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The interplay of thermal and pump fluctuations in stimulated Brillouin scattering

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Abstract

We present a experimental and theoretical investigation of spontaneously initiated stimulated Brillouin scattering in which the interplay of two independent noise sources (thermal and pump) can be studied by controlling the relative importance of each source. We vary the pump noise by adding a controlled amount of Gaussian noise to the input pulses, and we control the contribution of the thermal noise by examining the energy statistics of both entire scattered pulses and of temporal slices of the scattered pulses. We show that the energy of the whole Stokes pulses follow a Gaussian distribution but that the energy of the Stokes pulse slices do not.
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1. Introduction

We report on a coordinated experimental and theoretical study of the interplay of thermal and pump fluctuations in pulsed stimulated Brillouin scattering. In these experiments, we add controlled amounts of Gaussian amplitude noise to highly stable single-mode laser pulses to vary the relative importance of classical pump noise. We control the relative importance of the thermal fluctuations that initiate the scattering by looking at the statistics of the energy contained in narrow slices of the SBS waveforms or in the whole pulse. This last means of control is made possible because the SBS waveforms consist of a complex train of intensity spikes that represent independent scattering events so that integrating the intensity spikes contained in an SBS waveform essentially averages out the effects of thermal noise [1]. In this manner we are able to explore the interplay of two independent noise sources in a nonlinear stochastic system. This extends and complements our prior work on the shaping of classical pump fluctuations in pulsed stimulated Raman scattering [2–4].

Spontaneous Brillouin scattering occurs when an intense pump wave scatters off of high frequency acoustic waves that are excited by thermal fluctuations of the medium. The thermally generated acoustic waves can be represented as a zero-mean Gaussian random process with fluctuations that are uncorrelated in space and time. For this reason the waveforms produced by spontaneously initiated SBS can have exceedingly complex temporal structure and display large scale intensity fluctuations, as illustrated by a number of studies of SBS of continuous-wave laser light [5–8]. The detailed nature of the dynamics of the scattered light depends on whether or not feedback is present. This feedback can be intentional, as in reflections off of cleaved

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and polished end-faces of the fiber, or unintentional, as in the distributed "reflections" of Rayleigh scattering [5–14]. Most of the work on CW SBS has focused on dynamical aspects of the scattering when feedback is present, with a much more limited amount devoted to intrinsic or technical fluctuations.

There have been a number of studies on dynamical aspects of pulsed SBS in bulk media and in waveguides, with limited attention given to characterizing the statistical properties of the scattered light [15–26]. Much of the pulsed work has focused on pulse compression and clean-up of the transverse beam structure when an SBS cell or waveguide is used as a phase-conjugate mirror [27–30]. Some of the early studies of pulsed SBS in optical fiber focused on understanding the temporal structure of noise initiated scattering [15–20]. More recent theoretical and experimental work by Ogusu and Li have looked at the temporal dynamics of pulsed SBS and the interplay of SBS with Kerr nonlinearities for propagation through glass optical fiber, propagation through fiber Bragg gratings, and propagation through fiber ring resonators [21–23]. In the last few years, SBS has been used in proof-of-principle experiments to generate optical delay lines for pulses traveling through optical fiber with the aim of developing devices appropriate for communication applications [31,32]. The research on pulsed SBS that is most closely related to ours is a limited amount of early experimental and theoretical work addressing the statistical properties of transient SBS in gas and liquid filled cells [24–26].

The present work is focused on energy fluctuations in pulsed SBS under conditions where thermal and pump noise contribute to the statistical properties of the generated light. After describing the experimental procedures and the theoretical model, we will present results illustrating the interplay of thermal and controlled pump fluctuations under experimental conditions that allow us to control the relative importance of both noise sources. We are aware of no comparable work on the statistics of pulsed SBS.

2. Procedures

The experimental setup used to collect slice and whole pulse energies for the scattered light is described in detail in Ref. [1]; consequently, we will give a short summary here and highlight important differences from earlier experiments.

The laser system used to drive the scattering was a *Q*-switched, diode-pumped, Nd:YAG laser operating at 1.06 μm. The laser operated on a single longitudinal and transverse mode and emitted pulses with a width of approximately 30 ns at a repetition rate of 1 kHz. The pulses were temporally smooth with very stable total energies (standard deviation typically less than 1% of the mean pulse energy). The optical fiber was low-loss, single-mode, polarization-maintaining fiber with a length of approximately 71 m.

For most of the measurements Gaussian amplitude noise was controllably added to the input pump pulses that drive the scattering. The apparatus for adding the noise is shown in Fig. 1. The isolator prevents feedback between the laser system and the rest of the apparatus. The telescope reduces the beam diameter to match the aperture of the acousto-optic intensity modulator (AOIM). The beamsplitter on the input side of the AOIM directs part of the laser pulse energy to a fast photodiode (200 ps risetime) and a pulsed laser spectrum analyzer to monitor the temporal and spectral structure of the pulses straight out of the laser system. In this way we could continuously monitor the laser pulses to insure single-mode operation during data collection.

The beamsplitter on the output side of the AOIM directs the modulated pulses to a fast photodiode (1 ns risetime) that was connected to one of the inputs of a pair of fast gated integrators used to collect pump and Stokes pulse energy pairs. The rf power supply for the AOIM was modulated by the Gaussian noise output of a synthesized function generator. The offset voltage of the noise signal was fixed at 0.5 V, which placed it in the middle of the permissible range for the rf supply's modulation input, so that the average transmission losses of the AOIM remained the same for all noise levels. The amplitude of the noise signal was varied about this fixed offset to produce pulse trains with different levels of Gaussian energy fluctuations. For the measurements described here, the amplitude was varied from 0.05 V (pulse energy noise of approximately 1.5%) to 0.45 V (pulse energy noise of approximately 12.5%) in steps of 0.05 V. The modulated pulses exiting the AOIM had increased fluctuations in their peak amplitude and total energy but smooth temporal profiles just as the input pump pulses.

Two different photodiodes were used to detect the back-scattered Brillouin waveforms: a fast InGaAs photodiode (400 ps risetime) for measuring the energy in temporal slices of the Stokes pulses and a large area Ge photodiode for measuring whole pulse energies. The fast photodiode allowed us to resolve the detailed temporal structure of the back-scattered waveforms so that we could integrate the energy in narrow slices. The large area detector had a much slower response so that it produced a single pulse

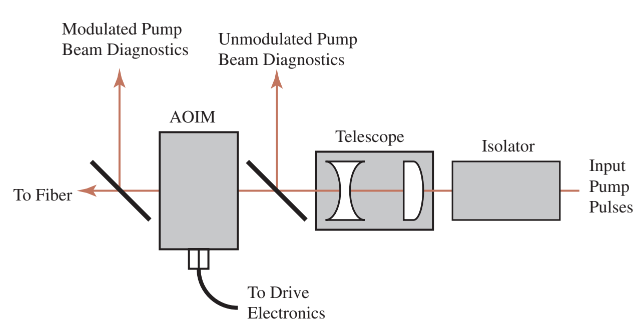

Fig. 1. Experimental setup for adding Gaussian noise to the input pump pulses.

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