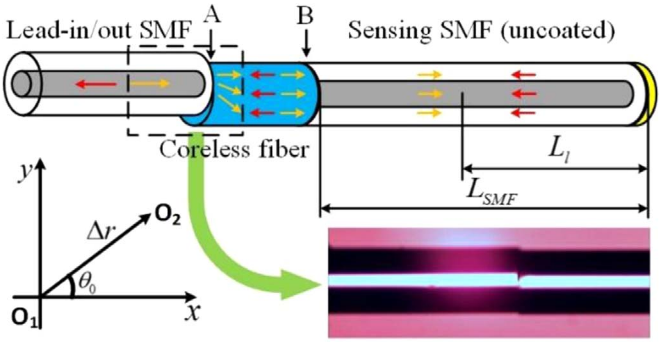

Fig. 1. The schematic configuration of SOCS fiber structure, orange arrows represent the injected light and the red arrows represent the reflected light. L_l is the measured liquid level. The inset is the micrograph of offset fusion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The power coupling coefficients of excited modes in coreless fiber are shown in Fig. 2. As the offset fusion breaks circular symmetry, not only LP_{0n} modes are excited, but also LP_{mn} $(m\geq1)$ modes [21]. Fig. 2 shows that when the offset distance less than 6 μm, larger offset distance can excite more effective HOMs.

Then the light travels through the coreless fiber and reaches the sensing SMF. Since the sensing SMF is coaxially fused with the coreless fiber, and the size of SMF is similar with the coreless fiber, HOMs will be coupled into the cladding of sensing SMF, i.e., LP_{0n} modes and LP_{mn} $(m\geq1)$ modes will exist in the cladding of sensing SMF. If point A is a coaxial fusing point, only LP_{0n} modes are excited in the cladding of sensing SMF. Thus, offset fusing structure can enhance the sensitivity of sensors.

Besides, core mode of sensing SMF will also be excited. Thus, the light field in sensing SMF can be described as:

$$E_2(r)=\sum_m\sum_n c_{m,n}^{(cl)}e^{(m,n)}(r)+c^{(co)}e^{(co)}(r) \tag{4}$$

where $c_{m,n}^{(cl)}$ and $c^{(co)}$ are the coefficients of cladding modes and core mode, respectively; $e^{(m,n)}$ and $e^{(co)}$ are the filed distributions corresponding to cladding modes and core mode in SMF, respectively.

After propagating along the sensing SMF and being reflected by silver film, the field returns to point B, then core mode and cladding modes interfere at this point. The interference spectra contain the sensing information. At point B, the field distribution are:

$$E_3(r)=\sum_m\sum_n c_{m,n}^{(cl)}e^{(m,n)}(r)\exp(i\varphi)+c^{(co)}e^{(co)}(r)\exp(i\varphi_0) \tag{5}$$

where φ and φ_0 are the phases shift of propagation. When a segment of sensing SMF is immersed in liquid, the effective indices of cladding modes increase, and the phase shift of propagation is:

$$\begin{aligned}\varphi&=\frac{4\pi}{\lambda_0}n_{m,n}^{(cl)}(L_{SMF}-L_l)+\frac{4\pi}{\lambda_0}\left(n_{m,n}^{(cl)}+\Delta n_{m,n}\right)L_l\\&=2\beta_{m,n}^{(cl)}(L_{SMF}-L_l)+2\left(\beta_{m,n}^{(cl)}+\Delta\beta_{m,n}\right)L_l\end{aligned} \tag{6}$$

where λ_0 is free space wavelength, $n_{m,n}^{(cl)}$ is the effective mode-index of the sensing fiber in air, $n_{m,n}^{(cl)}+\Delta n_{m,n}$ is the effective mode-index of the sensing fiber in liquid, and L_l is the length of immersed segment.

However, the core mode is hardly affected. The phase shift of core mode is fixed:

$$\varphi_0=\frac{4\pi}{\lambda_0}n^{(co)}L_{SMF}=2\beta^{(co)}L_{SMF} \tag{7}$$

where $n^{(co)}$ and $\beta^{(co)}$ is effective mode-index and propagation constant of core mode in SMF.

The phase difference between core mode and cladding mode of sensing SMF is:

$$\Delta\varphi=\varphi_0-\varphi=\frac{4\pi(L_{SMF}-L_l)}{\lambda_0}\Delta n_0+\frac{4\pi L_l}{\lambda_0}\Delta n_1 \tag{8}$$

where $\Delta n_0=n^{(co)}-n_{m,n}^{(cl)}$ and $\Delta n_1=n^{(co)}-n_{m,n}^{(cl)}-\Delta n_{m,n}$. When $\Delta\varphi$ is equal to $(2k+1)\pi$, the interference spectrum reach the minimum. Eq. (8) also indicates that the interference spectrum would shift when the sensing SMF is immersed in liquid.

3. Fabrication and experiment setup

To fabricate the SOCS structure, we set up a monitor system to measure the reflective spectrum. In this system, a super-continuum laser (Koheras Co., SuperK) is used as the light source. An optical spectrum analyzer (OSA,YOKOGAWA AQ6375) is used to monitor the reflective spectrum of the device. The resolution of