Distributed Measurement of Brillouin Gain Spectrum in Photonic Crystal Fibre

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Abstract *Distributed measurements of the Brillouin gain spectrum in a photonic crystal fibre have been carried out for the first time to our knowledge. These measurements confirm the strong increase of the Brillouin threshold as resulting from the broadband and multimode nature of the Brillouin gain spectrum all along the fibre.*

INTRODUCTION

The periodic wavelength-scale air-hole microstructure of solid-core photonic crystal fibres (PCFs) drastically alter their acoustic properties, compared with what is commonly observed in all-silica fibres [1,3,4]. It thus significantly impacts on stimulated Brillouin scattering (SBS), recent results have shown that the SBS spectrum in ultra-small core PCF is broadened and even turns multimode, leading to a higher SBS threshold than in standard fibres [2,5]. The aim of the present work is to clearly identify and understand the broadband and multimode nature of SBS spectra in PCFs as resulting from either the structural irregularities of the PCF or the large numerical aperture that allows for the simultaneous generation of several acoustic modes. To this end, we present distributed measurements of the SBS frequency shift in a 160m-long PCF using a recently-developed technique [6]. The results of our measurements indicate that the structural irregularities of the PCF have actually little impact on the SBS frequency shift. We also show that this PCF exhibits a strong 3-fold increase in the Brillouin threshold compared with a uniform all-silica fibre, in good agreement with the Brillouin linewidth broadening by 80MHz.

EXPERIMENTAL SETUP

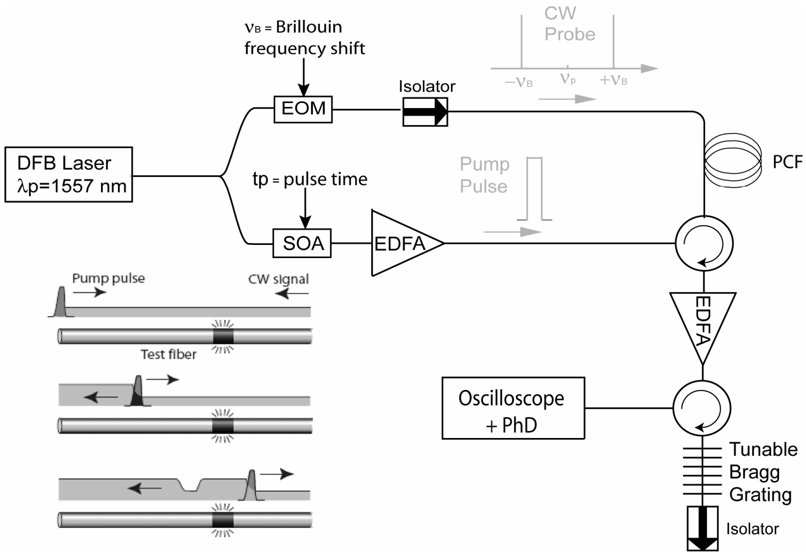

Fig 1: Experimental setup for distributed SBS measurement in PCF. The inset shows the principle of pulsed pump continuous probe waves configuration.

The distributed measurement technique called Brillouin optical time domain analysis (BOTDA) is schematically sketched in Fig. 1 [6]. We used the same laser source (a DFB laser emitting at a wavelength of 1557nm) to generate pump and probe waves. The pump pulses were generated by gating a semiconductor optical amplifier (SOA) with an electrical pulse train, and they were amplified by an EDFA to increase the power up to a few hundred mW. The pump pulses were then launched into the PCF under test through an optical circulator in the counter-propagating direction to provide local Brillouin gain on the CW-probe signal. The probe is modulated by an electro-optical modulator (EOM) to create two modulation frequencies at Brillouin Stokes ($-\nu_B$) and anti-Stokes (ν_B), respectively. The amplified probe was measured using a photodiode (PhD) and data were recorded using a digital oscilloscope synchronized with the Brillouin-pump pulse. The frequency detuning between the pump and the probe was swept around the ν_B and the gain was recorded at each point along the fibre. This method offers several advantages such as no laser frequency drift dependence and no need of a tuneable laser source. The spatial resolution is defined by the pump pulse duration. However, as a consequence of the small gain bandwidth, a high spectral resolution results in a low spatial resolution and vice-versa. Thus we performed several experiments with different pump pulse durations ranging from 20 ns to 100 ns. The PCF was spliced to a single-mode fibre using an Ericsson FSU-975 with a coupling efficiency of 60% and by inserting a segment of high numerical-aperture (HNA) fibre between the PCF and the SMF.

RESULTS

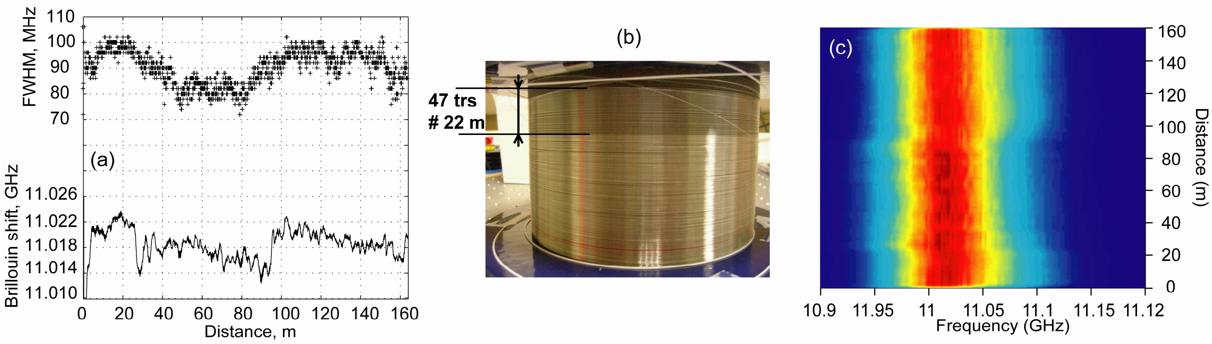

Fig 2: (a) SBS gain width (FWHM, crosses) and frequency shift (solid line) versus distance with a spatial resolution of 2m. (b) image of the fibre spool, (c) SBS gain spectrum evolution.

The photonic crystal fibre tested in our experiments has an effective area of 12 μm^2 at 1550 nm. The fibre consists of a triangular lattice with a core diameter equal to 4.4 µm (see inset of Fig. 4(a)). Fig. 2(a) shows the distributed measurement of the SBS frequency shift and spectral width (FWHM), respectively, with a spatial resolution of 2 m. As it can be noticed, the longitudinal irregularities of the air-hole microstructure induce a SBS frequency shift variation of 20 MHz, much more important than routinely observed in standard all-silica fibre. Moreover, we can clearly point out in Fig. 2(b) a significant frequency shift from 25 m till 90 m. To get a better insight, Fig 3 shows the same measurements as in Fig. 2 but with a pump pulse width of 100 ns. This corresponds to a spatial resolution of only 10-m but the Brillouin gain spectrum is more accurately detailed when compared to Fig. 2(b). We can clearly highlight Fig. 3 the SBS frequency shift between 25 m and 90 m and an asymmetric Brillouin spectrum. Actually, the Brillouin spectrum shown in Fig. 3(b) clearly reveals the co-existence of two main acoustic modes all along the fibre, except in the range from 25 m and 90 m. This is consistent with the measured Brillouin shift and the spectral width in this range.

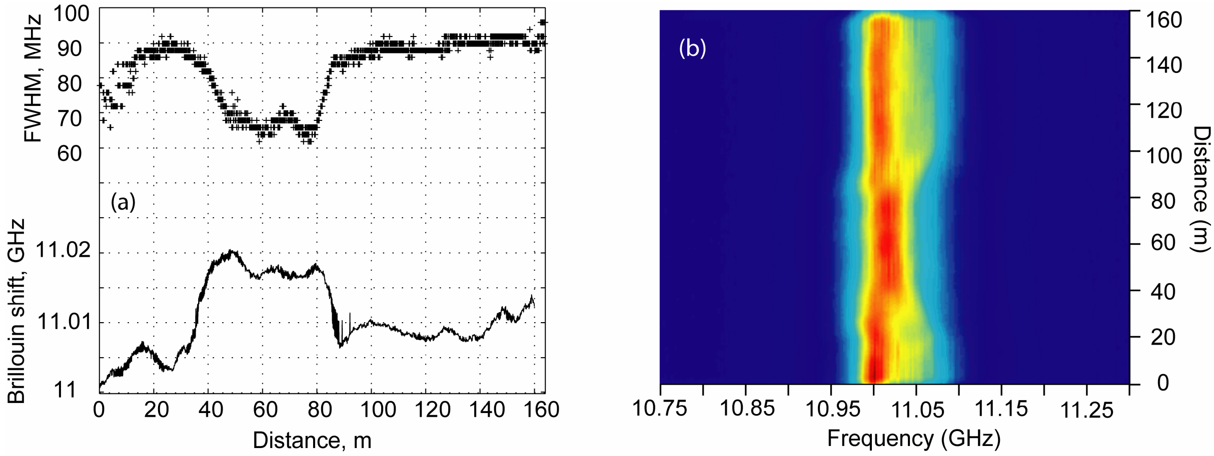

Fig 3: (a) SBS gain width (FWHM, crosses) and frequency shift (solid line) versus distance with a spatial resolution of 10m. (b) evolution of SBS gain spectrum along the fibre.

Such an important frequency shift in SBS spectrum can be explained by considering the acoustic velocity ν_A which is strain-dependent in optical fibres. Let remind that the Brillouin frequency depends on the acoustic wave velocity and is given by $\nu_B = 2n\nu_A/\lambda$, where ν_A is the acoustic wave velocity within the fibre, n is the refractive index and λ is the wavelength of the incident pump [7]. Therefore the central frequency of Brillouin spectrum ν_B is expected to vary when the fibre is under stress. As observed in Fig. 2(b), the first part of the PCF seems to be compressed as a result of winding by the subsequent part of the fibre since the distance (22m) of the first part corresponds to the beginning of the SBS frequency shift shown in Figs 2 and 3 (~25m).

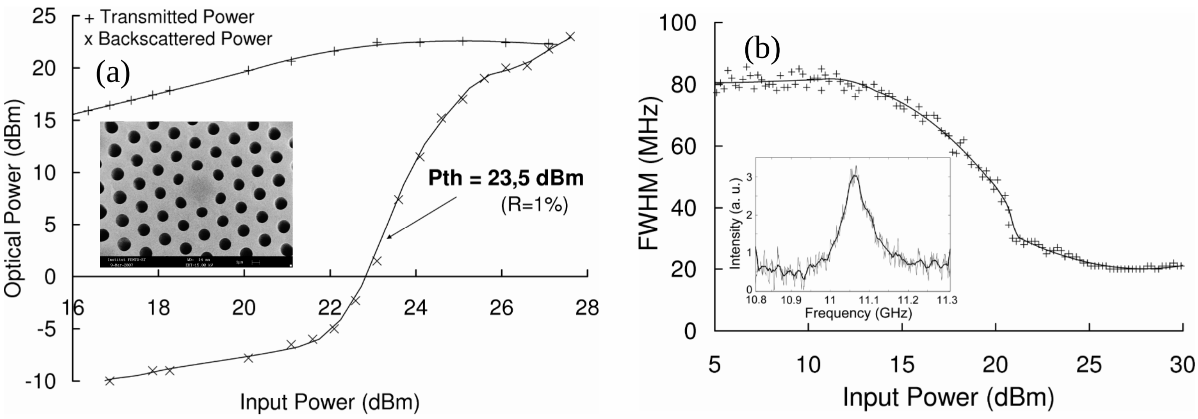

Fig 4: (a) Measured transmitted and backscattered powers as a function of the input pump power. Inset: SEM image of PCF cross section. (b) Brillouin spectrum linewidth as a function of injected pump power. Inset: Brillouin spectrum for Pin=Pth-15dB, using a heterodyne detection with 300 kHz of resolution. FWHM = 80MHz.

A preliminary work was performed for measuring the spontaneous Brillouin backscattering and the SBS threshold in the PCF by using a heterodyne detection. Fig. 4(a) shows the transmitted and backscattered power as a function of the input power, respectively, while Fig. 4(b) represents the spectral FWHM evolution. We measure a strong 3-fold increase in the Brillouin threshold compared with a uniform all-silica fibre with the same nonlinear coefficient. This increase is in quite good agreement with the Brillouin linewidth broadened by 80-MHz, shown in Fig. 4(b). Once again, this is fully consistent with the distributed measurements shown in Fig. 5 that also exhibits a Brillouin linewidth of 80 MHz. But we can see in Fig.5 that the Brillouin gain spectrum is not uniform along the fiber length. This is a clear illustration of the stress applied during winding which modifies the acoustic modes distribution in Brillouin gain spectrum.

CONCLUSION

We have carried out a distributed measurement of Brillouin gain spectrum in a large-core photonic crystal fibre together with a threshold measurement. We have shown not only the impact of the structural irregularities of the air-hole microstructure on the Brillouin frequency shift but also the co-existence of two main acoustic modes along the fibre length frequency-shifted by more than 40 MHz. The origin of these two acoustic modes is still not fully understood, but cannot be attributed to the structural irregularities of the PCF, according to our observations. We have also shown that the Brillouin spectrum is altered from 25m to 90 m due to a strain on the particular fibre spool used.

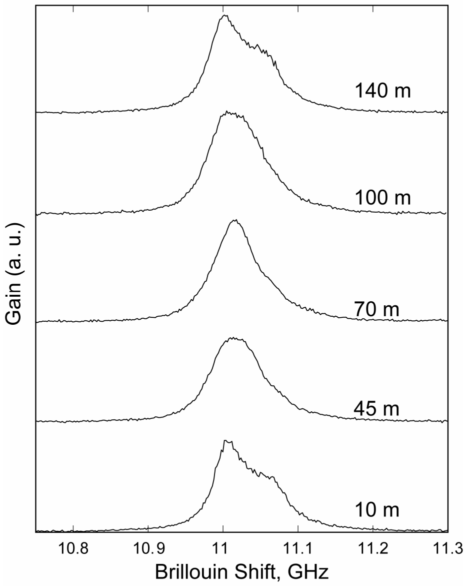

Fig 5: Brillouin spectrum measured at different position along the fibre for a pulse of 100ns width.

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