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ABSTRACT

Standard multimode optical fibers normally support transmission over some 100 modes. Large differences in the propagation constant and the spatial distribution of distinct modes degrade the performance of phase-sensitive optical time-domain reflectometry measurements. In this work, we present a new realization of a coherent time-domain interrogation technique using single-mode operation in multimode fibers. We demonstrate effectively distributed strain sensing on three different multimode optical fibers. Up to 4 km of multimode fiber has been correctly interrogated, featuring a spatial resolution of 20 cm.

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I. INTRODUCTION

Distributed optical fiber sensors (DOFS) based on Raman, Brillouin, or Rayleigh scattering become ubiquitous in situations where the measurement of physical quantities, such as vibration, strain, or temperature, induced by multiple events over long distances is required.^{1–6} Research on DOFS based on Rayleigh scattering has naturally focused on single-mode fibers due to the absence of intermodal effects. A major interest of DOFS lies in the opportunity to interrogate the already deployed fibers. However, a significant proportion of those is multimode, so it would be beneficial to take advantage of the existing multimode fiber networks. On top of that, aiming at overcoming the limitations of the current optical networks, a great investment in the development of few and multimode optical fibers for mode division multiplexing^{7–9} has been carried out, leading to an increase in the ratio of deployed multimode to single-mode fibers. It is, thus, reasonable to expect that

in the foreseeable future, the demand for DOFS utilizing multimode optical fibers will also grow. Coherent techniques based on Rayleigh scattering, in which the phase of the scattered signal is analyzed, need a more sophisticated setup when the fiber under test is multimode rather than single-mode. In fact, in the literature, demonstrations of detection of single or multiple speckles of scattered light in multimode links can be found.^{10–14} To enable proper coherent Rayleigh-scattering-based interrogation in multimode fibers, techniques developed for mode division multiplexing have been utilized, namely, selective mode excitation. In this paper, we report on direct strain measurements using phase-sensitive optical time-domain reflectometry [ϕ -OTDR (optical time-domain reflectometry)] based on single-mode operation in several few and multimode optical fibers. In addition to the above-mentioned advantages, this method also diminishes modal dispersion,¹⁵ which can lower the spatial resolution by tens of centimeters at a distance of 1 km. These results may facilitate the introduction and

adoption of not only Rayleigh-scattering-based DOFS in multimode optical fibers that are already deployed for telecommunication but also Raman-scattering-based sensors.

II. METHODOLOGY

In order to assess the strain response of the multimode fibers under test, we developed a high-resolution ϕ -OTDR setup similar to the one presented by Hartog,¹⁶ but combined with an additional higher-order mode filter (HOMF),¹⁵ as shown in Fig. 1. A distributed feedback (DFB) laser at a wavelength of 1550 nm was used as the light source. By tuning the driving current of the laser, the laser frequency can be scanned to characterize the frequency-dependent response of the backscattered signal. In this experiment, a 29 GHz scanning range was obtained with steps of 92 MHz, which results in 315 measured fiber responses. The frequency step size was chosen to finely retrieve the signal intensity as a function of the laser central frequency for each point along the fiber under test. The laser tuning accuracy was 10 MHz. An electro-optic intensity modulator (EOM) driven by a pulse generator was used to shape 2 ns square pulses (which render a 20 cm spatial resolution), launched with a repetition rate of 1 kHz. The expected FWHM of the peaks in the pattern is equal to 300 MHz for the used spatial resolution.¹⁷ To secure an extinction ratio over 60 dB, as required in order to achieve a 20 cm resolution over a 5 km range, a semiconductor optical amplifier (SOA) is inserted after the EOM to perform a second optical pulse gating, though with longer pulses. To increase the pulse power, an erbium-doped fiber amplifier (EDFA) is placed after the SOA. The power injected into each fiber was chosen separately such that it is the maximum power for which the measurement quality does not drop due to modulation instability. The maximum peak power that we could achieve with the described setup was 26 dBm. After the EDFA, the pulse is sent through a circulator to the multimode fiber under test. At the junction between the single and the multimode fibers, multiple modes are excited. A HOMF, manufactured by InPhoTech, is inserted to effectively filter out all higher-order modes propagating in the optical fiber while introducing additional 2 dB losses on the launch in the setup. These losses vary no more than 0.2 dB for the different multimode fibers used in the experiment.

To verify that the HOMF ensures single-mode operation, M^2 tests were performed. For every fiber under test, the M^2 value obtained at the far end of the fiber was below 1.1. This value indicates that in the worst possible scenario, the power in the fundamental mode is at least 10 times higher than in all the other modes combined. In the absence of strong perturbations applied to the fiber, e.g., a bad splice, during propagation along the multimode fiber, the power coupling occurs mainly between modes within one mode group, while coupling between different mode groups is negligible.¹⁸ At each point, part of the light is Rayleigh-backscattered into all modes propagating inside the fiber under test.¹⁹ The returning signal is once again filtered by the HOMF, and the retrieved fundamental mode signal is then amplified by a second EDFA to increase the signal to noise ratio. A tunable filter with a bandwidth of 1 nm is inserted to reject most of the amplified spontaneous emission (ASE) from the EDFA. The signal is then detected by a DC-coupled photodiode with a 1 GHz bandwidth, which is sufficient to properly retrieve the targeted spatial resolution. Finally, the electrical signal from the photodiode is digitized by means of a 4 GHz oscilloscope. The measured signal was averaged 100 times in order to increase the signal to noise ratio. The total time for a single scan was around 1 h due to communication between the devices used in the setup not being optimized. With appropriate optimization, the time can be reduced to below 5 min.

In order to apply a known strain, the fiber was fixed to a micrometric translation stage. Strain measurements were carried out by performing two scans of the laser frequency, i.e., before and after applying the strain. For each point along the fiber, the cross correlation of intensity vs laser frequency was calculated. From the maximum of the calculated cross correlation, a frequency shift is obtained, which is a linear function of the induced strain. Three different optical fibers have been tested: the first one is a multimode OM4 fiber manufactured by Draka, which supports 34 LP mode groups at a wavelength of 1550 nm. The second one is a 6 LP mode graded-index fiber also manufactured by Draka. The third one is a 4 LP mode graded-index fiber manufactured by InPhoTech. All of these fibers show a parabolic refractive index profile in the core. This choice is designed to test single-mode operation both for fibers with few-mode groups and for highly multimode optical fibers

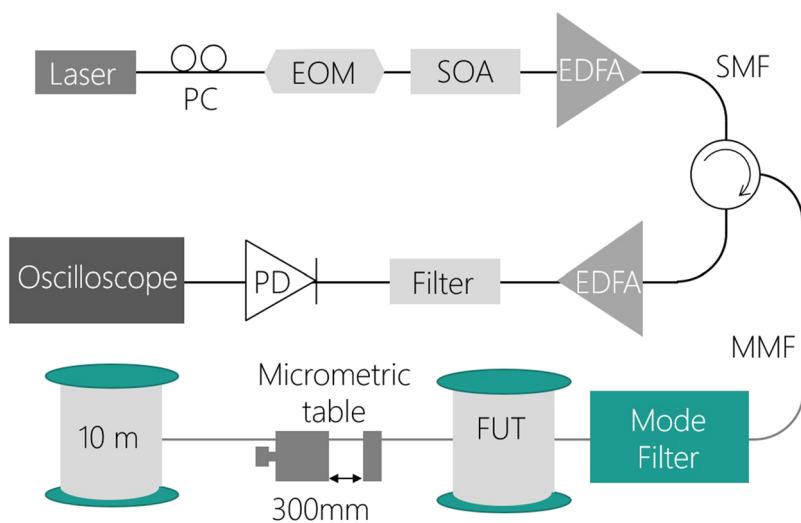


FIG. 1. Experimental setup used for strain measurements in multimode optical fibers with ϕ -OTDR. PC, polarization controller; EOM, electro-optic modulator; SOA, semiconductor optical amplifier; EDFA, erbium doped fiber amplifier; PD, photodiode; SMF, single mode fiber; MMF, multimode fiber; and FUT, fiber under test. For testing, three different optical fibers were used: 4 km of OM4, 1 km of 6 LP Draka, and 100 m of 4 LP InPhoTech.

commonly deployed in buildings and short-range telecommunication links.

III. MEASUREMENT RESULTS

For proper ϕ -OTDR measurements in a single-mode fiber, a high trace visibility (of at least 0.75) for every section of the fiber is expected, defined as

$$Visibility = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \quad (1)$$

where I_{max} and I_{min} are the maximum and minimum intensities of the fiber segment, respectively, for which visibility is calculated. To assess the performance of the system, visibilities observed for a single-mode fiber (SMF), the OM4 Draka, the 6 LP Draka, and the 4 LP InPhoTech optical fibers were calculated over every 20 m long segment from the acquired trace, as shown in Fig. 2. An SMF was characterized without a HOMF to verify the performance of the measurement setup in a known situation. The visibility values obtained for the SMF were lower than those reported in the state-of-the-art as a result of a limited extinction ratio. For each segment, the visibilities for few and multimode optical fibers are slightly lower than those obtained for the single-mode fiber, but all of them are still in excess of 0.8, confirming the proper single-mode operation. Visibility values lower than those for the SMF are probably an effect of the signal from other modes going through the HOMF. It turns out that the visibility is lower over the first 20 m in the 4 LP InPhoTech fiber, which is an artifact caused by a strong spurious reflection and the partial saturation of the detector.

As a second step, for each tested optical fiber, we investigated the frequency shift induced by an applied strain by performing a frequency scan for three different strain values. Each measurement

was performed twice to confirm that the results are stable if the strain is unchanged. The measured frequency change between the two measurements for the same applied strain turns out to be less than half of the frequency step, which is the minimum detectable change, confirming the correctness and repeatability of the tests. Strain noise estimated as the mean measured value for the whole fiber in a static situation was 0, which indicates that it is smaller than $0.3 \mu\epsilon$. Figure 3 shows the calculated cross correlation as a function of position in the fiber and frequency shift for the OM4 Draka, the 6 LP Draka, and the 4 LP InPhoTech fibers. It is clearly visible that a shift in the maximum of the cross correlation is observed only in the section where strain is applied for all these three types of fibers. For the 6 LP Draka optical fiber, there is a visible additional high peak in the cross correlation spectrum. Such false peaks are an inherent property of the measurement technique used, as they are the results of the statistical properties of Rayleigh scattering.²⁰ By measuring the frequency shift for three different strain values and performing a linear fitting over the measurement data for each fiber, we were able to estimate the strain sensitivity of the fundamental mode for all of the tested fibers (Fig. 4). There are two main sources of error during this characterization: a minor one, which is related to the frequency step while scanning the laser frequency, and the dominating one, which is due to the micrometric translation stage. Estimating changes smaller than half of the frequency step have limited reliability. Although there are methods to estimate such small changes, using them will not have much impact on the results due to the major source of uncertainty rendered by the use of the translation stage. Since strain was applied through a manually set translation, the level of accuracy for the applied strain is around $6 \mu\epsilon$. Under these uncertainties, the calculated sensitivities based on the experimental results are $138 \pm 16 \text{ MHz}/\mu\epsilon$, $133 \pm 17 \text{ MHz}/\mu\epsilon$, and $152 \pm 16 \text{ MHz}/\mu\epsilon$ for the OM4 Draka, the 6 LP Draka, and the 4 LP InPhoTech optical fibers,

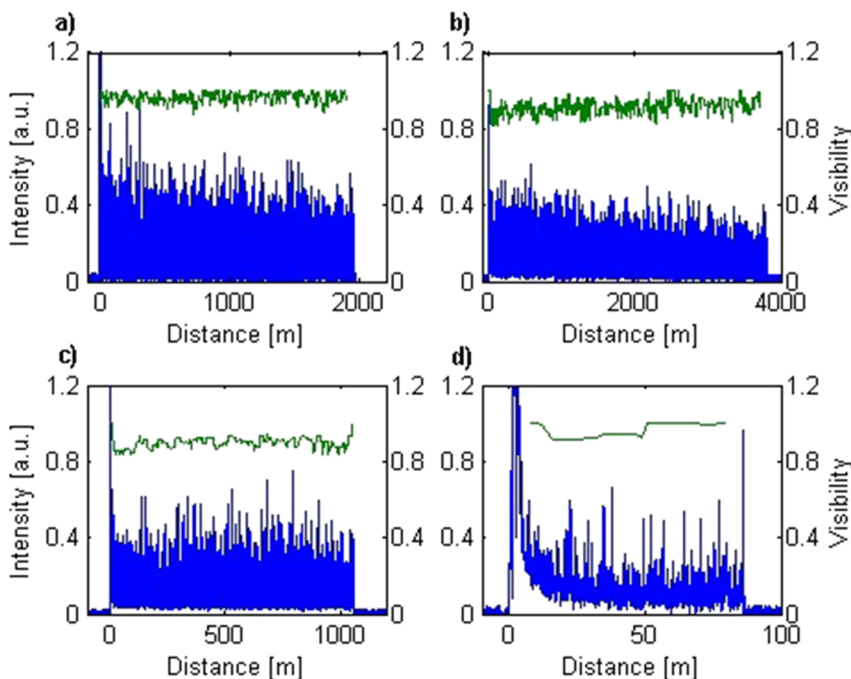


FIG. 2. Measured trace (blue line) and calculated visibility of the response over 20 m segments (green line) for (a) SMF, (b) OM4 Draka, (c) 6 LP Draka, and (d) 4 LP InPhoTech optical fibers. Visibilities of the measured response for few- and multi-mode fibers are similar to those obtained for a single mode fiber.

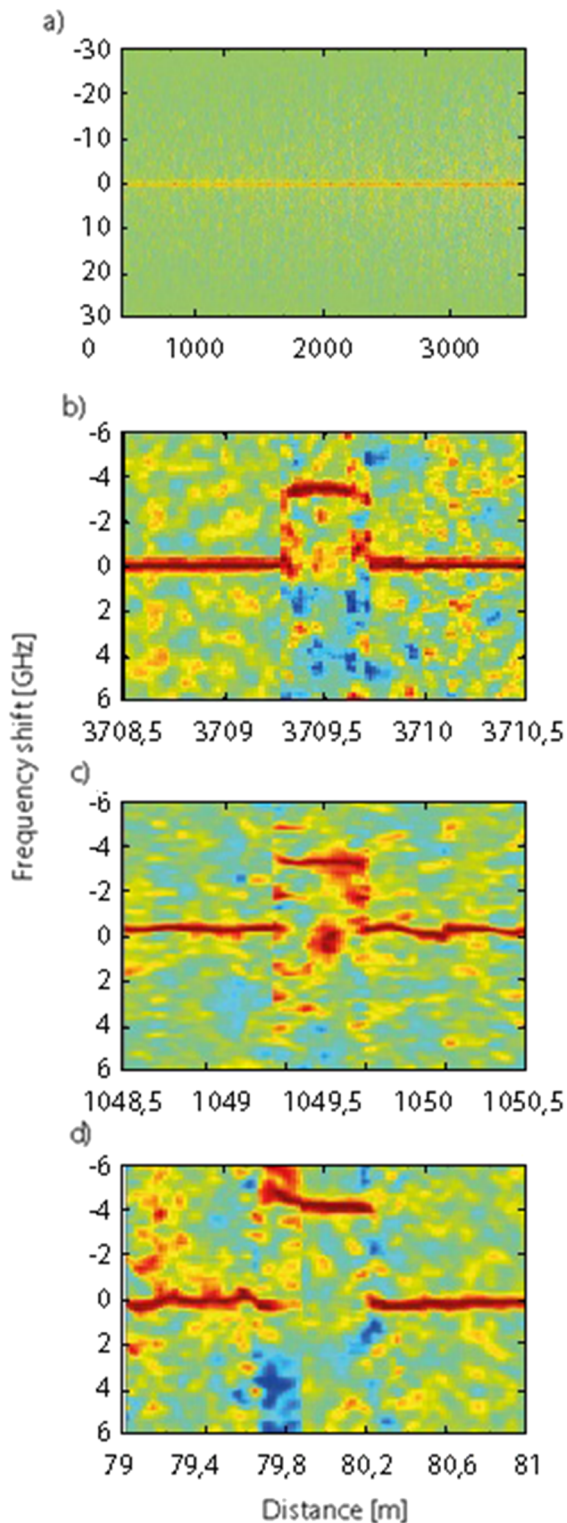


FIG. 3. (a) Calculated cross correlation in the frequency domain for each point of the OM4 Draka optical fiber. Other graphs represent zoomed-in sections where strain was applied for (b) OM4 Draka, (c) 6 LP Draka, and (d) 4 LP InPhoTech.

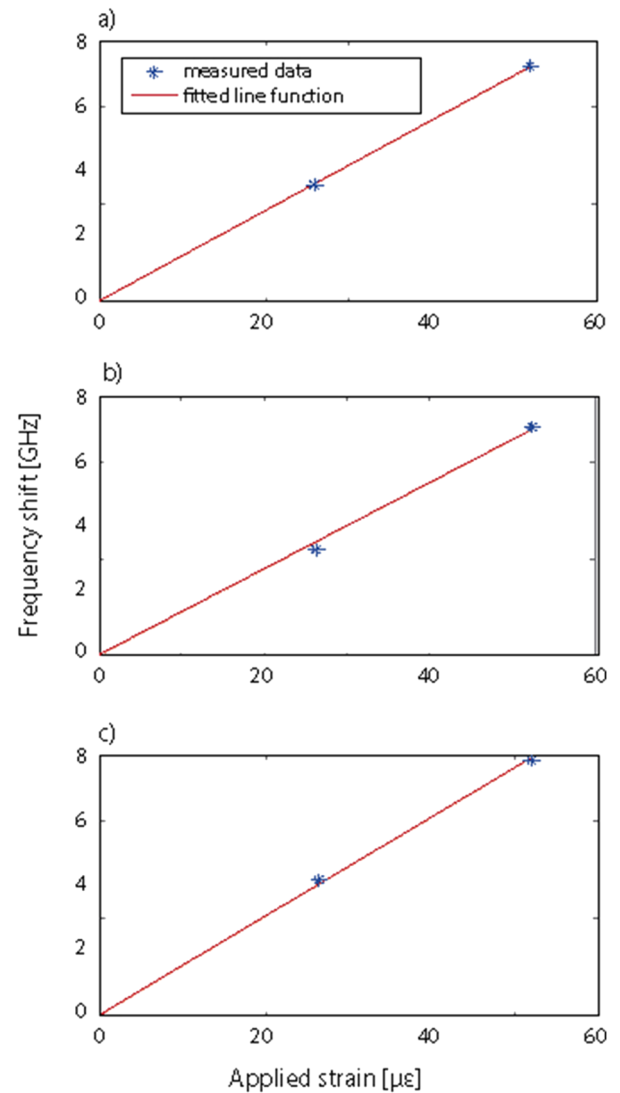


FIG. 4. Measured frequency shift as a function of the induced strain together with the fitted linear function for (a) OM4 Draka, (b) 6 LP Draka, and (c) 4 LP InPhoTech. The determined strain sensitivities for the fundamental modes of the tested optical fibers based on the linear fitting are equal to 138 ± 16 MHz/ $\mu\epsilon$, 133 ± 17 MHz/ $\mu\epsilon$, and 152 ± 16 MHz/ $\mu\epsilon$, respectively. Note that the fit was forced to cross the origin to be performed over three points.

respectively. Within this error range, the obtained values of strain sensitivity can be safely claimed to be close to a single mode fiber (150 MHz/ $\mu\epsilon$). As expected, the obtained values were similar due to the fact that most of the effect of strain sensitivity comes from elongation of the fiber and not from the change of refractive index of glass.²¹

IV. SUMMARY

In this work, we have demonstrated a new method for enabling ϕ -OTDR strain measurements in multimode optical fibers. This was

carried out by selectively exciting and detecting a signal from a given mode of a multimode fiber, thus enhancing ϕ -OTDR measurements in existing and future multimode links. The solution presented here solves the problem of modal dispersion for this kind of measurement and is easily applicable to existing DOFS based on Rayleigh scattering.

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