Unified description of Brillouin scattering in micro- and nano-structured waveguides based on the electrostrictive force

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Summary : We provide a unified model of Brillouin scattering in engineered micro and nanoscale waveguides based on the electrostrictive force. We further apply this model for an arbitrary cross-section photonic crystal fibre and found a very good agreement with experimental measurements.

Introduction

Brillouin scattering is a nonlinear process by which a fraction of the light incident upon a transparent material is frequency-downshifted through the excitation of acoustic phonons [1]. In an optical waveguide this phenomenon can appear in two different forms: forward or backward stimulated Brillouin scattering (SBS) involving transverse and longitudinal acoustic waves, respectively. These two forms so far have always been treated independently. However, several authors have recently reported in engineered micro and nanoscale photonic waveguides, e.g. photonic crystal fibres (PCF) or silicon waveguides, giant enhancement of Brillouin scattering and optical forces such as radiation pressure [2-5]. These new effects cannot be accounted for in standard Brillouin theory and thus a more accurate model including both longitudinal and shear waves is still needed to understand opto-acoustic interactions in such photonic waveguides. Herein, we provide a unified model of Brillouin scattering based on the elastodynamic wave equation subject to the electrostrictive force. From this model, we get the phonon wave packets and both the forward and backward Brillouin spectra without the need to perform a full band structure computation. We apply this new model for an arbitrary cross-section PCF and we found a very good agreement with experimental measurements.

Experimental measurements and numerical calculations

We consider for our unified model the 400-m long solid-core silica PCF shown in inset of Fig. 1a with hole diameter of 4.6 µm and air filling ratio $d/\Lambda = 0.58$. Figs. 1(a) and 1(b) show the experimental forward and backward Brillouin spectra, respectively, measured with the same techniques as in Refs. [3,6]. As can be seen, the forward spectrum exhibits a set of many sharp frequency peaks up to 400 MHz that are closely linked to the PCF air-hole microstructure [3], while the SBS spectrum has a single Lorentzian peak downshifted by Ω =11.1 GHz with a 30-MHz linewidth. These two spectra can be fully described by the electrostrictive force, which we obtain by considering the interaction of two incident photons K_p and K_s with frequency detuning Ω and inserting the fundamental optical mode (computed by a finite element method) in the electrostriction-driven elastic equation. This equation is then solved for the displacement of the elastic wave (u_i) by fixing the acoustic wavevector K and by sweeping Ω. On the one hand, if the two optical waves copropagate in the fibre (*i.e.* forward Brillouin scattering), K is set to zero [3]. On the other hand, for the counter-propagation SBS case, $K = 2K_p$. We also include the phonon lifetime by taking into account the elastic losses assuming a complex elastic tensor [7]. This loss model is compatible with the usual assumption that the product of the quality factor Q and the acoustic frequency is a constant for a given material (for silica, Qf = 5.10^{12} Hz). The computed kinetic energy of the acoustic phonon wave packet is shown in Figs.1(e) and 1(f) versus Ω for forward and backward case, respectively.

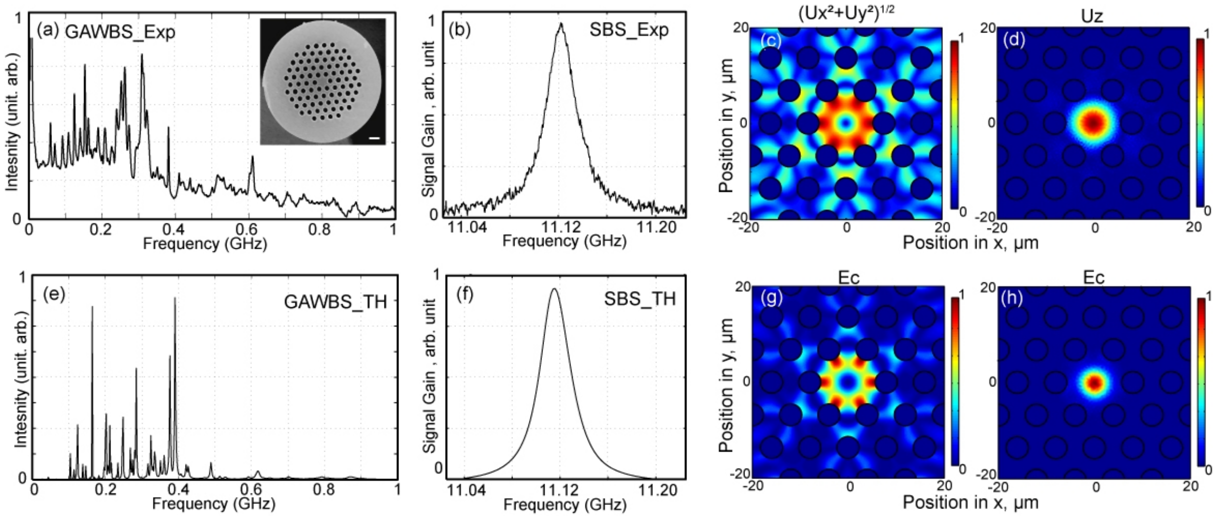

Fig 1 Experimental (a) forward and (b) backward SBS spectra of the PCF shown in inset and corresponding computed kinetic energy (e,f) versus frequency detuning Ω. Transverse displacement (c) and kinetic energy (g) of the elastic mode at 390 MHz. Longitudinal displacement (d) and kinetic energy (h) of longitudinal SBS elastic mode at 11.1 GHz.

A direct comparison with spectra of Figs. 1(a) and 1(b) demonstrates a quite good agreement between numerics and experiments. Figs. 1(c,g) show the calculated transverse displacement and kinetic energy of the most efficient transverse elastic mode at 390 MHz. This clearly highlights the crucial role of the PCF microstructure in forward scattering. In addition, Figs. 1(d,h) show that the longitudinal deformation and the kinetic energy in the SBS case are even more confined within the fiber core through the interplay of air-hole microstructure and optical force.

Conclusions

We have developed a unified electrostrictive model of Brillouin scattering in micro- and nano-structured optical waveguides, which accurately describes the experiments performed in a photonic crystal fiber. This work should contribute to a further understanding of the key phenomena at the origin of Brillouin scattering and optical forces such as radiation pressure in sub-wavelength waveguides.

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