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Proceeding Paper

High-Resolution Distributed Liquid Level Sensor Based on a Self-Heating Approach †

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Abstract: In this work, we propose a high-resolution distributed liquid level sensor based on a Cobalt-based, high-attenuation fiber (HAF), and a high-spatial resolution (5 mm) Brillouin Optical Frequency-Domain Analysis (BOFDA) sensor. In our method, the interrogating laser has a dual role: on one side, it excites the acoustic wave involved in the scattering phenomenon; on the other side, it heats up the fiber in a manner dependent on the surrounding medium (air or liquid). The proposed method has the potentiality of determining the liquid level with high spatial resolution, without requiring any additional component compared to a conventional BOFDA sensor.

Keywords: distributed optical fiber sensors; liquid detection

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1. Introduction

High-resolution liquid level sensing is relevant to industry monitoring. Compared to conventional electrical liquid-level sensors, optical-fiber sensors provide key advantages such as immunity to electromagnetic interference, good corrosion resistance, and high sensitivity. Actively heated fibers can be used for liquid level sensing, in which some heat source is employed to raise the fiber temperature. The temperature reached by the fiber, or the time required to recover the original temperature after heat source removal, may be employed to gain information about the medium surrounding the fiber, such as its phase (liquid or gas) [1], its speed [2,3], or its thermal conductivity [4]. Heat can be conveyed either electrically by Joule effect, or optically by use of specialty fibers. The latter solution is preferrable in those cases in which one should avoid the use of electrical currents (e.g., in hazardous environments). Specialty fibers whose core is doped with transition metal ions (namely Co^{2+} or Vn^{+}) can be employed, where absorption of light at specific wavelengths produces heat due to nonradiative relaxation. While conventional approaches recover the temperature using fiber Bragg gratings (FBGs) inscribed into the specialty fiber, a more convenient approach relies on the use of fully distributed sensing techniques. Chen et al. employed Optical Frequency-Domain Reflectometry (OFDR) in a Co^{2+}-doped fiber, realizing liquid level sensing at cryogenic temperatures [5]. In their work, the authors used an optical source at 1550 nm for heating, and a wavelength scanning laser in the C-band for sensing. More recently, a dual wavelength approach has been demonstrated by our group, in which a 1550 nm laser source was used for heating, while an 850 nm Brillouin setup was used for distributed temperature sensing [6]. The dual wavelength approach exploits the wavelength-selective absorption of the Cobalt-doped fiber, so that a wavelength falling into the low absorption band of the specialty fiber can be chosen for sensing. However, this also complicates the setup, due to the necessity to use separate laser sources and wavelength-division multiplexing (WDM) components.

In this work, we propose the use of a Brillouin Optical Frequency-Domain Analysis configuration featuring a spatial resolution of 5 mm, in order to perform liquid level sensing along a Co^{2+}-doped fiber. Differently from Ref. [6], a single wavelength approach is followed here, where the 1550 nm wavelength is adopted both for sensing and heating. The amount of self-heating is controlled by acting on the optical intensity of the pump (and probe) light used for BOFDA sensing. We will show experimentally that, the air/liquid interface can be easily recognized from the acquired temperature profile. In fact, the heat transfer in liquids is much more efficient than in air, leading to an abrupt decrease of the temperature along the optically heated fiber along the segment immersed into water.

2. Experimental Results

The BOFDA method consists in the acquisition of the amplitude and phase of the modulation impressed on a c.w. probe beam, due to the stimulated Brillouin scattering interaction with a counterpropagating pump beam, for a range of modulation frequencies. The two beams are separated by a frequency offset in the range of 10–11 GHz, corresponding to the so-called Brillouin Frequency Shift (BFS) of the fiber. The method is usually adopted for determining the BFS distribution along the fiber, with a spatial resolution not usually achievable with common time-domain reflectometric techniques [7]. As the BFS is linearly proportional to the temperature, the method is here applied to determine the temperature change along the Co^{2+}-doped fiber resulting from self-heating.

The experimental scheme adopted for the measurements is shown in Figure 1. The light from an external cavity laser, with a linewidth less than 100 kHz, is split into distinct branches for pump/probe generation. In the upper (probe) branch, the laser beam is double-sideband (DSB) modulated by means of an intensity electro-optic modulator (IM1) driven by an RF synthesizer. The upper sideband is filtered out by means of a narrowband fiber Bragg grating (FBG), while the lower sideband is first amplified by an Erbium-Doped Fiber Amplifier (EDFA1), then launched into one end of the fiber under test (FUT). In the lower (pump) branch, the laser beam is modulated by another electro-optic modulator (IM2) biased at its quadrature point and driven by the RF output of the vector network analyzer (VNA). The modulated pump passes through a polarization switch, used to suppress any polarization dependency from the measurements. Finally, the probe beam is amplified by EDFA2 and launched into the opposite end of the FUT. The backscattered light from the pump is fed into a high-bandwidth photodetector. The VNA covers the range from 300 kHz to 20 GHz, and thus permits us to investigate the Brillouin response at a minimum spatial resolution of 5 mm.

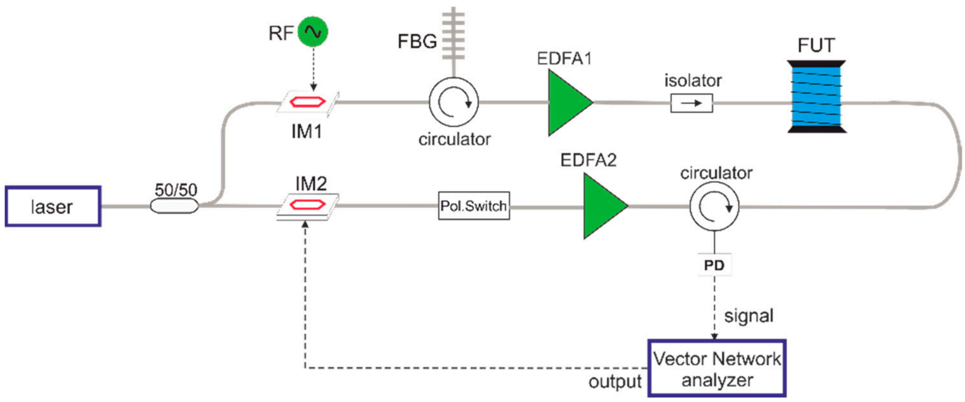

Figure 1. Experimental setup. IM, intensity modulator; FBG, fiber-Bragg grating; EDFA, erbium-doped fiber amplifier; Pol. Switch, polarization switch; PD, photodetector; FUT, fiber under test.

As a preliminary test, we prepared a FUT composed by a strand of 3 m of SMF-28 fiber, followed by a 9 cm length of high-attenuation fiber (HAF) with 40 dB/m attenuation at 1550 nm, and another strand of 3 m of SMF-28 fiber. We note that the attenuation along the HAF was ≈3 dB. We report in Figure 2 the cross-correlation between the Brillouin Gain Spectrum (BGS) at the far section of the HAF (i.e., at the section closest to the probe injection point), as acquired by the BOFDA sensor at a probe power of 16 dBm, with the BFS acquired by the same setup at slightly higher probe powers. Note that all measurements were done with the HAF surrounded by air. While the results shown in Figure 2 are quite noisy (mainly because of the low SBS efficiency of the HAF), a positive trend of the cross-correlation peak with the injected power can be appreciated. In fact, by performing a quadratic fitting around each peak, a shift of the cross-correlation peak of ≈28 MHz can be estimated when increasing the probe power from 16 dBm to 19 dBm. This corresponds to an approximate variation of 28 °C of the inner temperature of the fiber as a result of a 3-dB variation of the injected probe power (from 40 mW to 80 mW). This preliminary result confirms the occurrence of self-heating on the HAF during BOFDA measurements.

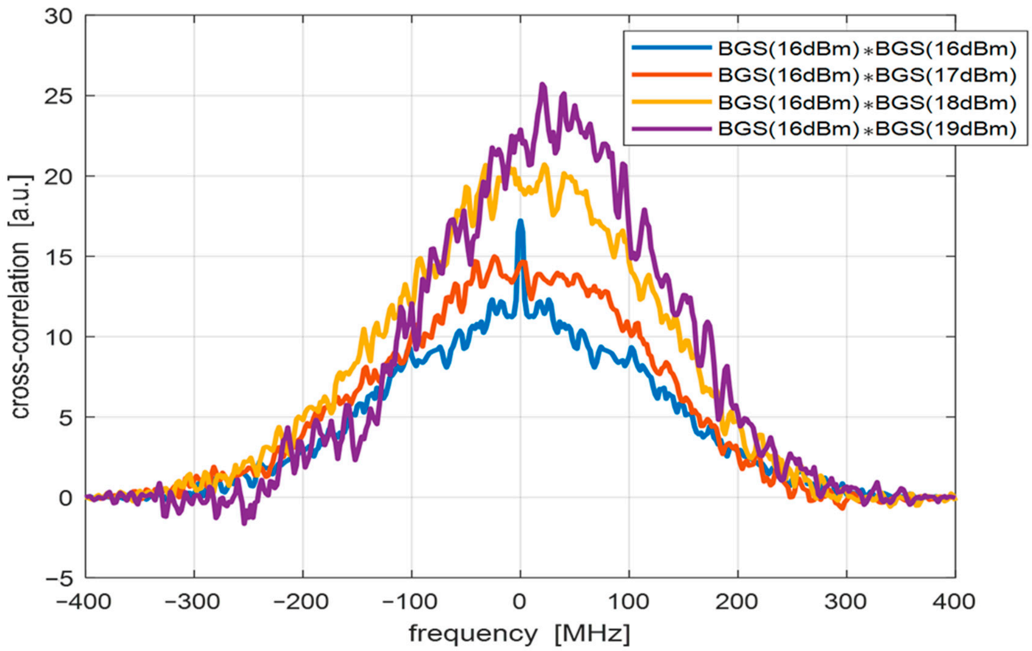

Figure 2. Cross-correlation between the BGS at the final section of the HAF, as acquired at various probe powers. The symbol * in the legend represents the cross-correlation operator.

As a next step, the BFS distributions along the FUT were measured upon immersion of the cobalt doped fiber into water at various levels. The temperature profiles, acquired by immerging progressively the HAF into the water at a step of 5 mm, are shown in Figure 3. The low Brillouin gain along the HAF is responsible of the irregularities exhibited by the temperature profiles. Nonetheless, each temperature profile shows an abrupt change in correspondence of the water/air interface crossing point. The position where the temperature drops abruptly can be used as an indicator of the liquid position. In particular, we set a threshold equal to 45 °C, so that the level position was identified as the threshold crossing position. The only exceptions are the profiles acquired with the fiber totally outside the water (for which the temperature was always higher than the preset threshold), or totally immersed into water (for which the temperature was always lower than the preset threshold). For these two special cases, the measured level was set to 0 cm and 9 cm, respectively.

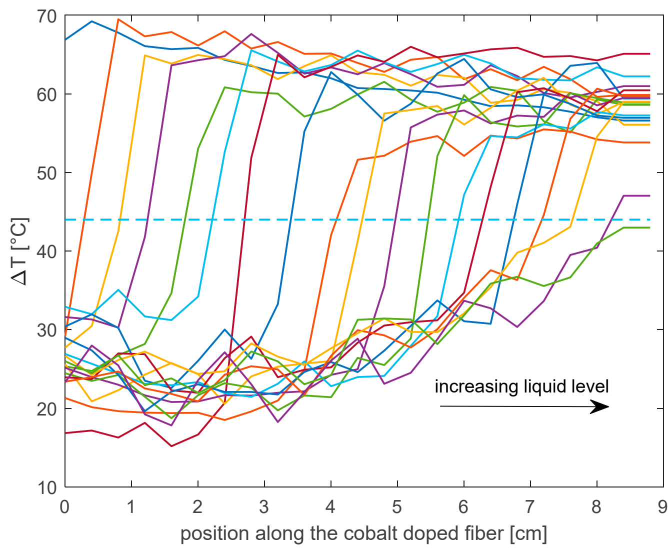

Figure 3. Temperature rise profiles acquired along the cobalt doped fiber, for L_W ranging from 0 cm to 9 cm at a step of 5 mm. The dashed line represents the threshold used for liquid level position measurements (From [8]).

In order to improve the resolution of the level measurement in the intermediate cases, we have performed a linear interpolation of the temperature profiles, acquired at a spatial resolution of 8 mm, using an interpolated step of 1 mm. In Figure 4, we report the liquid level obtained by localizing the threshold-crossing position in the interpolated temperature profiles, compared to the level set by experiments. The reported graph shows that a good linear relationship exists between the experimentally determined liquid level and the nominal level. In particular, the acquired data indicate a maximum deviation between the measured level position and the linear fitting curve equal to 2.3 mm, while the mean square error is 1.1 mm. Note that, while the reported experiments were performed using water as liquid medium, any other liquid could be used as well. In fact, our system is not sensitive to the refractive index of the liquid, as the optical field remains well confined in the HAF core. The only physical parameter of the liquid medium coming into play is its heat transfer coefficient, which is usually much larger than the corresponding coefficient in air, leading to the abrupt change in temperature distribution observed experimentally.

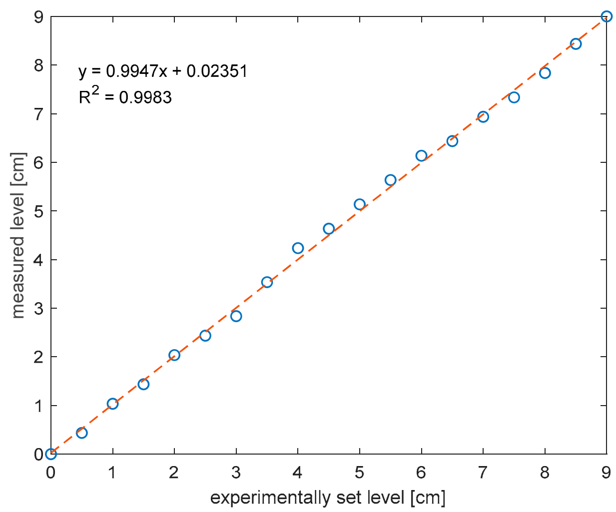

Figure 4. Measured level versus experimentally set level. Circles represents the experimental data, while the solid line represents the linear fitting curve (From [8]).

In conclusion, we have demonstrated the use of a self-heating approach for liquid level sensing measurements in cobalt-doped optical fibers. The main novelty of our proposal is the absence of any dedicated laser source for optical heating. In fact, we have shown that the strong c.w. components of the pump and probe waves, involved in the BOFDA configurations, are sufficient to heat the HAF at a sufficient temperature, allowing the localization of the air/liquid interface with a resolution dictated by the spatial resolution of the BOFDA setup. Future works will be devoted to enlarging the sensing range so as to cover a larger number of applications.

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