Observation of Brillouin Linewidth Broadening and Decay Time in Photonic Crystal Fiber

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Abstract

We present a novel distributed sensing technique that allows for the observation of Brillouin gain spectral distribution and acoustic decay time in photonic crystal fiber as well as in standard single-mode fiber.

I. INTRODUCTION

Acoustic properties of photonic crystal fibers (PCF) play a crucial role for a better understanding of acousto-optical interactions such as stimulated Brillouin scattering (SBS) as well as for applications such as distributed sensors. In the past few years, several authors have reported specific features of SBS in PCF such as higher threshold power and wider or multi-peak Brillouin gain spectrum compared to what is commonly observed in conventional single-mode fibers (SMF) [1]–[3]. These new characteristics mainly rely on the air-hole periodic microstructure which impacts on the acoustic modal distribution and leads to a strong coupling between the longitudinal and transverse acoustic modes.

In this paper, we present a novel Brillouin echoes distributed sensing (BEDS) technique that allows for the observation of Brillouin gain spectral distribution as a function of the position inside the optical fiber [5]. Distributed measurements have been carried out in a 100-m long PCF as well as in a short length of an SMF. Our results show in particular an asymmetrically-broadened Brillouin gain spectrum all along the PCF due to the presence of several acoustic modes. The Brillouin linewidth broadening for PCF is also interpreted in term of a multiple-Lorentzian model. The BEDS technique also enables to observe the apparent acoustic exponential decay time which agrees very well with the brillouin linewidth for both fibers. Unlike SMF, the exponential decay time shows that the Brillouin linewidth of the PCF is not directly related to the fundamental acoustic phonon lifetime.

II. EXPERIMENT AND RESULTS

The BEDS technique basically differs from a conventional Brillouin optical time domain analysis (BOTDA) as it makes possible precise Brillouin gain spectrum (BGS) distributed measurement with enhanced spatial resolution by applying short π-phase shifts in the CW pump wave instead of using plain intensity pulses. A complete description of the method can be found in Ref. [5]. For the sake of comparison, the results obtained in the PCF are summarized in Fig 1(a-c) and those obtained with G652D SMF are presented in Fig 1(d-f). The inset of Fig 1(c) shows the cross-section of the PCF under test. It consists of a standard triangular lattice of air holes with a core diameter of 5.5 μm, a pitch of 4 μm and a hole diameter of 2.2 μm. The PCF has a 100-m length and an effective mode field area of 16 μm^2 at 1550 nm. Fig 1(a) shows the distributed BEDS measurement that maps the BGS distribution as a function of the position inside the PCF. First, we can see some large short-scale fluctuations on the Brillouin gain peak value as a result of significant polarization state variation and structural irregularities [4], [7]. Some long-scale fluctuations can also be viewed in Fig 1(a) and are essentially due to the effect of applied strain by the fiber spool. Fig 1(b) shows the BGS at a propagation distance of 97 m. One can clearly observe an asymmetric and broadened Brillouin spectrum with a linewidth of $\Delta\nu_B$=52 MHz (FWHM) greater than the Brillouin linewidth commonly observed in SMF ($\Delta\nu_B$=28 MHz, see Fig 1(e) for comparison). These new features mainly rely on the air-hole periodic microstructure which alters the acoustic modal distribution and leads to a strong coupling between the longitudinal and transverse acoustic modes. Note that such new characteristics are difficult to model numerically because each PCF exhibits completely different BGS [1]–[3]. Nevertheless, by expanding the gain spectrum in terms of a multiple-Lorentzian model based on the SMF linewidth, we found that the BGS is made with the superposition of four main incoherently-coupled acoustic modes with slightly different central frequencies as indicated in Fig 1(b). The fitting curves are also plotted on Fig 1(b) in blue and the retrieved BGS is plotted in red.

Using the BEDS technique, we are also able to observe the slow exponential apparent decay time of the acoustic wave which is directly scaled by the acoustic phonon lifetime. This effect is called the second echo and appears because of the damping of the acoustic wave [6]. The red line in Fig. 1(c) is an exponential fit of this decay time and we find a value T_a of 7.6 ns

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for the PCF in good agreement with the Brillouin linewidth measurement ($\Delta\nu_B = 1/(\pi T_a)$). For comparison, Fig. 1(f) shows the same experimental measurement for the SMF that shows a decay time of 12 ns which is also in good agreement with the Brillouin linewidth measurement of Fig. 1(e) and the value found in the literature [8]. Unlike SMF, the Brillouin linewidth in PCF is not defined by the damping of the acoustic wave. The superposition of multiple acoustic modes actually artificially modifies the measured acoustic lifetime at the Brillouin resonance. The distribution of these acoustic modes is related to the hypersound propagation waveguide characteristics which is self-influenced by the air-hole microstructure.

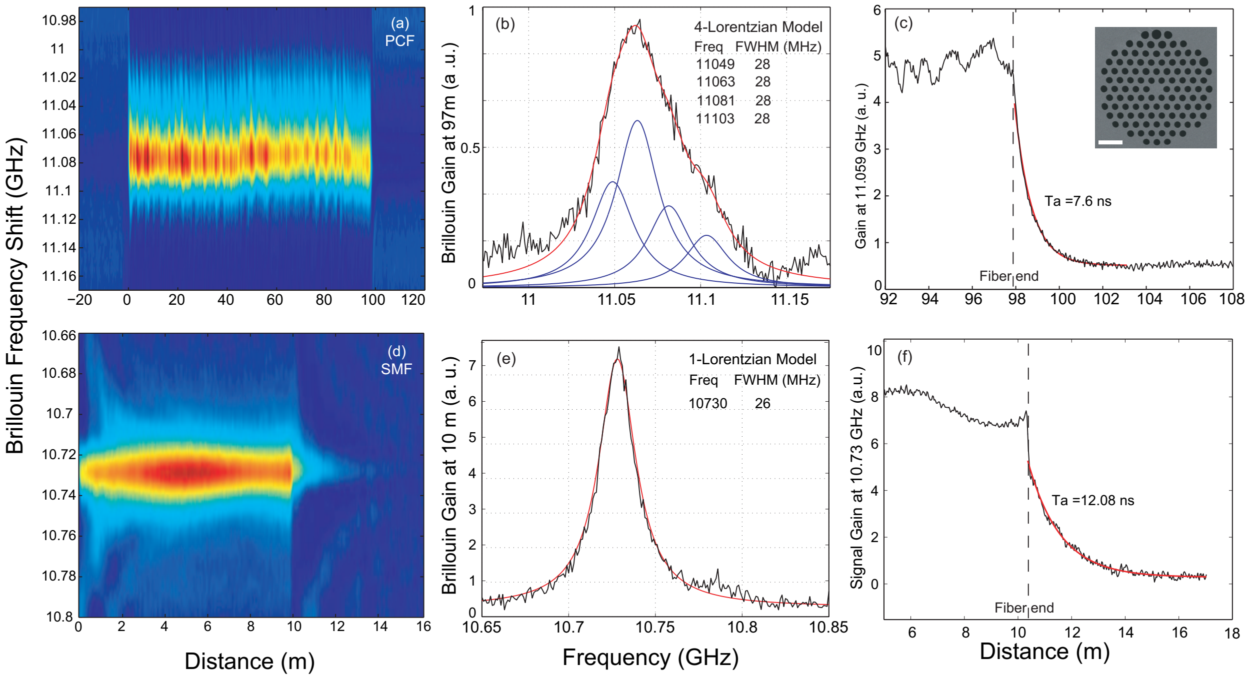

Fig. 1. Experimental results : (a,d) 3D color plot of the Brillouin gain spectral distribution along the PCF and the SMF, respectively. The spatial resolution is 30 cm. (b,e) Brillouin gain spectrum at a distance of 97m and 10m. Red curves are four and single Lorentzian fit of the gain spectrum. (c,f) Brillouin gain at the peak frequency in the time domain at the end of the PCF and the SMF. The red curves show exponential fit curves to estimate the acoustic decay times.

III. CONCLUSION

We have carried out a high spatial resolution distributed measurement of the Brillouin gain spectrum along a photonic crystal fiber and compared it with the measurement in a standard single-mode fiber. Using this technique, we have reported the observation of Brillouin linewidth broadening in PCF and the measurement of the acoustic decay time. These observations can help for fundamental understanding of SBS and for the design of PCF in view of applications to passive suppression of SBS.

IV. ACKNOWLEDGEMENT

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REFERENCES

[1] P. Dainese, P.J. Russell, N. Joly, J.C. Knight, G.S. Wiedehecker, L.H. Fragnito, V. Laude, and A. Khelif, “Stimulated Brillouin scattering from multi-GHz-guided acoustic phonons in nanostructured photonic crystal fibres,” Nature Physics 2, pp.388-392, 2006.

[2] J.E. McElhenny, R. Pattnaik, J. Toulouse, K. Saitoh, and M. Koshiba,“Unique characteristic features of stimulated Brillouin scattering in small-core photonic crystal fibers”, J. Opt. Soc. Am. B. 25, pp.582-583, 2008.

[3] J-C. Beugnot, T. Sylvestre, H. Maillotte, V. Laude, N. Traynor, A. Monteville L. Provino, S. Foaleng Mafang, and L. Thévenaz, “Complete experimental characterization of stimulated Brillouin scattering in photonic crystal fibers”, Opt. Express 15 pp15517-15522, 2007.

[4] L. Thévenaz, S. Foaleng Mafang and M. Nikles, “Fast measurement of local PMD with high spatial resolution using stimulated Brillouin scattering”, ECOC 2007, Berlin, Germany, paper 10.1.2, 2007.

[5] S. Foaleng Mafang, J-C. Beugnot, and L. Thévenaz, “Optimized configuration for high resolution distributed sensing Brillouin echoes”, Proceedings of 20th international Conference on optical fibre sensors SPIE, UK, Edinburgh 7503, 75032C, 2009.

[6] L. Thévenaz and J-C. Beugnot “General analytical model for distributed Brillouin sensors with sub-meter spatial resolution”, Proceedings of 20th international Conference on optical fibre sensors SPIE, UK, Edinburgh 7503, 75036A, 2009.

[7] B. Stiller, M. Delqué, M. W. Lee, H. Maillotte, T. Sylvestre, S. Foaleng Mafang, J.-C. Beugnot, L. Thévenaz, and A. Kudlinski, “Effect of inhomogeneities on backward and forward Brillouin scattering in photonic crystal fibers ”, Proceedings of SPIE Photonics Europe, Paper 7714-3 , Brussels, Belgium, 2010.

[8] G. P. Agrawal, in *Nonlinear Fiber Optics*, 3rd ed. (San Diego, CA, Academic Press, 2001).