Distributed Birefringence Measurements Using Polarisation Correlation in Phase-Sensitive OTDR

Hugo F. Martins(1,2,3), Xin Lu(4), Marcelo A. Soto(4), Miguel Gonzalez-Herraez(3), Luc Thévenaz(4)

(1) INESC Porto, Rua do Campo Alegre, 687, 4169-007 Porto, Portugal
(2) Faculdade de Ciências da U. do Porto, Rua do Campo Alegre, 687, 4169 007 Porto, Portugal
(3) Departamento de Electrónica, Universidad de Alcalá, Escuela Politécnica DO-231, 28871 Spain
(4) EPFL Swiss Federal Institute of Technology, Institute of Electrical Engineering, SCI STI LT, Station 11, CH-1015 Lausanne, Switzerland (email: marcelo.soto@epfl.ch)

Abstract A method based on phase-sensitive OTDR is proposed for distributed birefringence measurements along optical fibres. A high accuracy is experimentally demonstrated, enabling the characterisation of single-mode fibres with a minimum detectable birefringence of the order of 10^{-7}.

Introduction

Birefringence in optical fibres can arise from many factors that introduce asymmetries in the fibre core. While currently manufactured single-mode fibres (SMF) are expected to have birefringence of the order of 10^{-7}, polarisation-maintaining fibres (PMF) are characterised by larger levels of birefringence (e.g. ~10^{-4}), making them very attractive for many applications. Usually the birefringence is not constant along an entire optical fibre, not only due to non-uniformities in the fibre drawing process, but also due to bending and twists introduced during cabling and installation processes, as well as due to external environmental conditions such as temperature and stain variations. Thus, some short fibre sections can abnormally show large birefringence, being a crucial factor on scaling polarisation-mode dispersion (PMD), which can significantly distort optical signals, especially over long distances and at very high data rates.

A technique to measure the local birefringence along an optical fibre location could be of great interest for the fibre characterisation. There are many measurement techniques proposed in the literature; however, most of them only provide measurements of the average birefringence, and cannot be used to measure the local birefringence at each fibre position. Methods for distributed birefringence measurements have been recently proposed[1-3]; these are basically based on optical frequency-domain reflectometry (OFDR)[1,2] and dynamic Brillouin gratings (DBG)[3]. On the one hand, OFDR provides very high spatial resolution along a limited fibre range of a few hundreds of metres[2]. This limits significantly the possibilities to characterise long fibres, as typically employed in optical communication systems. On the other hand, DBG uses a complex system[3]: the generation of the grating by stimulated Brillouin scattering actually requires high power and a precise adjustment of frequency and polarisation of the three interacting optical waves. In addition, these methods have only been used for birefringence measurements along PMFs, showing larger birefringence with respect to standard SMFs.

In this paper a method to measure local variations of the phase birefringence of any kind of optical fibre is proposed. The technique is based on the correlation of phase-sensitive OTDR (ϕOTDR) measurements at two orthogonal states of polarisation. It allows the precise characterisation of very long optical fibres, including not only PMFs but also SMFs showing low birefringence, with an ultimate accuracy of 10^{-7} for a spatial resolution of 2 m.

Theory

Conventional ϕOTDR is an accurate and efficient method to measure refractive index variations along an optical fibre. Measured time-domain traces show a zigzag-shaped pattern that originates from the random interference of the coherent Rayleigh backscattering light inside the fibre. This pattern is strongly determined by the optical frequency, scattering size and refractive index[4]. However, if the refractive index changes between two measurements, the same time-domain pattern can be retrieved by simply changing the light frequency. Thus, the principle of the ϕOTDR technique is based on the cross-correlation of the spectra obtained from two set of measurements. The procedure results in a spectrum showing a correlation peak at a frequency shift $\Delta\nu$ which is proportional to the refractive index change[4].

The main difference of the method proposed in this paper, with respect to conventional ϕOTDR, is that in this case the two measurements are performed at orthogonal state of polarisation. Birefringence actually imposes a refractive index difference Δn between the two measurements, and therefore a correlation peak is expected to

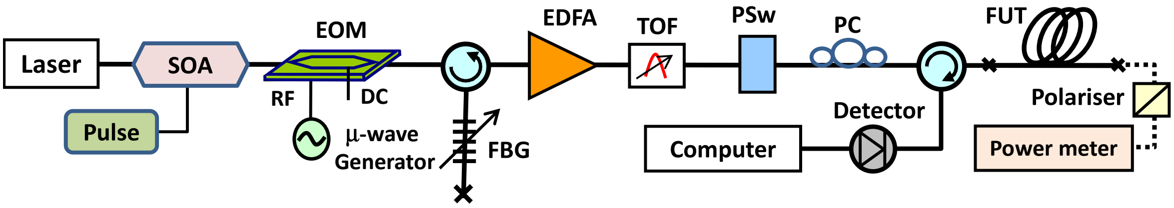

Fig. 1: Experimental setup of a polarisation and phase-sensitive OTDR utilised for local phase birefringence measurements

be found at a frequency shift $\Delta\nu=\nu_f-\nu_s$ that is proportional to the fibre phase birefringence $\Delta n=n_s-n_f$, described as follows[4]:

$$n_s(\nu_s)\nu_s = n_f(\nu_f)\nu_f \Leftrightarrow -\frac{\Delta\nu}{\nu_f} = \frac{\Delta n}{n_f^g} \qquad (1)$$

where ν_s, ν_f and n_s, n_f are the frequencies and refractive indexes at two orthogonal polarisation axes (slow and fast axes), and n_f^g is the group refractive index of the fibre.

If the cross-correlation between measurements in the same polarisation axis is performed, then $\Delta n=0$ and a perfect correlation peak should be found at $\Delta\nu=0$. In practice, this correlation peak provides a measurement of the averaged laser frequency drift, as well as fluctuations of the fibre temperature during the acquisition time[4]. Since these effects can significantly impact on the accuracy of the frequency measurements, measuring the peak at $\Delta\nu=0$ provides a reliable method to evaluate the stability of the system and to compensate undesired cross-sensitivities.

Experimental setup

The experiment setup is shown in Fig. 1. A distributed-feedback (DFB) laser operating at 1535 nm and a semiconductor optical amplifier (SOA) are used to generate optical pulses with high extinction ratio. The pulse width is set to 20 ns, corresponding to a spatial resolution of 2 m. While the laser temperature is tuned to coarsely scan the optical frequency of the pulses in a wide frequency range (many tens of GHz), an electro-optic modulator (EOM) driven by a microwave source is used to accurately scan the light frequency with steps of 10 MHz. A tuneable 10 GHz fibre Bragg grating (FBG) is utilised to select one of the sidebands generated by the EOM. Then, optical pulses are amplified by an Erbium-doped fibre amplifier (EDFA), followed by a tuneable optical filter (TOF) used to suppress the amplified spontaneous emission (ASE) noise. Before launching the pulses into the fibre under test (FUT) using a circulator, a polarisation switch (PSw) and a polarisation controller (PC) are used to launch light into the FUT with orthogonal states of polarisation. At the output of the FUT, a polariser and a power meter are used for monitoring and to ensure optimised polarisation alignment in the PMFs.

At the receiver, Rayleigh backscattered signals are sent to a 125 MHz bandwidth photodetector, and then acquired by a computer.

Experimental results

Using the setup depicted in Fig. 1, Rayleigh backscattered traces are measured for three different fibres: two PMFs (an 80 m Panda and a 100 m elliptical-core fibre) and one SMF. In order to ensure an optimised polarisation alignment to the slow and fast axes of PMFs a well-defined procedure has been followed. By adjusting the PC placed before the FUT input, the monitored power at the fibre output has been maximised/minimised, thus ensuring a maximum coupling of light into the slow/fast axis (in this case the polariser is aligned to the slow axis of the PMF). This way the correlation peak amplitude is enhanced, enabling measurements with improved frequency accuracy.

Fig. 2 shows the profile of the birefringence-induced frequency shift (left-hand side vertical axis) as a function of distance, obtained from correlating Rayleigh spectral measurements at the two orthogonal states of polarisation for the Panda (Fig. 2a) and elliptic-core (Fig. 2b) fibres.

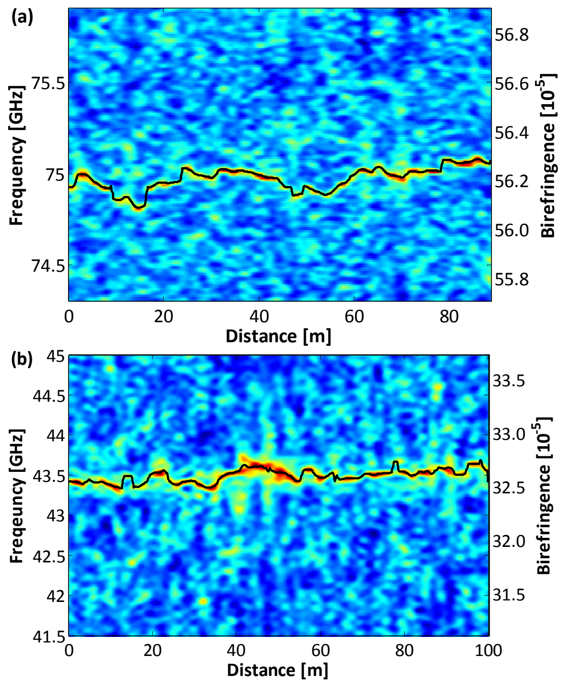

Fig. 2: Distributed profile of phase birefringence versus distance along (a) a 80 m Panda PM fibre and (b) a 100 m elliptical-core PM fibre.

Using the measured correlation frequency profile and Eq. (1), the distributed profile of the local birefringence Δn has been obtained, as shown on the right-hand side vertical axis of the figures. It is interesting to notice how the method provides clear measurements of non-uniform phase birefringence along both optical fibres.
Then, the technique has been used for birefringence measurement along a 3-km standard SMF. The fibre corresponds to an old SMF drawed on the mid 80's, and therefore non-uniform and larger birefringence values are expected in comparison to more recent SMF. Since the fibre in this case does not have clearly defined polarisation axes, there is no polarisation adjustment to make. However, measuring orthogonal states of polarisation is still essential to ensure that no correlation fading impairs the measurements along the fibre.
Since SMFs are characterised by very small birefringence, the measurement accuracy has to be highly controlled. For this reason, the laser frequency has been locked on an absorption line of a gas cell, corresponding to a hollow-core photonics crystal fibre filled with 5 mbars of acetylene gas. A lock-in amplifier is used as a feedback system that provides injection current corrections to the laser driver, thus compensating the laser frequency drifts.
Considering that small birefringence-induced frequency shifts are typically expected from SMF, the frequency scan in this case has been performed only scanning the microwave frequency driving the EOM in a range of 3 GHz. Fig. 3a shows the measured frequency shift and

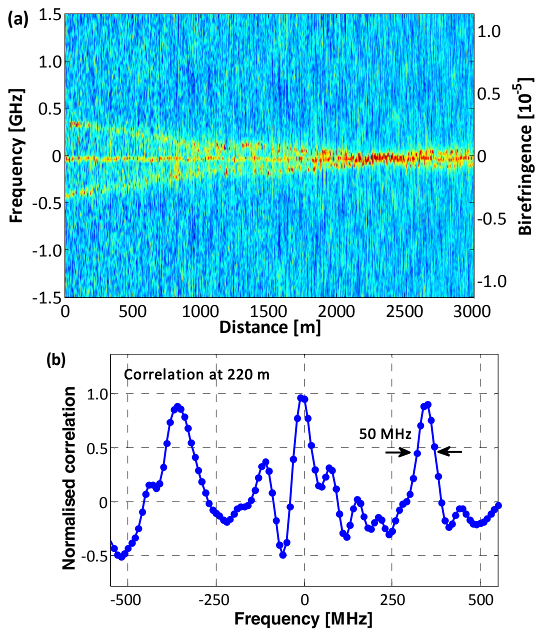

Fig. 3: Distributed birefringence measurement in a single-mode fibre. (a) Measured frequency and birefringence profile versus distance (b) correlation spectrum at 220 m distance.

the respective birefringence profile along the entire SMF length. Since the polarisation of the pulses is not aligned to any particular axis, each ϕOTDR measurement actually contains light backscattered in both axis of polarisation. It is therefore expected that the cross-correlation spectrum would show three peaks, one at 0, and two other symmetrically placed at $\pm\Delta\nu$. The local amplitude of these peaks depends on the ratio of light coupled into the slow/fast axis on at each fibre location. It is interesting to notice that clear variations of the local birefringence can be precisely measured along the entire fibre length. Actually the best measurable birefringence it is ultimately limited by the correlation peak width, which is 50 MHz, as shown in Fig. 3b. This is consistent with the spectral width defined by the pulses of 20 ns, and corresponds to a measurable birefringence of ~$3*10^{-7}$.

Conclusions

A technique that makes use of the cross-correlation between ϕOTDR measurements at orthogonal states of polarisation has been proposed and experimentally validated. The method offers the possibility to discriminate local birefringence variations along many tens of km of optical fibres with metric spatial resolution. The high birefringence accuracy demonstrated (~10^{-7}) enable a proper characterization of low birefringence single-mode fibres.

Acknowledgements

This work was performed in the framework and with the support of the COST Action TD1001 OFSeSa. M. A. Soto and L. Thévenaz acknowledge the support of the Swiss State Secretariat for Education, Research and Innovation (SERI) through the project COST C10.0093.

References

[1] B. Huttner et al., "Local Birefringence Measurements in Single-Mode Fibers with Coherent Optical Frequency-Domain Reflectometry," Photon. Technol. Lett., Vol. **10**, no. 10, p. 1458 (1998).
[2] M. E. Froggatt et al., "Characterization of Polarization-Maintaining Fiber Using High-Sensitivity Optical-Frequency-Domain Reflectometry," J. Lightwave Technol., Vol. **24**, no. 11, p. 4149 (2006).
[3] Y. Dong et al., "Truly distributed birefringence measurement of polarization-maintaining fibers based on transient Brillouin grating," Opt. Lett., Vol. **35**, no. 2, p. 193 (2010).
[4] Y. Koyamada et al., "Fiber-Optic Distributed Strain and Temperature Sensing With Very High Measurand Resolution Over Long Range Using Coherent OTDR," J. Lightwave Technol., Vol. **27**, no. 9, p. 1142 (2009).