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Cavity enhanced cw stimulated Brillouin scattering in a fused silica plate

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Abstract

We have observed cavity enhanced stimulated Brillouin scattering (SBS) in a high finesse optical ring resonator. Brillouin scattering occurs in a fused silica plate placed in the focus of the light beam inside the cavity. The frequency spacing of the Brillouin scattered wave relative to the incident beam at 23.5 GHz has a linewidth of less than 500 Hz. In preliminary experiments we extracted a scattered optical power of 25 mW from the resonator. Possible applications are discussed. © 1997 Elsevier Science B.V.

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1. Introduction

Since its first observation [1] stimulated Brillouin scattering (SBS) has attracted much attention. In pulsed high power experiments SBS is exploited as a convenient and efficient technique of creating optical phase conjugation (see e.g. Ref. [2]). On the other hand stimulated Brillouin scattering can be observed in optical fibers already at very moderate optical pump powers (down to optical powers ≤ 100 μW) [3–5]. In all-fiber ring resonators SBS has been used to realize stimulated Brillouin fiber lasers with submilliwatt pump threshold and a spectral width of a few kHz [6].

In this paper we report the observation of stimulated Brillouin scattering of a continuous wave laser beam in a fused silica plate inside an external resonator. We use a high finesse ring cavity with gyro-quality mirrors, where the fused silica plate is placed at Brewster angle in a tight focus of the cavity. To our knowledge, this is the first experimental demonstration of continuous wave single-frequency stimulated Brillouin scattering that does not originate from an optical fiber. Whereas in all-fiber ring resonators one is restricted to comparatively small optical powers, we have achieved SBS powers of up to 25 mW in first experiments which will be improved in the future. Our experimental method produces a frequency shifted beam with a linewidth of the SBS beam relative to the pump laser of less than 500 Hz.

From another point of view, we here experimentally demonstrate the physical limits one approaches when inserting optical elements into a high finesse cavity. Much research work has been done in this field in the context of optical gravitational wave detectors, where effects such as thermal lensing were considered [7]. For focused beams in an enhancement resonator the threshold for SBS can be lower than power limits imposed by self-focusing in optical glasses, as will be demonstrated below. In contrast to e.g. self-focusing cavity enhanced SBS can be suppressed easily if desired by inserting frequency selective elements into the resonator.

Stimulated Brillouin scattering is a nonlinear process in which an intense beam of light, the pump, generates gain for a counterpropagating, red-shifted SBS wave. In a simplified explanation of the SBS process, a small fraction of the circulating power being stored in the resonator initially undergoes spontaneous Brillouin scattering from thermally

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generated phonons. Of particular interest is the backscattered radiation which has a Stokes frequency shift relative to the circulating beam of $(2nv_a/c)f_p$, where n denotes the refractive index at the pump frequency and v_a the velocity of sound in the medium, c the vacuum speed of light, and f_p the frequency of the pump beam. Radiation that is scattered back along the direction of the circulating beam interferes with the pump beam. The interference pattern of the two optical waves generates a weak intensity grating that copropagates with the pump at the speed of sound. This intensity grating drives the acoustic wave at the differential frequency via the electrostrictive effect, which again increases the Brillouin backscattering.

If the power in the resonator exceeds the threshold level for stimulated Brillouin scattering, the process is characterized by an extremely high nonlinear gain. In a high-finesse cavity having a free spectral range of the same order or smaller than the SBS bandwidth the threshold pump level is greatly reduced for two reasons. First, the ring resonator leads to a large circulating pump power enhancement factor. Second, part of the backscattered radiation is also stored and enhanced in the resonator and acts as a seeding field. Therefore the scattering process is no longer initiated from spontaneous noise but rather from a comparatively large Stokes feedback seeding signal [8–10].

2. Experiment

Our experimental setup is schematically depicted in Fig. 1. Light at 732 nm from a Ti:sapphire laser is coupled into a high-finesse ring resonator. The resonator is built up using gyro-quality mirrors with total losses of less than 15 ppm per mirror. A 3.5 mm thick fused silica plate is inserted under Brewster angle in the 35 μm beam-waist of the cavity. The round trip length in the cavity is 2.5 m, resulting in a free spectral range of approximately 120 MHz. The light in the cavity is stored and enhanced by a factor of about 1500. The finesse presently is limited by the optical quality of the Brewster plate and could be further improved by using a super-polished plate. The Ti:sapphire laser frequency is locked to the center of a cavity resonance by a feedback loop based on a radio-frequency sideband modulation technique for generation of an error signal [11]. Inside the laser cavity a galvo-mounted Brewster plate, a piezo-mounted mirror and an additional electro-optic modulator compensate for frequency fluctuations.

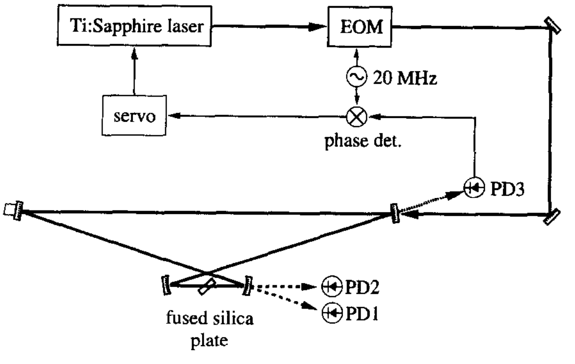

Fig. 1. Experimental setup for cavity enhanced stimulated Brillouin scattering in a fused silica plate (EOM: electro-optic modulator, PD: photodiode, phase det.: phase detector). The photodiodes PD1 and PD2 are used to monitor the power levels of the pump beam and the SBS beam, respectively.

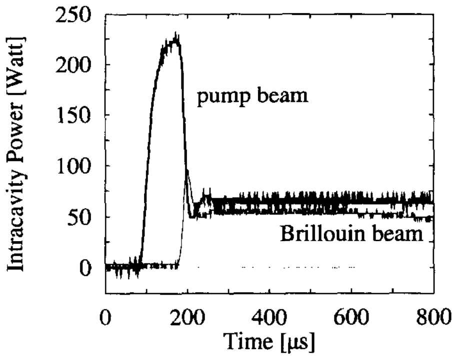

Fig. 2. Build-up of the stored and enhanced pump beam (thick line) and the SBS beam (thin line) observed with the photodiodes PD1 and PD2, respectively (see Fig. 1). The input laser pump power at 732 nm was 145 mW.

The cavity enhanced Ti:sapphire laser beam acts as a pump for stimulated Brillouin scattering. Both levels of the stored and enhanced power in the pump beam and the Brillouin scattered wave can be monitored with two photodiodes PD1 and PD2 positioned behind a cavity mirror. The two beams there are spacially separated since a ring build-up resonator is used. When the laser frequency is tuned into resonance with the resonator, the enhanced power in the pump beam increases up to a maximum value, as shown in Fig. 2. The observed time constant for the build-up in Fig. 2 is dominated by the 100 kHz bandwidth of the photodiode. After about 100 μs the gain for SBS is high enough to backscatter an appreciable amount of power from the pump beam and to generate a second beam circulating in the opposite direction with a Stokes shift in frequency. After a short period of transient behaviour [5] the steady-state power levels in the two beams are reached. Note that when the SBS beam appears, a reduction of the finesse of the resonator is observed which lessens the coupling efficiency into the cavity and decreases the total stored power level.

In order to allow both a determination of the frequency shift of the Stokes beam and the linewidth of the frequency spacing, we have observed the beat node of the pump beam and the Brillouin scattered beam on a fast photodiode (not shown in Fig. 1). The signal frequency was down converted using a rf-mixer and monitored with an electronic spectrum analyzer. A typical observed beat signal at about 23.5 GHz is shown in Fig. 3. The width of the gain of SBS in fused silica at 732 nm is approximately 100 MHz, being determined by the phonon lifetime in the medium [12]. Since the build-up of SBS is strongly enhanced by optical feedback in the cavity, its linewidth is narrowed to less than 500 Hz. This experimental value is probably limited by acoustic noise in the optics used to combine the two beams outside the cavity.

Cavity enhanced stimulated Brillouin scattering was typically observed above a threshold laser pump power of 45 mW at 732 nm measured in front of the input mirror. With increasing pump intensity the SBS beam itself can become strong enough to act as a pump for a secondary SBS beam. When the pump power exceeded about 220 mW, we observed a secondary SBS beam copropagating with the unshifted pump beam and downshifted from the pump by twice the Brillouin shift, i.e., $(4nv_a/c)f_p$ or about 47 GHz in our case. We detected the beat node of the two frequencies in the beam copropagating with the pump beam with a fast photodiode. The signal was mixed down in frequency and monitored both with a spectrum analyzer and a digitizing oscilloscope. The temporal behaviour of the beat signal mixed down in frequency is shown in the lower part of Fig. 4 for a laser pump power of 250 mW. The amplitude of the observed beat signal gives a measure for the secondary SBS beam. In the upper part the power level of the stored beam copropagating with the pump beam as detected by the photodiode PD1 is plotted as a function of time. At the time when the secondary SBS beam appeared, an increase in the stored power was detected. This secondary SBS beam clearly limits the power of the primary SBS beam. By using an optical isolator behind the Ti:sapphire laser to extract the counterpropagating primary SBS beam, we obtained a first order Stokes shifted power of 25 mW. This probably can be improved in the near future by proper selection of the resonator parameters.

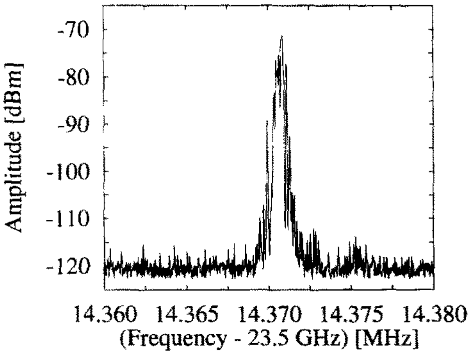

Fig. 3. Beat signal of the pump beam and the SBS beam at 23.5 GHz monitored with a fast photodiode. The linewidth is less than 500 Hz.

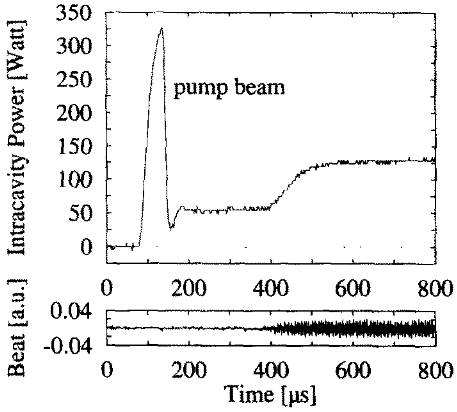

Fig. 4. Temporal behaviour of the power level of the stored beam copropagating with the pump beam (upper part) and of the beat signal of the pump beam and the secondary SBS beam (lower part) for 250 mW laser pump power. The power level was observed with the photodiode PD1. The beat node near 47 GHz was detected with a fast photodiode and mixed down in frequency.

On the other hand, if desired, cavity enhanced stimulated Brillouin scattering can be suppressed by using frequency selective elements within the ring resonator, which reduces the optical feedback. When we inserted a well polished 0.5 mm thick etalon in the long arm of the resonator (beam waist here: ≈ 400 μm), the power transfer from the pump to the SBS beam dropped by more than two orders of magnitude. No significant decrease in the circulating beam intensity could then be observed due to SBS for laser input powers up to 550 mW.

3. Applications

The result of this SBS process is the generation of a second continuous wave beam shifted in frequency by 23.5 GHz relative to the initial pump beam. After overlapping these two beams, this can be considered as single sideband generation with a fixed frequency spacing. Since the power of the Brillouin scattered beam produced with this scheme reaches at least a few 10 mW, it should be possible to use this method as a tool for spectroscopy. For a given application one has to choose the suitable SBS active medium to obtain the desired frequency shift. Note that the frequency shift scales linearly with the inverse pump wavelength.

A second possible use of our scheme takes advantage of the fact that the acoustic wave in the fused silica plate is freely accessible, in contrast to the acoustic wave generated in stimulated Brillouin fiber lasers. The acoustic wave induces a travelling density grating from which a further laser beam fulfilling the Bragg-condition relative to the acoustic wave could be deflected. As a consequence the arrangement could be used as an acousto-optic modulator at 23.5 GHz for light with a wavelength below that of the incoming beam. The acoustic power is estimated to be roughly (70 W/1500) × (23.5×10^9 Hz / 4×10^{14} Hz) ≈ 3 μW which leads to a deflection efficiency of 10^{-7} to 10^{-8} for light with a wavelength differing significantly from the pump wavelength. In order to experimentally observe this effect one should enhance the light to be deflected to obtain a reasonable amount of scattered light. Note that by choosing an appropriate wavelength for the pump beam, one then could tune the frequency shift of the acousto-optic modulator.

Although the appearance of a secondary order SBS beam limits the performance of the primary SBS beam, this effect however could be advantageous for generation of even higher-order SBS beams. These high-order SBS beams have an even larger frequency shift from the pump, thus extending the possible frequency shift.

4. Conclusion

In summary, we have demonstrated single frequency continuous wave stimulated Brillouin scattering in a fused silica plate inserted into a high finesse ring resonator. The frequency spacing of 23.5 GHz at 732 nm of the SBS beam relative to the pump beam has a linewidth of less than 500 Hz. We extracted up to 25 mW optical power in the Stokes shifted beam from the resonator which opens up the way for practical applications of this frequency shifter. Our work also demonstrates cavity enhanced SBS to be a power limitation one approaches when inserting optical elements into a high finesse resonator. Cavity enhanced stimulated Brillouin scattering can be suppressed by inserting frequency selective elements into the cavity.

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