Sub-micrometer resolution liquid level sensor based on hollow core fiber structure

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Liquid level measurement in Lab on a chip (LOC) devices is a challenging task due to the demand for a sensor with ultra-high resolution but miniature in nature. In this letter we report a simple, compact in size, yet highly sensitive liquid level sensor based on a hollow core fiber (HCF) structure. The sensor is fabricated by fusion splicing a short section of HCF between two singlemode fibers (SMFs). Sensor samples with different lengths of HCF have been studied; it is found that the sensor with a HCF length of ~4.73 mm shows the best sensitivity of ~0.014 dB/µm, corresponding to a liquid level resolution of ~0.7 µm, which is over five times higher than that of the previous reported fiber optic sensors to date. In addition, experimental results have demonstrated that the proposed sensor shows good repeatability of measurement and a very low cross sensitivity to changes in the refractive index of the surrounding medium. © 2019 Optical Society of America

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Liquid level measurement has been attracting intensive interest in numerous applications, such as in warning of floods, monitoring of fuel storage and public water supplies. A number of sensing techniques based on mechanical, electrical, ultrasonic and optical methods have been proposed for monitoring changes in liquid level [1-3]. Among them, optical fiber based liquid level sensors stand out with their inherent advantages such as miniature size, non-metallic nature, immunity to electromagnetic interference, remote sensing capability, high resistance to corrosion and ability to work up to high temperatures (up to 1000 °C), making them more attractive over other sensor types in applications where explosive, corrosive, and conductive conditions and flammable hydrocarbons are present.

During the past decade and more, tremendous effort has been put into liquid level monitoring and numerous optical fiber based liquid level sensors have been proposed. In general, those sensors can be classified into two types: type I sensor provides continuous liquid level (CLL) measurement while sensor of type II provides discrete (point) liquid level (DLL) measurement. Both direct and indirect approaches have been reported for CLL measurement based on either wavelength modulation or intensity modulation. Direct approaches are usually implemented utilizing a Mach-Zehnder interferometer (MZI) and Michelson interferometer (MI). Examples include sensor configurations based on long-period fiber gratings (LPGs), side polished (etched) fiber structures, polarization maintaining fiber and no core fiber structure [4-9]. For indirect approaches the sensor usually measures the variations in the optical properties of a fiber resulting from bending, strain or pressure when the liquid level changes [10-11]. DLL sensors are typically operated based on intensity modulation by monitoring the power change in optical reflection or transmission through the sensor head, where prism and polymer optical fiber based sensor configurations are most widely reported [12-14]. Compared with the sensor designed for DLL measurement, a sensor for CLL measurement suffers from a narrower measurement range, but compensates for this shortcoming with a better sensitivity and hence a better resolution.

Nowadays, lab on a chip (LOC) devices are driving many innovations in various engineering fields involving life sciences, diagnostics, analytical sciences, and chemistry [15]. Liquid level measurement in such devices is important, for example to estimate and control the volume of the fluids flowing inside the micro-channels. However, in such devices fluids are manipulated with a typical scale length ranging from one hundred nanometers to several hundreds of micrometers, thus detection of a very small liquid level variation is required. Fiber optic sensor is a good candidate to be used in LOC devices for monitoring liquid level variations due to its inherent advantages. To date, to the best of our knowledge, the highest sensitivities for fiber optic liquid level sensors based on wavelength modulation is demonstrated with a sensitivity of ~0.62 nm/mm based on a MZI configured with a pair of LPGs [4]. The most sensitive liquid level sensor based on intensity modulation is realized utilizing an etched fiber grating structure with a sensitivity of ~2.56 dB/mm [7]. Assuming a wavelength resolution of 0.01 nm and intensity resolution of 0.01 dB for a typical detector, the calculated resolutions for the above sensors are ~16 μm and ~3.9 μm, which are still insufficient for the application in LOC devices. Recently, hollow core fiber (HCF) based structures have been intensively investigated for high sensitivity detection of humidity, magnetic field amplitude, temperature and twist angle [16-19]. Most recently, two liquid level sensors have been proposed based on different types of HCF structures, but offer relatively low sensitivities of ~0.4 dB/mm and ~1.1 dB/mm [20-21]. In this letter, we report a simple, cost effective, yet highly sensitive liquid level sensor based on a hollow core fiber structure with a resolution better than 1 μm which is over 13 times higher than that of the previously reported HCF structure based liquid level sensors and furthermore is five times higher than that of the most sensitive fiber optic liquid level sensors reported to date [7, 20-21].

The proposed liquid level sensor is simply fabricated by fusion splicing a short section of HCF (air core diameter ~30 μm, outer silica cladding diameter ~126 μm) between two singlemode fibers (SMFs) as illustrated in Fig. 1(a). In this figure for the sake of clarity, light interference and transmission inside the HCF structure are illustrated only for the top half of the structure. Since the refractive index (RI) of the air core is smaller than that of the silica cladding, light propagating in the HCF leaks out along the HCF and reflects at both the interfaces of air core/cladding and cladding/outer air (the two interfaces can be considered as a pair of Fabry–Perot (FP) etalons). Multiple reflections within the air core and silica cladding of the HCF interfere with each other, resulting in the periodic transmission dips with high quality factors and large extinction ratios measured by an optical spectrum analyzer (OSA). Waveguides that operate based on such a light guiding mechanism are known as the "anti-resonance reflecting optical waveguides (ARROW)" where only certain wavelengths, which meet the anti-resonance condition in the cladding, are confined and transmitted inside the air core [22].

Assuming the HCF has a cladding thickness d and RI n, the light ray (L) propagating from the leading SMF to the HCF has an incident angle θ_1 and a refraction angle θ_2 at the interface between the air core and silica cladding, then the phase difference between the two adjacent reflected light rays inside the air core of the HCF (L_1, L_2, L_3 . . .) can be calculated by

$$\delta = \frac{4\pi}{\lambda} n d cos\theta_2 \pm \pi \quad (1)$$

As can be seen from the above equation, if the incident light (light wavelength λ and incident angle θ_1) and the physical parameters of the HCF (fiber diameter and RI of the silica cladding) are known, then δ is a constant. It is thus possible to assert that the resonant wavelength is independent of the length of the HCF and SRI. Assuming A is the amplitude of the incident light ray, the light intensity transmitted in the HCF (I_r) can be expressed as follows [19]:

$$I_r = \left| \frac{r_1 + r_2 e^{i\delta}}{1 + r_1 r_2 e^{i\delta}} \mathrm{A} \right|^2 \quad (2)$$

As one can see I_r is only dependent on the reflection coefficients at the interfaces of the air core/cladding (r_1) and cladding/outer air (r_2). r_1 and r_2 can be calculated by the Fresnel equations:

$$TE\ mode \quad r_1 = \frac{cos\theta_1 - n cos\theta_2}{cos\theta_1 + n cos\theta_2}, r_2 = -r_1 \quad (3)$$

$$TM\ mode \quad r_1 = \frac{cos\theta_2 - n cos\theta_1}{cos\theta_2 + n cos\theta_1}, r_2 = -r_1 \quad (4)$$

If r_1 and r_2 are fixed, the resonant dip strength is dependent on how many reflected light rays interfered inside the air core. A longer HCF section leads to a greater number of reflections and hence stronger interferences which produces stronger dips in the transmission spectrum. However, the amplitudes of the reflected light rays also experience attenuation along the HCF length. Thus after a certain HCF length instead of contributing to the increase of the dip strength, the reflected light rays lead to a more significant loss in transmission and thus a decrease in the measurement accuracy [18].

When the HCF is partially immersed into a liquid then some of the HCF cladding is surrounded by air and some by liquid. The reflection coefficients at the point where the surrounding medium changes from air to liquid also change resulting in the change of transmitted light intensity at the end of the HCF and accordingly the change of the spectral dip strength, which is related to the position of the liquid-air point. It is this effect that is used to provide liquid level measurement.

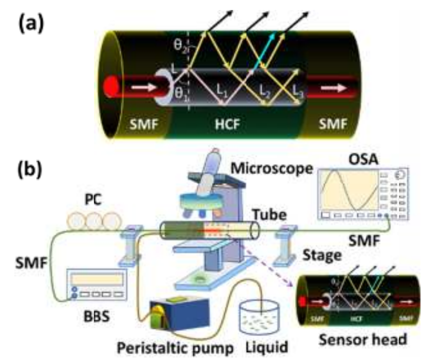

Fig. 1. (a) A schematic diagram of the proposed HCF structure and (b) the experimental setup for liquid level measurement.

Figure 1(b) illustrates a schematic diagram of the experimental setup for the liquid level measurement. The sensor structure was inserted into a transparent plastic tube (diameter ~3 mm) with its two SMF ends fixed straight on two stages; liquids were injected into the tube by a peristaltic pump at a very low speed. A tube with relatively large diameter is chosen here for the sake of better control of the flow speed of the liquid. Light from a broadband light source (BBS) was launched into the HCF based structure and the transmitted light was interrogated by an OSA. A polarization controller (PC) connected to the light source and the HCF structure though SMFs is employed to adjust the polarization state of the light before it enters the HCF section to achieve the strongest transmission dip strength. Since the monitored liquid level variations are in the order of micrometers, in our experiment all liquid level variations were measured with the help of an optical microscope as a reference.

In the experiment, four sensor samples with different lengths of HCF were prepared and their measured transmission spectral responses in air (solid line) and water (dashed line) are presented in Fig. 2(a). As one can see from the figure, the central dips wavelengths are almost fixed with the increase of the HCF length, which fits well with the analysis of equation (1) above. When the sensor heads were exposed to air, no obvious transmission dips were observed for the sensor with a HCF length of ~1.02 mm, however periodic dips show up and the dips strength increases significantly to ~25 dB as the length of HCF increases to ~4.73 mm. Interestingly, all dips disappeared in the transmission spectra when the sensor heads were totally covered with water. In the previous report [19], we have demonstrated that the dip strength decreases significantly as r_2 deviates from r_1. When the sensor head is covered with water, there is a large difference between r_1 and r_2, which consequently leads to the disappearance of the dips. Therefore it is reasonable to conclude that for an HCF structure, water inhibits the leakage of the light energy out of HCF at the resonant wavelengths. It should be noted that this effect could also be useful in a design of band-pass filters with easy control of the pass bands and reject bands at certain frequencies.

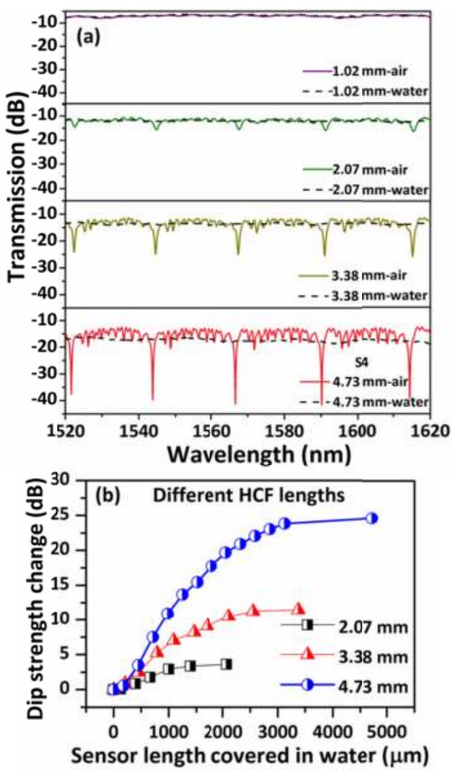

Fig. 2. (a) Measured transmission spectra in air and in water for a HCF based fiber structure with different lengths of HCF and (b) Measured dips strength changes of HCF based sensor samples with different lengths of HCF during liquid level measurement.

It is also noted that ideally the longer the length of HCF exposed to air, the higher the spectral dip quality (Q) factor and the greater the dips strength. However, when the HCF is over a certain length the dips Q factor and strength may decrease in real fabrication process due to the increased cladding diameter variation (e.g. bending) [18]. In addition, a longer length introduces larger losses in the transmission spectrum, which may decrease the accuracy of measurements. In this work, a ~4.73 mm-length HCF is chosen as the longest HCF section for the test based on our previous results which have demonstrated that around this particular HCF length a transmission spectrum with a relatively high Q factor and low loss is produced [18].

Sensor samples with HCF lengths of ~2.07 mm, ~3.38 mm and ~4.73 mm were then chosen for the demonstration of liquid level measurement in water (RI=1.3355). The measured experimental results for the dips strength variations at ~1566.6 nm with the increase of the water level are shown in Fig. 2(b). As can be seen from the figure, the sensor sample with a longer length of HCF offers a better sensitivity to the change of liquid level. The sensor sample with a HCF length of ~4.73 mm (denoted as S4) shows the highest sensitivity and was thus chosen for a more detailed investigation in the following experiments.

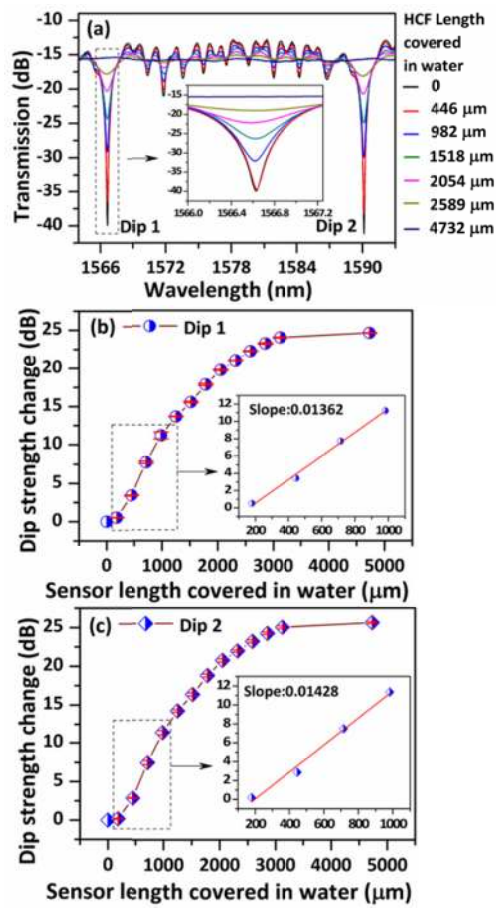

Fig. 3. (a) Measured spectral responses of S4 at different liquid levels, the inset figure shows the enlarged picture of the spectral response of dip 1; Measured spectral dip strength changes and the corresponding standard deviation in four cycles tests for (b) dip 1 and (c) dip 2 when water is flowing along the HCF.

Figure 3(a) shows the measured transmission spectral responses for sample S4 at various liquid levels. Dips with central wavelengths at ~1566.6 nm and ~1590.1 nm are denoted as Dip 1 and Dip 2 respectively. Fig. 3(b) and (c) summarize the changes of the spectral dips strength and their standard deviation in four consecutive tests as the sensor head S4 was gradually covered in water and then fully dried. As can be seen from the figures, the sensor shows very good repeatability of measurement for both dips. The highest sensitivity is obtained in the measurement range from ~200 μm to ~1000 μm. The inset figures in Fig. 3(b) and (c) show the measured data of this range and their linear fit. The calculated best liquid level sensitivities for both dip 1 and dip 2 are ~0.014 dB/μm, which corresponds to a liquid level resolution of ~0.7 μm assuming the OSA has an intensity resolution of 0.01 dB. This is the highest liquid level resolution reported to date, to the best of our knowledge. It is noted that the proposed liquid level sensor only works with such high resolution in a very narrow measurement range (~1 mm), but considering its proposed application in LOC devices, this measurement range is sufficient.

The dependence of sensitivity of S4 (Dip 1) on the SRI of the surrounding liquid was also investigated as shown in Fig. 4. It can be seen that the influence of the surrounding liquid's RI within the range from 1.3355 to 1.3812 on the dependence of the dip strength versus the change in the liquid level is very small, which gives the proposed sensor a big advantage against the previously reported liquid level sensors which suffer from a high cross sensitivity to changes in the SRI [4-9].

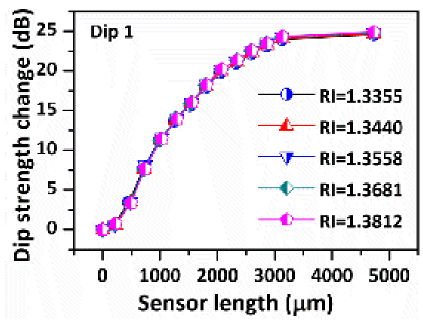

Fig. 4. Measured dip strength changes of Dip 1 during liquid level measurement in a range of SRI liquids.

Figure 5 compares the measured dip strength changes of Dip 1 during liquid level measurement for different water flow directions (water input from the left or right side of the tube respectively). The measured dip strength changes for both water flow directions are highly symmetrical with very little variations. Therefore, it is concluded that the proposed sensor is not capable of telling the direction of the liquid flow. However, this function could be achieved by replacing the input or the collecting SMF sections with a different type of fiber or using coating techniques, which will be further investigated in the future work. It is noted that more robust and integrated LOC devices for liquid level measurement could be realized by imprinting directly such an ARROW structure inside the devices [23]. In addition, due to the presence of periodic transmission dips in the transmission of the HCF structure, a high sensitivity liquid flow rate sensor could be potentially realized by simultaneous monitoring dips strength variations of two or more dips as the liquid flows along the HCF, as demonstrated by C. Shen et al. [24].

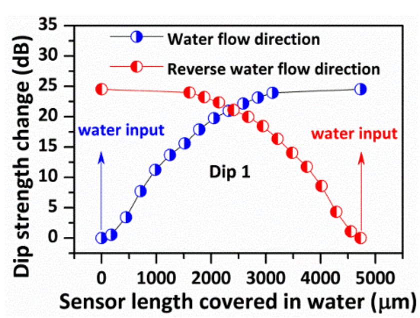

Fig. 5. Measured dip strength changes of Dip 1 during liquid level measurement for different water flow directions.

In conclusion, a highly sensitive liquid level sensor is demonstrated based on an HCF structure by monitoring the transmission spectral dip strength changes. Sensor samples with different lengths of the HCF section were investigated. It is found that the sensor sample with a longer length of HCF shows a better sensitivity to the liquid level change. The sensor sample with a HCF length of ~4.73 mm demonstrates the highest sensitivity of ~0.014 dB/μm in a liquid levels range from 200 μm to 1000 μm. To the best of our knowledge, this is the highest liquid level measurement sensitivity reported to date. The corresponding liquid level resolution is as high as ~0.7 μm. In addition, experimental results have demonstrated that the proposed sensor has good measurement repeatability and the sensor's sensitivity shows a very low dependence on the SRI.

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