Distributed high-temperature optical fiber sensor based on a Brillouin optical time domain analyzer and multimode gold-coated fiber

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***Abstract*—A high-temperature distributed sensor system based on a Brillouin optical time domain analyzer and a multimode gold-coated fiber is presented in this paper. Distributed measurements of temperatures up to 600$^{\circ}C$ are demonstrated with a temperature accuracy of about 10$^{\circ}C$. The system shows a consistent response for repetitive measurements, even considering increasing or decreasing temperature changes. This is the first time to our knowledge that a gold-coated fiber is used for high-temperature distributed measurements in a Brillouin-based system. The proposed solution via the gold-coated fiber allows a feasible deployment in field applications such as industrial scenarios.**

***Index Terms*—Stimulated Brillouin scattering, distributed systems, optical fiber sensors, gold-coated fiber, high-temperature measurements**

I. Introduction

Optical fiber distributed sensor systems have been an intense area of research in the last years due to their unique features to provide strain and temperature distributed measurements over tens of kilometers with meter spatial resolutions and exhibiting immunity to electromagnetic interference and harsh and highly radiative environments [1]. Since the first proposal to measure distributed temperature using the nonlinear Brillouin effect [2], Brillouin optical time domain analyzers (BOTDAs) have been extensively used for over two and a half decades [3]. It is based on the stimulated Brillouin scattering (SBS), where two counter-propagating waves, the so-called pump and probe waves, interact within the optical fiber via acoustic phonons [4]. The spatial information where the interaction takes place can be retrieved provided that the pump wave is pulsed, with the pulse duration defining the achieved spatial resolution. For standard long-range BOTDA implementations, the spatial resolution is limited to 1m (10 ns pulse) due to the limitation imposed by the phonon lifetime [4]. Alternative proposals, such as the differential pulse pair (DPP) technique [5], pre-pumping [6] or dark pulses [7] allow to reach improved sub-meter spatial resolutions.

Among the diverse applications of these systems, e.g. structural health monitoring [8], there are several based on the estimation of temperature along the fiber cable. Solutions for the detection of fires [9], leakages in large oil, gas or water infrastructures [10], [11] or failures in power cables [12] have been proposed. Raman-based distributed systems have also been employed as distributed temperature sensors (DTSs). Among other differences, they are based on intensity-detection schemes in comparison to the frequency detection implemented in SBS approaches, higher optical powers are required to allow a suitable performance and they are not affected by strain-induced errors. High-temperature distributed sensing (above 300$^{\circ}C$), required for applications such as the monitoring of oil wells or industrial sectors like the manufacturing of heavy components for nuclear power stations, has been explored in Raman-based solutions [13]. Ge doped and pure silica core multimode optical fibers have been used for temperature measurements up to 600$^{\circ}C$ [14]. High-temperature distributed sensing via BOTDAs has also been recently demonstrated by Wang et al. using a BOTDA system to measure temperatures up to 1000$^{\circ}C$, with 5m spatial resolution, although the optical fiber employed in this work was not specified [15]. Dong et al. have presented 1100 and 1200$^{\circ}C$ distributed measurements with a BOTDA configuration using single mode fiber (SMF) and a pure-silica photonics crystal fiber (PCF) and measurement accuracies of ± 2 and $\pm 4^{\circ}C$, respectively [16].

The deployment of these distributed system in real field scenarios will imply the necessity of considering special coated fibers able to resist harsh environments. For temperatures under 300$^{\circ}C$, polyimide-coated fibers can be considered, but higher temperatures will require the employment of other solutions, such as metal coatings like aluminium or gold [17]. The manufacturing of these special coated fibers can be performed after drawing in a separate process (off-line) or during drawing (in-line). The so-called freezing method is applied when the latter option is chosen. In this case, the fiber is passed through a layer of approximately few millimeters of molten metal. Provided that the melt exhibits a temperature close to the melting point of the metal and that the temperature of the fiber is somewhat lower, a layer of metal can freeze on the surface of the fiber. The duration

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of the contact of the fiber with the molten metal should be shorter than the time of the fiber heating to the metal melting point. If this condition is not fulfilled, the frozen layer will melt again and the fiber will exit the metallizer without any coating [18]. These metal coated fibers allow high-temperature measurements, but they exhibit high attenuation, especially at low temperatures, due to both hydrogen ingression and microbending losses due to thermal stress [17]. This may be a problem for Raman-based systems where the measurement of temperature is based on the detection of the intensity of the scattered signals, due to the considerably attenuation decrease for higher temperatures, which can give rise to errors in the measurements. However, distributed systems based on the Brillouin scattering perform a frequency-based detection, thus being more suitable to scenarios where attenuation can be very dependent with temperature.

In this paper we present a high-temperature distributed system based on a BOTDA implementation and a gold-coated multimode optical fiber. In a previous work a gold-coated fiber was used to achieve centimeter spatial resolution over a 1 meter fiber using a system based on swept wavelength interferometry and Rayleigh scattering [19]. This is the first time to our knowledge that such fiber is used in a Brillouin-based distributed system for high-temperature sensing. In comparison to the fibers employed in previous works dealing with distributed high-temperature measurements via BOTDAs [15], [16], the fiber considered in this work is suitable for its deployment in real field scenarios and to survive to a wide range of temperatures (from -269 to $700°C$) and to harsh environments due to the mechanical properties of the gold coated protection.

II. Fundamentals

Brillouin optical time domain analyzers are based on the stimulated Brillouin scattering generated via the interaction of the counter-propagating pump and probe waves. The frequency difference between both signals is important, as the maximum Brillouin gain will be achieved when they are separated ν_B, the Brillouin frequency of the fiber under analysis:

$$\nu_B = \frac{2 n_{eff} V_a}{\lambda_p}, \tag{1}$$

where n_{eff} is the effective core refractive index, V_a the acoustic velocity and λ_p the wavelength of the pump wave in vacuum. To acquire the whole Brillouin Gain Spectrum (BGS) it is necessary to scan a certain frequency range by modifying the frequency difference between pump and probe waves. This is typically accomplished by sweeping the probe wave with a modulator driven by a RF generator. Provided that the BGS has been acquired, the Brillouin Frequency Shift (BFS) can be estimated via Lorentzian fitting.

The BFS exhibits a linear dependence on the local temperature variation Δ_T and the applied strain $\Delta\epsilon$ that for low temperatures that can be expressed as follows [20]:

$$\nu_B(T,\epsilon) = C_\epsilon \Delta_\epsilon + C_T \Delta_T + \nu_B(T_0, \epsilon_0), \tag{2}$$

where C_ϵ and C_T are the strain ($MHz/\mu\epsilon$) and temperature ($MHz/°C$) coefficients and T_0 and ϵ_0 the reference temperature and strain. These values are mainly determined by the fiber composition and external protections (coatings and jackets) [21].

Results provided by other authors suggest that the best fitting when dealing with high-temperature measurements may be accomplished by means of a negative exponential [16].

When monomode fibers are used as the sensing element, part of the energy of the higher frequency pump (if a gain configuration is considered) will be transferred to the chosen lower frequency probe sideband via the acoustic wave. The use of a multimode fiber enables the appearance of several optical and acoustic modes. This implies that the resulting BGS will be formed by the addition of the contributions of various pairs of counter-propagating optical modes interacting through a given acoustic mode [22]. Although this broaden and even non-symmetrical BGS may affect the final system accuracy, if a lateral offset in the splicings between the optical fiber transitions is avoided, the contribution of higher-order modes will be suppressed [23], thus favoring the system performance. The vast majority of BOTDA implementations reported in the literature has considered monomode fibers, given their superior features for long distance sensing. However, the study of the performance of multimode fibers may prove interesting, for example to achieve bend-insensitive solutions or to explore the possible use of the multiple mode interactions to enable the discrimination between strain and temperature measurements.

III. Experimental setup

The fiber under test (FUT) designed setup and employed in the experimental tests shown in Fig. 1 (a). It can be observed how the multimode gold-coated fiber is accessed via conventional silica graded-index multimode fiber and, additionally, two short sections of monomode fibers have also been spliced at both ends to allow a straightforward connection to the BOTDA system access ends. The gold-coated section (FiberGuide AFS50/125/155G) is formed by 78m, where the last 4m are placed within a furnace chamber. Longer lengths of this fiber might be employed in the proposed system, with the only limitation of the fiber attenuation (around 20dB/km). This high attenuation is mainly due to the microbendings generated by the metal coating. The gold fiber is a 50μm Pure Fused Silica Core and 125μm Fluorine Doped Silica Cladding. The optical losses are around 20dB/km.

Conventional BOTDA systems are typically implemented using monomode optical fibers as FUT, given mainly to their higher performance in terms of attenuation. There are few works where multimode fibers are used for distributed measurements based on SBS. Minardo et al. [22] carried out a numerical and experimental study with graded-index multimode fibers and Xu et al. [23] developed a bend-insensitive distributed BOTDA sensor using a graded-index multimode fiber as sensing fiber.

The experimental setup described in Figure 1(b) was employed to carry out the experimental tests. The BOTDA system is formed by a distributed feedback laser (DFB) source, whose

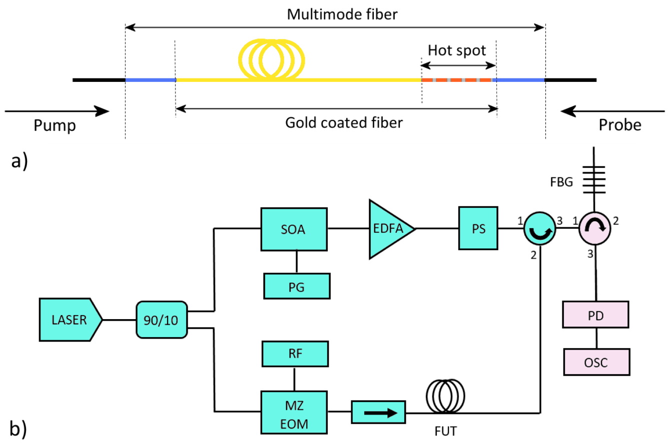

Fig. 1. (a) Fiber under test employed with standard monomode fiber on both sides (black), multimode graded index fiber (blue) and gold-coated fiber of 74m length (yellow) and 4m length (red dashed line); (b) Schematic setup of the BOTDA system used in the experimental tests: semiconductor optical amplifier (SOA), pulse generator (PG), erbium-doped fiber amplifier (EDFA), polarization scrambler (PS), Mach-Zender electro-optical modulator (MZ-EOM), RF Generator (RF), fiber under test (FUT), fiber Bragg grating (FBG), photodetector (PD) and oscilloscope (OSC)

output is divided by a 90/10 coupler into two branches. The upper branch generates the pulsed pump wave (10 ns) via a semiconductor optical amplifier (SOA) (connected to a pulse generator (PG)) providing an extinction ratio above 40 dB. An erbium-doped fiber amplifier (EDFA) is used to boost the pump pulse power and a polarization scrambler (PS) is used to avoid the polarization dependence of the SBS gain along the fiber. The probe wave is formed in the lower branch by an electro-optical modulator (EOM) driven by a RF generator, followed by an isolator and the FUT. The system works in a balanced configuration, i.e. both Stokes and anti-Stokes signals enter the FUT and participate in their corresponding SBS processes. At the output of the system, once the SBS interaction has taken place within the FUT, the resulting optical signal is filtered by a narrow fiber Bragg grating (FBG) and only the Stokes component is directed to a 125 MHz photodetector (PD) by an optical circulator, thus a gain configuration is considered. Finally, an oscilloscope is employed to acquire and perform a 1024 averaging of the BOTDA traces. In our system, a probe power of 8mW and a pump peak power of 2W are used to obtain an optimal signal at detection. It is worth noting that Raman distributed systems typically use pump powers of around tens of W, i.e. in a 40 km long Raman sensor a pump pulse of 10 ns and 20 W was employed [24].

IV. Experimental Issues

A set of experimental tests was carried out to study the ability of the designed system to perform distributed high-temperature measurements. A 4 meter section of the gold-coated fiber (at the end of the FUT) was placed within a furnace chamber and different temperatures between $50°C$ and $600°C$ were analyzed (with temperature steps of $50°C$), with the temperature provided by the furnace thermocouple used as reference. 4 measurements were performed at each temperature. Figure 2 presents these results, where the estimated BFS (after the Lorentzian fitting process) has been represented against the FUT distance. It can be clearly observed how the temperature differences give rise to different BFSs that are clearly distinguishable at the hot-spot section.

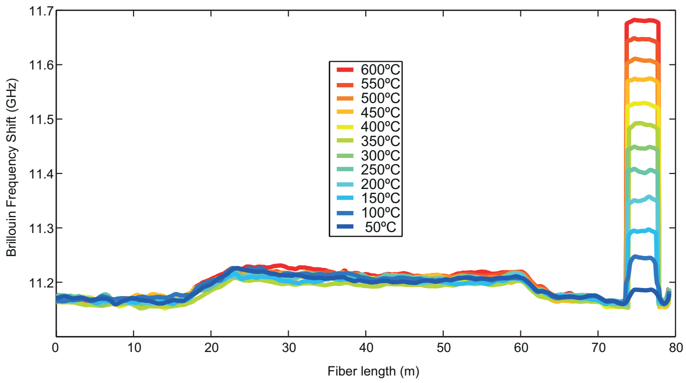

Fig. 2. Brillouin frequency shift vs. fiber length for temperatures at the hot-spot section from 50 to $600°C$.

Figure 3 shows the same results previously discussed but considering descending temperatures from 600 to $50°C$. This study is important to verify that a similar response is obtained and that the measurement system is free from hysteresis. Again, it can be validated how the temperature differences clearly appear at the hot-spot section with a behavior similar to the one presented in Figure 2.

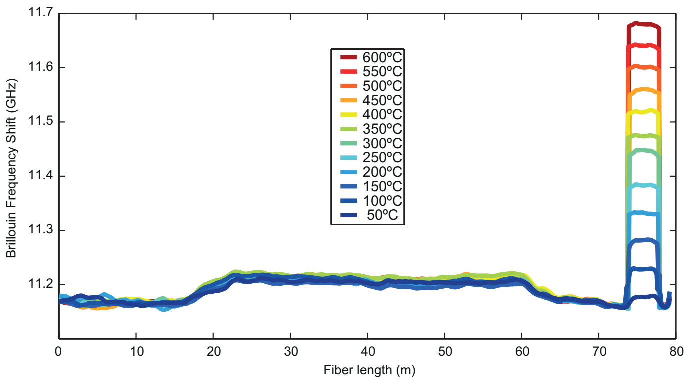

Fig. 3. Brillouin frequency shift vs. fiber length for temperatures at the hot-spot section from 600 to $50°C$.

Figure 4 shows the resulting fitting of the BFS measured for each considered temperature at the hot-spot section of the FUT. 8 different measurements were carried out for each temperature. The blue markers in Figure 4 are associated with a cycle of increasing temperature from 50 to $600°C$, while the green markers are associated with the corresponding decreasing cycle. These markers show the mean of the BFS at different temperatures for each spatial point at the hot-spot section when the temperature of the furnace is stable. It is also worth noting that there appears no temperature hopping [16] given that the considered temperatures are below $800°C$. A fitting of these data gives rise to an exponential fitting expressed via the following expression:

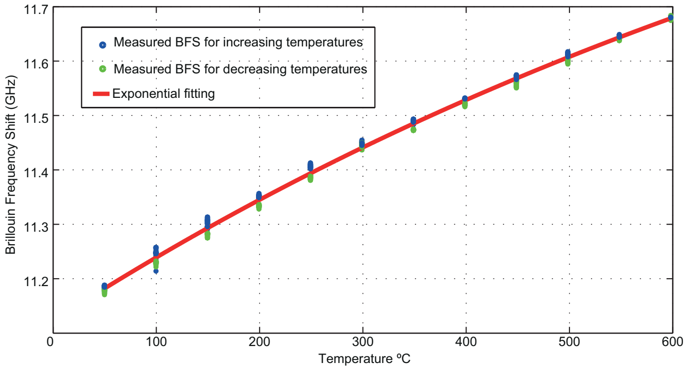

Fig. 4. Brillouin frequency shift vs. temperature at the hot-spot section. The red line shows the fitting of BFS for the temperature between 50 to 600°C. Blue/green markers show the measured BFS for the increasing/decreasing temperatures.

$$\nu_B = -1269e^{-0.0010T} + 12390 \tag{3}$$

where ν_B is the BFS expressed in MHz and T is the temperature in Celsius. Using this exponential curve the value of R^2 is 0.9976 and the mean error between the measured data and the real temperature is $\pm 7.7°C$.

To validate the fitting equation obtained employing the previous data, additional temperature measurements have been carried out. Given that the process of changing and stabilizing the temperature of the furnace chamber is very slow, several measurements have been done for each temperature. In this case, a new cycle of increasing temperatures has been considered. The differences between the measured temperatures (applying Eq. 3 to the measured Brillouin frequency) and the temperatures provided by the furnace thermocouple are presented in Table I. The temperature error of Table I is calculated subtracting the average of the different measurements for each temperature and the reference temperature of the furnace.

TABLE I
AVERAGED BFS VALUES, ESTIMATED TEMPERATURE AND MEAN ERROR FOR EACH TEMPERATURE.

Reference Temperature (°C)	Measured BFS (GHz)	Measured Temperature (°C)	Temperature error (°C)
50	11.187	55.69	5.69
100	11.239	101.95	1.95
150	11.295	152.93	2.93
200	11.346	202.72	2.72
250	11.394	251.17	1.17
300	11.443	304.35	4.35
350	11.483	349.15	0.85
400	11.525	397.41	2.59
450	11.566	447.84	2.15
500	11.602	493.78	6.21
550	11.636	540.00	9.99
600	11.672	590.46	9.53

The analysis of the evolution of the BGS for each scenario has been represented in Figures 5 and 6 for increasing and decreasing temperatures. It can be appreciated that no significant distortions appear in the BGS as the temperature varies. In both cases, a constant gain appears at a fixed frequency (natural Brillouin frequency of the fiber) away from the one associated

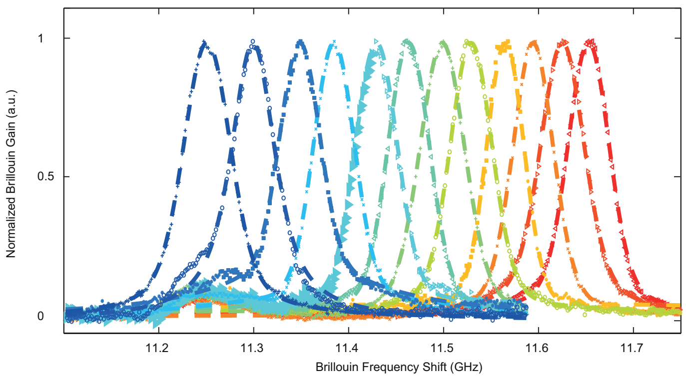

Fig. 5. Evolution of the BGS for increasing temperatures.

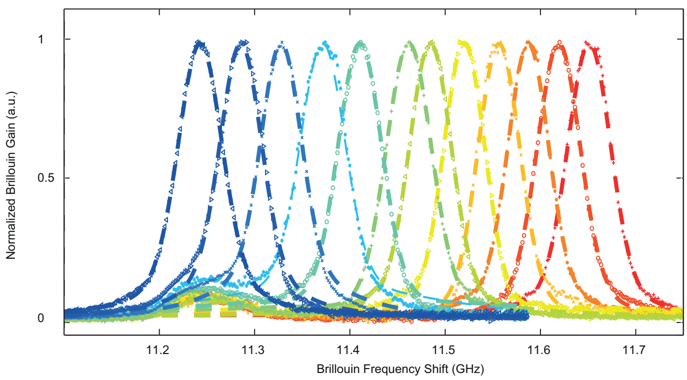

Fig. 6. Evolution of the BGS for decreasing temperatures.

with the measured temperature. This effect is provoked by the leakage signal generated during the pulse formation at the SOA due to the high pump power required.

V. Conclusions

In this work, a distributed high-temperature measurement system based on a Brillouin optical time domain analyzer and a multimode gold-coated fiber has been presented. This is the first time to our knowledge that a multimode gold-coated fiber has been used for high-temperature measurement in a SBS-based optical fiber distributed system. A few previous works have dealt with high-temperature sensing via BOTDAs [15], [16], but the gold-coated fiber ensures a feasible fiber deployment in field applications for temperatures up to 600°C. Experimental tests have been carried out demonstrating the feasibility of the proposed approach. The system response for both increasing and decreasing temperatures between 50 and 600°C has been obtained, showing a very similar behavior that can be modeled via exponential fitting. A good temperature mean accuracy of about 10°C has been estimated, showing a suitable system performance. High-temperature field tests in an industrial environment with the proposed solution are in process. Studies devoted to the minimization of the fiber attenuation and the maximum achievable measurement length with this kind of fiber in a BOTDA system will also be performed.

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