Design and numerical simulation of SPF-PCF-SPF fluid sensing system based on photoelectric oscillator*

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(Received 11 October 2021; Revised 14 November 2021)

In this paper, an optical fiber fluid sensing system based on optoelectronic oscillator (OEO) was proposed and studied numerically. The fluid sensor head is constructed by splicing two sections of side-polished fiber (SPF) to one section of photonic crystal fiber (PCF). Fluid sample can flow continuously through the holes of PCF. The refractive index (RI) change of the fluid sample can lead to the effective RI change of the fiber, resulting in frequency change of microwave signal generated by OEO. By monitoring the oscillation frequency using an electronic spectrum analyzer (ESA), the RI of fluid sample can be measured. Thanks to the fast interrogation speed of ESAs, the measuring speed can be increased significantly compared to traditional optical fiber RI sensing systems using optical spectrometers. The sensing principle of the system was studied. The sensitivity of the proposed system was evaluated by simulation, and an RI sensitivity of −14.20 MHz/RIU can be achieved. The results show that with proper system design, real-time RI measurement with high sensitivity can be achieved. Increasing the length of the PCF while under the premise of the fluid parameters will be the most reasonable way to improve the sensitivity. The proposed design and simulation results can provide suggestions for the fabrication and optimization of fluid sensing systems used for real-time detection and measurement of biological elements and heavy metal ions in liquid environment.

Document code: A **Article ID:** 1673-1905(2022)06-0326-5

DOI https://doi.org/10.1007/s11801-022-1159-x

The photonic crystal fiber (PCF) cladding has air holes, which is suitable for high-sensitivity fiber fluid sensing applications[1-3]. The fluid sensors using different types of PCFs have been proposed and applied to the measurement of refractive index (RI)[4-7]. Sensing performances including measuring speed, accuracy, stability and environmental adaptability of fiber sensors based on optical spectra demodulation heavily rely on the performance of optical spectrometer. However, most modern optical spectrometers still need to scan the wavelength by using mechanical driven grating modules, which is time consuming. Even high-end spectrometer can hardly provide the sampling rate and accuracy needed for many applications, like real-time detection and measurement of chemical reactions, biological elements and heavy metal ions in liquid environment.

With the development of microwave photonics, fiber optic sensors based on optoelectronic oscillator (OEO) have drawn lots of attention due to that sensing information can be demodulated by measuring the frequency of microwave signals generated by the OEO process with pure spectra and low phase noise[8-10]. Due to the much higher sampling rate and accuracy of modern electronic spectrum analyzer (ESA), OEO based fiber sensors can complete interrogation process in less than 1 s, which can meet the requirement of real-time sensing applications. NGUYEN et al[11] demonstrated the RI measurement using an OEO based sensing system, in which a cell of liquid was inserted as a part of optical path of the global OEO loop. Other OEO based RI sensors utilizing phase shifted fiber Bragg grating and Fabry-Perot interferometer have been reported with high sensitivity and fast interrogation speed[12-14]. Comparing to RI fiber sensors based on fiber Bragg gratings or fiber cavity[15-18], the PCF based fluid sensor offers a more stable optical environment, less light loss and consumes much less sample volume, which makes it suitable for the accurate measurement of valuable or trace samples. Thanks to its excellent fluid channel compatibility, the PCF based sensors can be easily integrated to fluid sensing system, and enable real-time detection and measurement of a variety of chemical reactions, biological elements and heavy metal ions in liquid.

In this paper, a fluid RI sensing system based on PCF

* This work has been supported by the Science and Technology Research Program of Chongqing Municipal Education Commission (Nos.KJQN201800626 and KJQN20200605), the National Key R&D Program of China (No.2018YFF01010202), and the Basic Research Project of Chongqing Science and Technology Commission (No.CSTC-2018jcyjax0619).

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was proposed and simulated. The fluid sensor head is constructed by fusion splicing PCF to side-polished fiber (SPF). The system combines PCF fluid sensor with OEO technique to improve the measuring speed of fluid RI, which makes it suitable for the real-time detection of RI changes. The sensing principle of the system was studied and the sensitivity was analyzed by simulation. The results show that with proper PCF and system design, real-time RI measurement with a sensitivity of −14.20 MHz/RIU can be achieved. The proposed design and simulation results can provide suggestions for the fabrication and optimization of fluid sensing systems used for the detection and measurement of biological elements and heavy metal ions in liquid environment.

A PCF fluid sensing system based on OEO to measure RI is shown in Fig.1. The system includes a laser diode (LD), an electro-optic modulator (EOM), a photodetector (PD), an electrical amplifier (EA), an electrical band pass filter (EBPF) and an SPF-PCF-SPF fluid sensor. The laser from the light source is modulated by the EOM, and then the polarization is adjusted to be parallel to the slow axis (y axis) of the PCF sensor by a polarization controller for better sensitivity. After passing the fluid sensor and fiber loop, the optical signal is converted to electrical signal by using a high-speed PD. The electrical signal is amplified by the EA and the oscillation frequency can be selected by adjusting the EBPF. The output electrical signal is then fed back to the EOM to close the OEO loop and generate microwave signals. In the simulation, the frequency of microwave oscillation is set to gigahertz range. The RI change of the fluid sample in the PCF sensor head can lead to the change of effective RI of the PCF and effective OEO loop length, resulting in the frequency change of microwave oscillation which can be observed by an ESA.

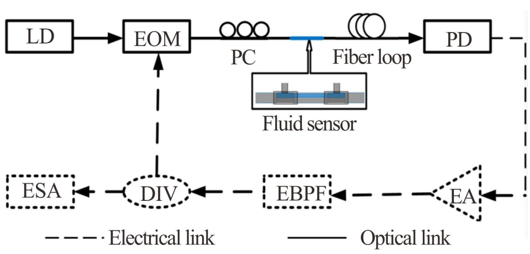

Fig.1 Optical fiber fluid sensing system based on OEO

The key component in the proposed RI sensing system is an SPF-PCF-SPF fluid sensor shown in Fig.2. The fluid sensing structure is formed by fusion splicing two sections of SPF with one section of PCF. The two sections of SPF and splicing points are sealed in two three-way tubes for the fluid samples flowing in and out. The cross-sectional views of the SPF and PCF are shown in Fig.3. The solid core PCF simulated in this study has five layers of air holes in a hexagonal arrangement. The air hole diameter is 3.5 μm and the lattice pitch is 5.5 μm. The center air hole is absent. The SPF is obtained by lateral polishing a single-mode fiber. In this study, the polishing depth of the fiber was 57 μm, and the end face of the SPF is shown in Fig.3(b). The cross-section of the liquid filled PCF is shown in Fig.3(c). In the proposed SPF-PCF-SPF sensor design with 57 μm side polishing, five layers of air holes can be filled to maximize the RI sensitivity. And after liquid filling, the PCF will show a birefringence with y axis becoming its slow axis.

Fig.2 SPF-PCF-SPF fluid sensor

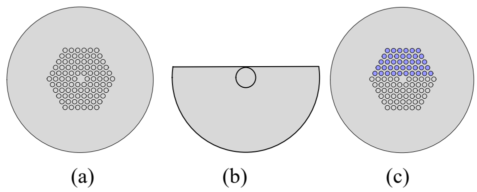

Fig.3 Cross sectional views of (a) PCF, (b) SPF, and (c) liquid filled PCF

The oscillation frequency of OEO loop is determined by the global loop delay τ_g of the oscillator and the mode number k, and the frequency can be expressed as

$$f_{0k}=\frac{k}{\tau_g}. \tag{1}$$

The global loop delay is the sum of electronic delay and optical delay $\tau_g=\tau_{op}+\tau_e$. When the optical path is much longer than the electrical path, the global delay can be considered equal to the delay of the optical fiber loop, $\tau_g\approx\tau_{op}=n_{op}L_g/c$, where L_g is the length of the fiber, c is the velocity of light in vacuum and n_{op} is the effective RI of the fiber. The oscillation frequency can be expressed as

$$f_{0k}=\frac{kc}{n_{op}L_g}. \tag{2}$$

The free spectral range (FSR) of the OEO can be expressed as

$$FSR=\frac{1}{\tau_g}=\frac{c}{n_{op}L_g}. \tag{3}$$

When an SPF-PCF-SPF fluid sensor is added in the OEO loop, the RI change of the fluid sample will lead to the change of the effective index of PCF and the optical path length. Then the oscillation frequency can be expressed as

$$f_{0k}=\frac{k}{\tau_g+\tau_{ac}}, \tag{4}$$

where τ_{ac} is the delay induced by the PCF fluid sensor. It can be expressed as

$$\tau_{ac}=\frac{n_y l}{c}, \tag{5}$$

where n_y is the effective RI of slow axis (y axis) of the PCF and l is the length of the PCF sensor. Then the oscillation frequency f_{0k} can be expressed as

$$f_{0k} \approx \frac{ck}{(n_{\text{op}}L_{\text{g}}) + (n_y l)}. \quad (6)$$

From Eq.(6), we can get

$$\Delta f \approx \frac{-\Delta n_y lck}{(n_{\text{op}}L_{\text{g}})^2} = \frac{-\Delta n_y l \cdot FSR \cdot f_{0k}}{c}, \quad (7)$$

$$\Delta n_y = \frac{-\Delta f \cdot c}{f_{0k} \cdot FSR \cdot l}. \quad (8)$$

Changes in the length of the optical fiber loop and the filling length of the optical fiber sensor will cause changes of the oscillation frequency and the sensitivity. The dependency of the sensitivity on the liquid filling length was analyzed. Finite element method was used to calculate effective RI of the liquid filled PCF. The effective RI of fundamental mode was calculated with wavelength set to 1 500 nm.

Fig.4 shows the *FSR* as a function of the OEO loop length. It can be seen that the *FSR* decreases with the increase of the fiber loop length. The oscillation frequency with higher order *k* can be measured by modern spectrum analyzers (i.e., Keysight PXA series) at tens of gigahertz with a resolution bandwidth (*RBW*) as low as tens of hertz, which can guarantee the measurement accuracy.

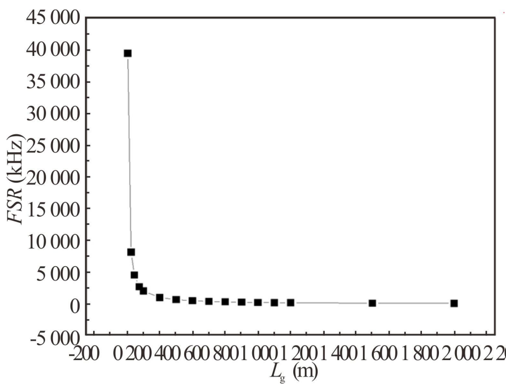

Fig.4 *FSR* as a function of OEO loop length L_g

It can be inferred from Eqs.(7) and (8) that high RI sensitivity requires longer PCF length, larger *FSR* (shorter fiber loop length) and higher oscillation frequency (large mode number *k*). Considering the electrical delay dominates the global delay when using short fiber loop, the total equivalent OEO loop length is set to 30 m according to existing report[11] and the PCF length is set to 30 cm, 50 cm and 100 cm, respectively for comparison. The corresponding *FSR* is *c*/30 m=10 MHz. By properly adjusting the EBPF, OEO at around 10 GHz (*k*=1 000) can be screened out and then monitored by ESA. The ESA could be set with a span of 10 kHz and an *RBW* of about 20 Hz at 10 GHz. With this setup, the sensitivity of the proposed sensing system will be evaluated.

The effective RIs of the *y*-polarized fundamental mode of PCF filled with fluid are calculated. The RI of the filled fluid for sensitivity evaluation is 1.500—1.516. The calculated effective RIs and field distribution of the *y*-polarized fundamental mode are shown in Fig.5. The imaginary part of the calculated effective RIs is on the order of -1×10^{-8}, which indicates a transmission loss of about 1 dB/m. Due to the PCF used in the sensor is relatively short, the total transmission loss including absorption of filled fluid won't be too significant. The oscillation frequency can be calculated using the effective RI and the OEO loop parameter mentioned above. The calculated oscillation frequencies as a function of the liquid RI with three different PCF lengths are shown in Fig.6. For the proposed SPF-PCF-SPF fluid sensing system and ESA setups, a sensitivity of −14.20 MHz/RIU can be achieved using a 100-cm-long PCF sensor. With shorter PCF sensors, the sensitivities decrease to −7.44 MHz/RIU and −4.55 MHz/RIU. The sensitivity of the OEO sensing system is proportional to the PCF length. It can be noticed that the change of the PCF length will cause the change of the oscillation frequency, but since the main contribution of the global delay comes from the electrical path which is fixed, and the frequency change is relatively small (9.54—9.86 GHz) compared to oscillation frequency, the impact of oscillation frequency change on the sensitivity (~3% in this simulation) can be ignored. So the sensors with three selected lengths still can be compared and analyzed together. Considering the resolution of modern ESA is less than 50 Hz, the minimum RI change that can be detected by the system is about 50 Hz/14.20 MHz/RIU=3.5×10^{-6}, which is on par with those traditional fiber RI sensing systems using optical spectrometers. And with OEO technique and modern ESA, the measurement speed can be improved by several orders of magnitude comparing to traditional fiber sensing systems, making it more suitable for sensing applications, such as real-time detection and measurement of chemical reactions, biological elements and heavy metal ions in liquid environment.

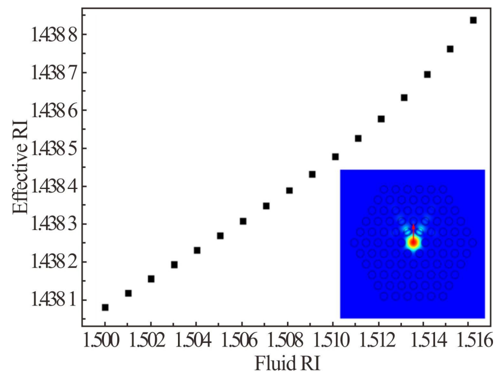

Fig.5 Effective RI of the *y*-polarized fundamental mode as a function of the fluid RI (The inset shows the electric field of the fundamental mode)

According to Eqs.(7) and (8), the sensitivity of the OEO system is proportional to oscillation frequency, *FSR* value and PCF length. It can be improved by optimizing the OEO loop design. In practical OEO setups, the *FSR* is mainly limited by the minimum electrical delay, so it can hardly be increased. In order to utilize higher oscillation frequency, high-end ESA should be used, which can measure microwave signals in the order of hundreds of gigahertz. But it is very costly, and can only improve the RI sensitivity by an order of magnitude. Increasing the length of PCF will be the most efficient method to improve the RI sensitivity. However, longer PCF will lead to larger flow resistance, which is not ideal for fluid sensing. The PCF length should be chosen while taking the measurement sensitivity, the viscosity of the sample and the required sample flow rate into comprehensive consideration in practical applications.

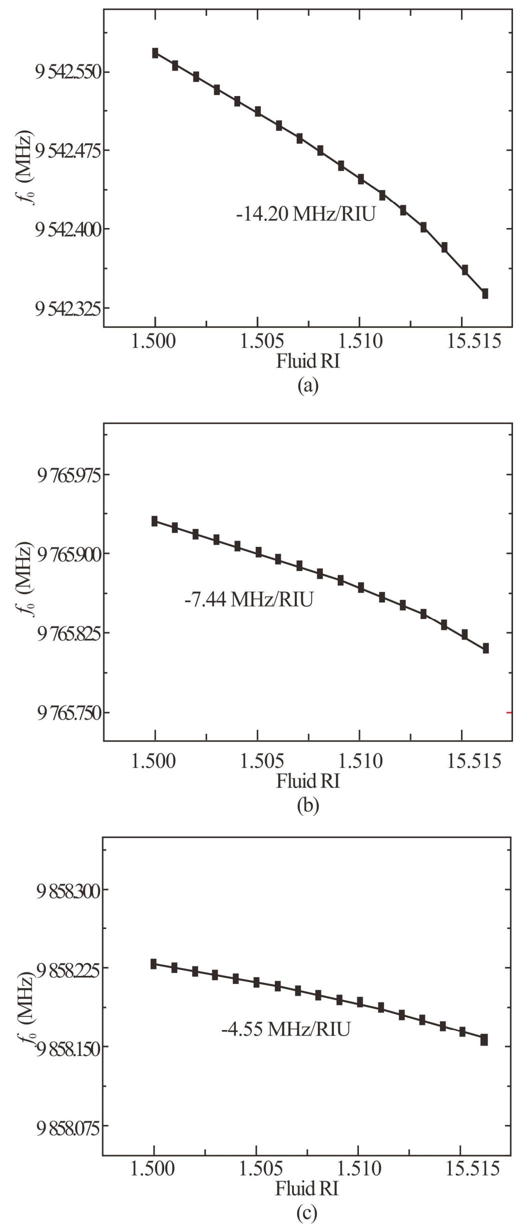

Fig.6 Oscillation frequency as a function of the fluid RI with different PCF lengths: (a) 100 cm; (b) 50 cm; (c) 30 cm

In this paper an SPF-PCF-SPF fluid sensing system based on OEO was proposed and studied numerically. The system combines PCF microfluid sensor with OEO technique to improve the measuring speed of fluid RI, which can be used for the real-time detection of RI changes. The sensing principle of the system is studied. The sensitivity of the proposed sensing system was evaluated by simulation, an RI sensitivity of −14.20 MHz/RIU was achieved. The results show that with proper PCF length and system design, real-time RI measurement with high sensitivity can be achieved. Increasing the length of the PCF while under the premise of the fluid parameters will be the most reasonable way to improve the RI sensitivity. The proposed design and simulation results can provide suggestions for the fabrication and optimization of fluid sensing systems used for the real-time detection and measurement of biological elements and heavy metal ions in liquid environment.

Statements and Declarations

The authors declare that there are no conflicts of interest related to this article.

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