Experimental 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 makes possible the observation of Brillouin gain spectral distribution and acoustic decay time in photonic crystal fiber as well as in standard single-mode fiber.*

Introduction

Passive suppression of stimulated Brillouin scattering (SBS) in optical fiber is of great interest for applications to fiber-based optical communication systems. 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 technique named Brillouin echo distributed sensing (BEDS) that permits the observation of Brillouin gain spectral distribution as a function of the position inside the optical fiber [4]. The BEDS technique basically differs from a conventional Brillouin optical time domain analysis (BOTDA) as it makes precise Brillouin gain spectrum (BGS) distributed measurements possible with enhanced spatial resolution. This is done by applying short π-phase shifts on the CW pump wave instead of using plain intensity pulses. 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 gives access to the observation of the apparent acoustic exponential decay time which agrees very well with the Brillouin linewidth for both fibers. Unlike SMF, the decay time indicates that the Brillouin linewidth of the PCF is not stricly related to the fundamental acoustic phonon lifetime.

Experiment and Results

A set of distributed Brillouin gain spectra along diverse fibers was carried out using the Brillouin echo distributed sensing (BEDS) [4]. The optical waves were both generated from the same laser at a wavelength of 1550nm its light was split in two arms using a directional coupler. In one arm the probe wave was generated using the sideband technique. In the other arm the pump

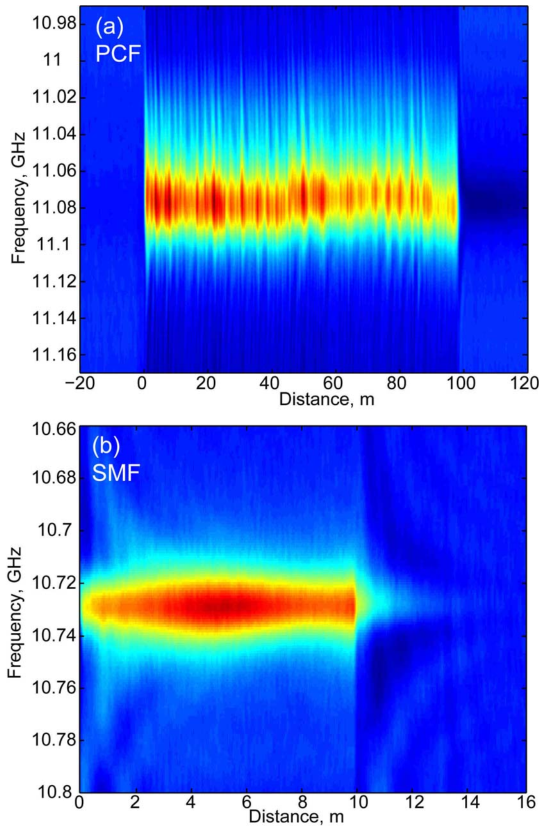

Fig. 1: (a,b) 3D Experimental Brillouin gain spectral distribution along the PCF and the SMF, respectively. The spatial resolution is 30 cm.

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was modulated by a phase modulator. Short π-phase shifts were applied on the pump wave and the duration of these brief phase shifts defines the spatial resolution. The signal gain was measured using a photodiode and data were recorded using a digital oscilloscope. For the sake of comparison, the results obtained in the 10m G652D SMF are summarized in Fig 1(b) and Fig 2(c,d). The inset of Fig 2(b) 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 µm² at 1550 nm.

Fig 1(a) shows the BEDS measurement that maps the Brillouin gain along the PCF as a function of frequency and position. First, we can see some large short-scale fluctuations on the Brillouin gain peak value as a result of significant variations of the state of polarization and structural irregularities [5], [7]. Some long-scale fluctuations can also be visualized in Fig 1(a) and are essentially due to the effect of the strain applied by fibre spooling. Fig 2(a) 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) definitely larger than the Brillouin linewidth commonly observed in SMF ($\Delta\nu_B$ = 26 MHz, see Fig 2(c) for comparison). These features are mainly due to 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 novel characteristics are difficult to model numerically because each PCF exhibits entirely different BGS [1]–[3]. Nevertheless, by expanding the gain spectrum as a superposition of multiple Lorentzian lines showing a linewidth identical to a SMF, we found that the BGS is made of four main incoherently-coupled acoustic modes with slightly different central frequencies as show in Fig 2(a). The fitting curves are also plotted in Fig 2(a) in grey and the resulting BGS is plotted in black. The frequency of four Lorentzian shapes fitting the experimental Brillouin spectrum in PCF is shown in Fig (3). A variation in the air-hole microstructure induces an identical variation for the estimated four frequencies fitting the Brillouin spectrum in PCF. Using the BEDS technique, we are also able to observe the slow exponential apparent decay tof the acoustic wave which is directly scaled by the acoustic phonon lifetime. This effect is called the second echo and appears as a consequence of the acoustic wave damping [6]. The black line in

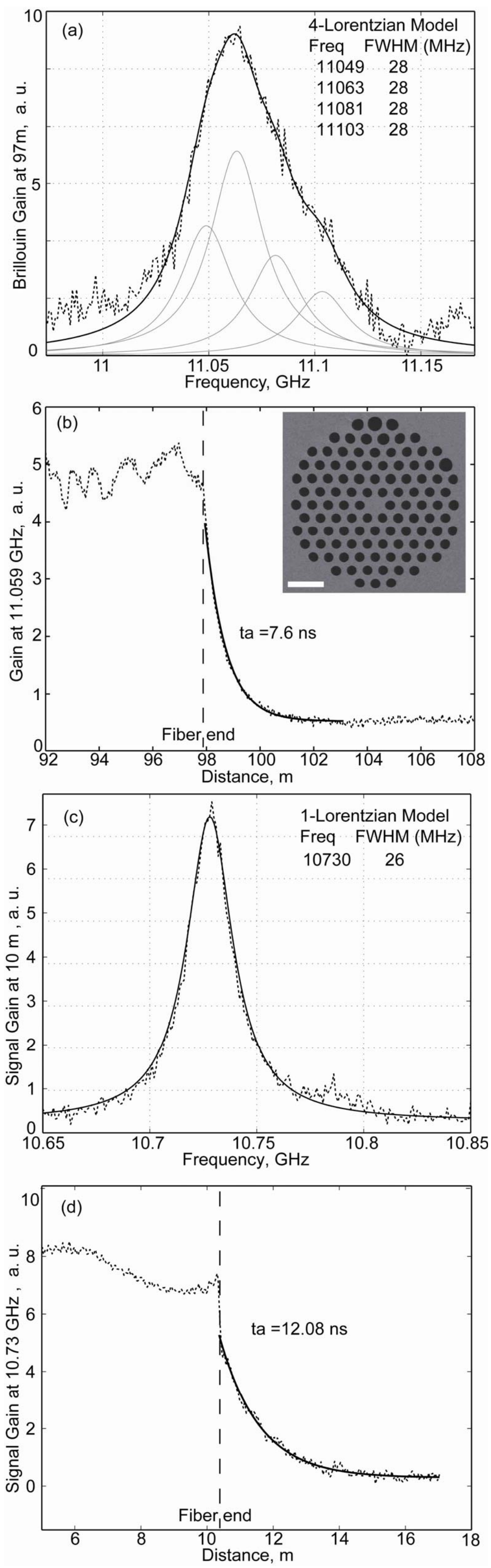

Fig. 2: (a,c) Brillouin gain spectrum at a distance of 97m in PCF and 10m in SMF respectively. Grey curves are four and single Lorentzian fit of the gain spectrum. (b,d) Brillouin gain at the peak frequency in the time domain at the end of the PCF and the SMF. The black curves show exponential fit curves to estimate the acoustic lifetimes.

Fig 2(b) is an exponential fit on this decay and we find a value t_a of 7.6 ns for the time constant in the PCF. For comparison, Fig 2(d) shows the same experimental measurement for the SMF that shows a decay time of 12 ns in exact agreement with the Brillouin linewidth measurement of Fig. 2(c) and the value found in the literature [8].

Unlike SMF, the Brillouin linewidth in PCF is not uniquely defined by the damping of the acoustic

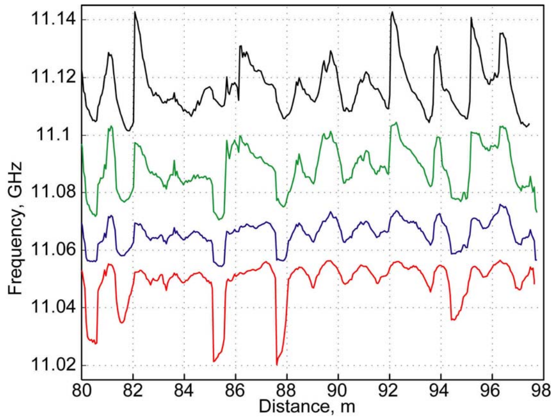

Fig. 3: Frequency of four Lorentzian fit based on the SMF linewidth (28 MHz) of the Brillouin gain spectrum in PCF as a function of position.

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 waveguide characteristics for the hypersound propagation which is self-influenced by the air-hole microstructure.

Conclusions

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 independent 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.

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