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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.

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 Fibre 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, thus permits to investigate the Brillouin response at a minimum spatial resolution of 5 mm.

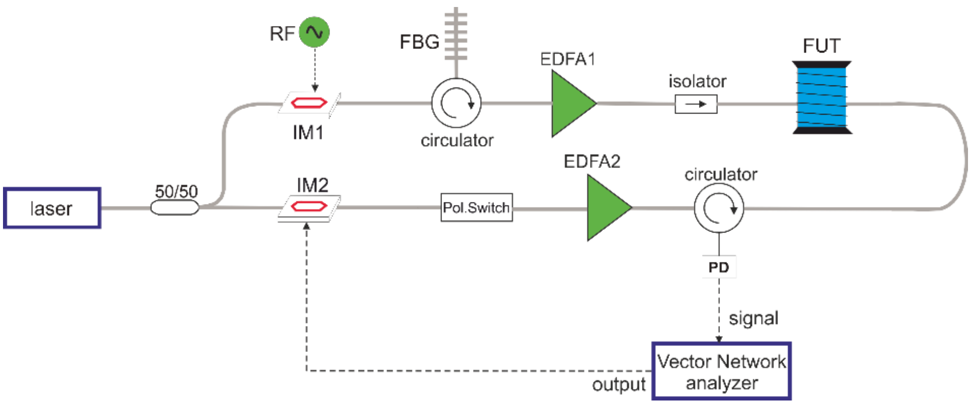

Figure 1. Experimental setup. IM, intensity modulator; FBG, fiber-Bragg grating; EDFA, erbium-doped fiber amplifier; Pol. Switch, polarization switch; PD, photodetector; FUT, fiber under test.

As a preliminary test, we prepared a FUT composed by a strand of 3 m of SMF-28 fiber, followed by an 8-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.

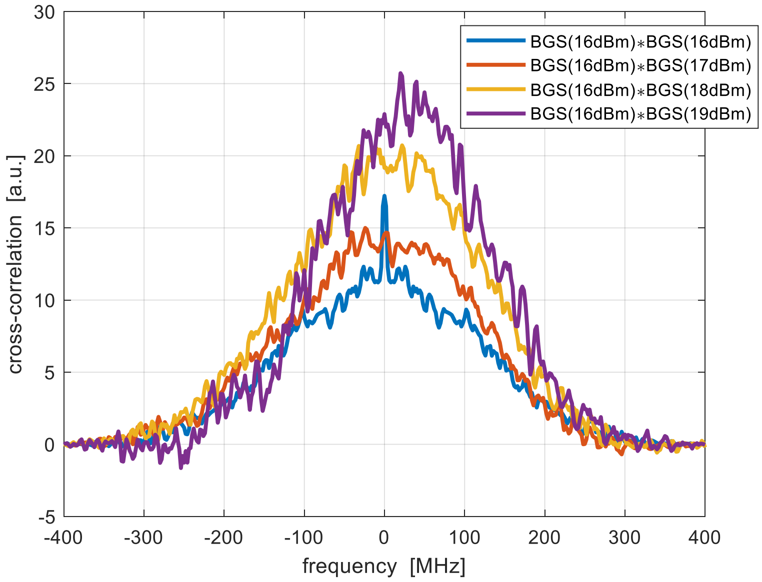

Figure 2. Cross-correlation between the BGS at the final section of the HAF, as acquired at various probe powers. The symbol * in the legend represents the cross-correlation operator.

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