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To cite this article: D Elser et al 2007 J. Phys.: Conf. Ser. 92 012108

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Guided acoustic wave Brillouin scattering in photonic crystal fibers

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Abstract. In silica glass fibers, thermally excited acoustic phonons scatter light into the beam propagating in the forward direction. At acoustic frequencies up to several hundreds of megahertz, the wave vectors of the phonons interacting with the light propagate essentially transversally to the fiber axis. This effect is known as Guided Acoustic Wave Brillouin Scattering (GAWBS) and leads to phase and polarization noise in the guided light. For fiber-based quantum optics experiments, this excess noise is a major limitation. In Photonic Crystal Fibers (PCFs), light is guided by a microstructure simultaneously acting as a 2D transversal phononic crystal which modifies the acoustic noise spectrum. We demonstrate a GAWBS-noise reduction in commercially available PCFs. This gives rise to the prospect of fiber-based quantum optic devices exhibiting less excess noise, thus resulting in higher quantum state purity. Further improvement can be achieved by tailoring the photonic microstructure such that a reduction of phonon noise by design is achieved.

Phonons lead to an inelastic scattering of photons, which is known as Brillouin scattering for acoustic phonons or as Raman scattering in the case of optical phonons. In fiber optics, the nonlinear effects of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) have been thoroughly investigated (see [1] for an overview). Due to energy and momentum conservation, SBS in single-mode fibers can only occur in the backward direction since in the forward direction no other than the fundamental optical mode exists. A detrimental consequence of SBS is the limitation of transmittable power in a fiber, whereas useful applications are fiber-based Brillouin lasers and amplifiers.

Spontaneous Brillouin scattering in the forward direction is likewise prohibited in a bulk material. The guiding properties of a glass fiber, however, allow for forward scattering, as discovered by Shelby et al. in 1985 [2]. Instead of the plane acoustic waves described in the original theory of Brillouin and Mandel’shtam [3, 4] the vibrational modes of a long cylinder [5] represented by the fiber participate in the scattering process. Introducing these boundary conditions allows the scattered and frequency-shifted photons to travel to the fiber output thus leading to noise in the output beam. This thermal effect is known as Guided Acoustic Wave Brillouin Scattering (GAWBS). For typical fiber parameters, the phonons can be considered to travel transversally to the fiber axis for frequencies up to several hundreds of megahertz. The acoustic modes can thus be represented in a two-dimensional model. Two families of vibrational
cylinder modes exhibit essential overlap of the acoustic strain field with the light field in the fiber core: the radial \( R_{0,m} \)- and the mixed torsional-radial \( TR_{2,m} \)-mode families whose fundamental modes are shown in Fig. 1.

The scattering efficiencies being in the order of \( 10^{-10} \) m\(^{-1} \), the influence of GAWBS is too weak to play a role in classical optical telecommunication systems. In quantum optics experiments, however, this effect can be a severe limitation. In quantum communication schemes with continuous variables [6] a bright beam usually is transmitted along with the signal states. This bright beam serves as local oscillator permitting the receiver to characterize the received quantum states via a homodyne measurement [7]. Quantum communication protocols in which the local oscillator takes the same optical path as the signal are particularly interesting since no interference has to be stabilized at the receiver station. Such a protocol has been used e.g. for free space quantum key distribution [8]. There, the signal encoded in polarization states travels in the same spatial mode as the local oscillator. Problems arise when transferring such a protocol to a fiber communication link: in Fig. 2 we show the excess noise a light beam accumulates after passing through a standard fiber of length 1 km. Although the light power is only at the typical value for a weak local oscillator, the amplitudes of the GAWBS peaks are such that their broadening leaves no frequency range where a quantum noise limited operation is possible. Photons at every frequency are scattered from the local oscillator into the signal beam.

One possibility to reduce the harmful effect of GAWBS is to mechanically decouple the light guiding fiber core from the surrounding cladding. A phononic crystal could allow the fiber vibrations to be suppressed in the core. Such phononic crystals have actually been developed, originally as photonic crystal fibers (PCFs) [12] with the goal to obtain advantageous optical properties. Measurements and simulations show that the photonic crystal structure indeed serves
Figure 2. Excess polarization noise accumulated by light after passing through 1 km of the standard fiber FI506C from Lightwave Technologies. The measurement has been performed with a grating-stabilized diode laser which is measured to be quantum noise limited above 100 kHz. The measurement setup is described in detail in [9]. In the whole measured spectral range the fiber generates excess noise above the quantum noise limit (0 dB). Below 7 MHz, thermally activated material fluctuations of the fused silica lead to quasi-elastic scattering [10, 11]. GAWBS peaks are found at discrete frequencies starting at 21 MHz.

Figure 3. Polarization noise accumulated by a light beam of 1.8 mW having passed through 8 m of fiber (solid line: PCF NL-PM-700 from Crystal Fibre, see picture on the right side; dotted line: standard fiber HB800G from Fibercore). For direct comparison, the inset numbers (2, m) mark the cladding $TR_{2,m}$-modes visible in the PCF spectrum as well as the corresponding modes in the standard fiber. The fibers have different cladding diameters which leads to a frequency shift. Those modes for which the noise in the PCF is below the quantum noise limit (0 dB) are not marked.
at the same time as a phononic crystal [9]. Figure 3 shows a comparison of the polarization noise spectra of a PCF and a standard fiber measured under the same conditions (fiber length, optical power, polarization extinction ratio)\(^1\). Comparing with the standard fiber, we can clearly see that the acoustic modes of the PCF are highly suppressed in the considered frequency range. This arises from an accumulation of the vibrational energy outside the core region. In our measurements, we find two frequency regimes: up to 200 MHz the cladding modes are predominant. In the PCF, these exhibit similar vibrational modes as in the case of a standard fiber with the difference that the light-guiding core is less affected. Above 200 MHz, eigenmodes of the hole structure start to be excited. For the GAWBS induced phase noise, similar frequency behavior and suppression in a PCF are described in [9]. At frequencies above 1 GHz (not shown in our measurements), the decoupling of the PCF core from the cladding leads to core vibrations which do not exist in standard fibers [13, 14, 15]. As shown in [16], these core vibrations can also be suppressed by an appropriate structuring of the core itself.

In conclusion, we have shown that in photonic crystal fibers the acoustic properties can be modified such that a broad frequency range with suppressed GAWBS noise can be achieved. Quantum states transmitted through fibers thus accumulate less detrimental excess noise. For the generation of squeezed light [7] improved fiber-sources can be built using PCFs [17].

**references**


\(^1\) The fibers now are much shorter than the one in Fig. 2. Due to the linear scaling of GAWBS with the fiber length the wings of the peaks are masked by the quantum noise.