Pulse compression by stimulated Brillouin scattering

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Abstract

Laser pulse compression by the process of stimulated Brillouin scattering in a tapered glass fiber is discussed. A 20 mJ pulse from a Nd:YAG laser is compressed from 20 nsec to 3 nec in a fiber 7 feet long.

Introduction

New laser applications often require pulse lengths significantly shorter than those of available lasers. Typical applications arise from such diverse fields as precision ranging and laser fusion. This paper describes recent progress in pulse compression using the process of stimulated Brillouin scattering (SBS). Following the initial experimental demonstration[1] of the compression of a Nd:YAG laser pulse from 20 nsec to 2 nec by SBS in pressurized methane, we have proceeded to show similar results using a glass fiber. This latter accomplishment is significant because it shows the pulse compression will be possible in a very small volume, the volume of a coiled fiber, with powers lower than are required for other configurations.

The theory of stimulated Brillouin scattering is reviewed in the next section, followed by a description of the experimental arrangement and a presentation of the results.

Stimulated Brillouin scattering

Brillouin scattering is the process by which light is scattered by the density fluctuations which accompany ordinary sound waves. The process is generally very weak, but with the availability of intense fields in focused laser pulses, the process becomes stimulated and the scattering efficiency can become appreciable (>70 percent). Stimulated Brillouin scattering (SBS) is a threshold process, but is rather easily generated since SBS enjoys one of the largest cross-sections[2] among the many known stimulated nonlinear optical effects. This is the case provided that the coherence time of the incident light is long compared to the response time, τ_s, of the acoustic phonon. Typically, τ_s is on the order of nanoseconds for solids and liquids, and tens of nanoseconds for pressurized gases. Hence, the employment of a single longitudinal mode laser can satisfy the coherence time requirement.

The basic macroscopic equations describing the process[2] start with the Navier-Stokes equation describing the medium and Maxwell's equations describing the electromagnetic field. The coupling between the equations arises from electrostriction: the electric field in the laser beam induces changes in the medium density which in turn scatter the incident light. The scattering is strongest in the backward direction.

The SBS gain depends on the incident optical intensity; hence one can utilize a guided wave structure (e.g., a lightpipe or an optical waveguide) to minimize the required input power necessary to realize the onset of the stimulated scattering process. The reduction of the required input power can also be useful in avoiding competing (and perhaps undesirable) nonlinear processes such as self focusing or Raman scattering. Moreover, the guided wave structure can maintain a given modal distribution over long distances, which may be useful for certain applications. This geometry enables one to realize SBS using standard Q-swtiched, single mode lasers, even with submillijoule output energy. The employment of a long optical fiber can enable one to observe SBS even on a cw basis, using modest (e.g., 1 Watt) laser powers[3].

Using a tapered light guide guarantees that the scattering process only begins when the leading edge of the pump pulse reaches the far end of the guide where the smaller diameter forces an increase in power density. As the SBS pulse sweeps backward, it beats with the remainder of the incident laser pulse to create a strong acoustic wave with a wavevector twice the optical wavevector. This growing acoustic wave acts as a bulk grating to scatter coherently more of the incident wave. The pulse compression results from strong pump depletion by the leading edge of the SBS pulse. Ideally, the length L of the tapered guide should be at least half the physical length of the laser pulse:

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$$L \gtrsim \frac{c\tau}{2n} \qquad (1)$$

where c is the velocity of light, τ is the laser pulse length, and n is the refractive index of the SBS medium. Even though the phonon wave travels in the forward direction at a phase velocity of ~10^5 cm/sec, its amplitude envelope must necessarily expand itself rapidly backward, following closely the leading edge of the SBS wave which travels with a speed of c/n. It is postulated that the leading edge of this phonon envelope forms the "mirror" that reflects and, owing to its growing reflectivity, compresses the pulse. This is illustrated in the time sequence in Fig. 1. Such a postulate leads to a quantitative model[1] which predicts the compressed pulse width is

$$\tau_c \simeq \frac{\lambda}{2n^3 p_{12}} \sqrt{\rho_o v_s / I} \qquad (2)$$

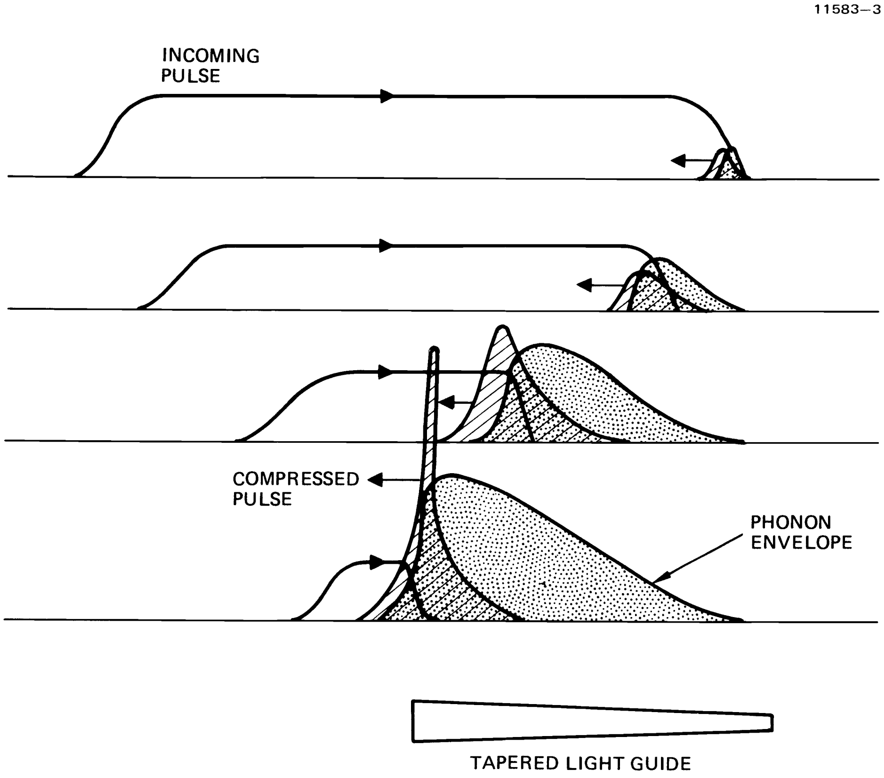


Figure 1. Time sequence of SBS pulse compression in a tapered light guide. The leading edge of the incoming pulse reaches SBS threshold first because of the reduced diameter at the far end of the guide.

where λ is the optical wavelength, n is the refractive index, p_{12} is the relevant photoelastic constant of the medium, ρ_o is the medium average density, v_s is the sound velocity, and I is the optical power density.

Experimental results

The experimental arrangement is shown schematically in Figure 2. A 20 nsec (FWHM) output pulse from a single longitudinal mode Nd:YAG oscillator traverses a polarizer, a quarter-waveplate, and two laser amplifiers. This amplified, circularly polarized pulse is then coupled into a tapered light guide. The resultant SBS-generated, temporally compressed output pulse, circularly polarized in the opposite sense, retraces its original path, extracting more energy from the amplifiers; it is then deflected by the polarizer as useful laser output. Because of the low SBS threshold in the fiber, the necessary incident pulse energy was only ~10-30 mJ.

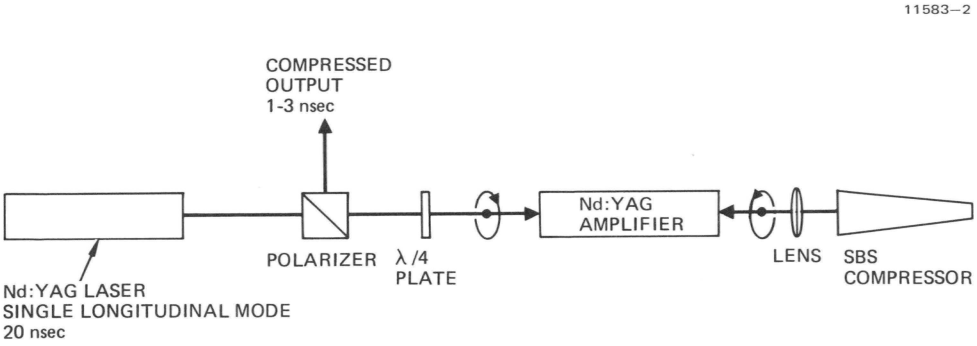
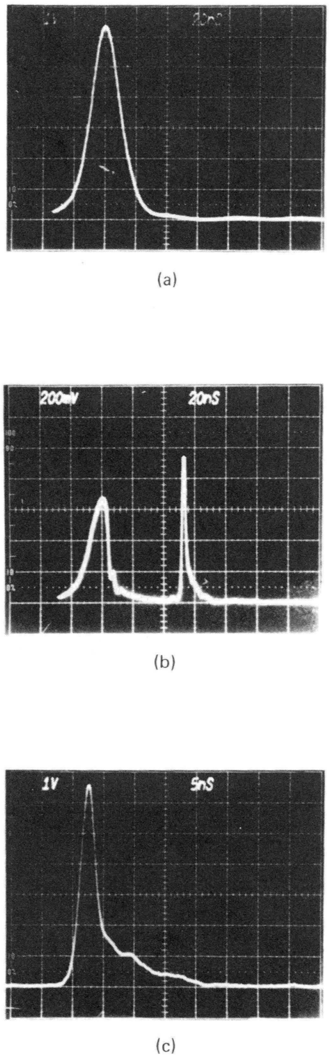


Figure 2. Schematic diagram of the experimental apparatus to achieve SBS pulse compression in a tapered light guide.

The solid glass fibers used were tapered. The diameters of the tapered fibers typically range from 1.5 mm at one end to 0.5 mm at the other, with varying degrees of uniformity. Because of the refractive index of ~1.5, a length of 7 feet is adequate to compress a normal 20 nsec pulse. Typical experimental results for one of these fibers are shown in Figure 3. Figure 3a shows the 20 mj input pulse; Figure 3b shows the transmitted pulse and the compressed pulse on the same oscilloscope trace, but with differing vertical calibrations. Note that the transmitted pulse rises like a Gaussian and drops precipitously before reaching the peak. Figure 3c is a display of the compressed pulse, using an expanded temporal scale. In contrast to the multiple pulse sequence often seen in the case of a uniform (i.e. untapered) fiber, there was only one SBS compressed pulse, which was initiated at the far end of the tapered fiber where the smaller diameter forced the power density to go above threshold. The measured pulsewidth of 3 nsec is in approximate agreement with Eqn (2). Unfortunately, the unclad fibers used in our initial experiments were so lossy that a detailed quantitative comparison with the theory could not be achieved. We note that the use of a tapered glass fiber is an attractive SBS candidate in that it is potentially easy to fabricate and could be made into a coil for compact device applications.



(a)

(b)

(c)

Figure 3. SBS pulse compression with a tapered solid glass fiber 7 feet long; (a) incoming pulse, (b) transmitted and attenuated backward-going compressed output pulse, (c) compressed pulse with an expanded time scale.

Conclusions

SBS appears to hold a great deal of potential for improving laser performance in the near future. Several properties contribute to this assessment: SBS generally has large cross-sections; it is a simple, passive interaction, free of additional optical sources or electronics; it can yield wavefront reversal; pulse compression can occur; it has a very small frequency shift, relative to other stimulated processes (e.g., stimulated Raman scattering); it has negligible forward scattering, thus eliminating the greatest cause of multiple scattering; and the polarization state of the scattered wave behaves in a manner similar to that of a conventional mirror.

There are, however, several system considerations that still need further attention; most important of these are: (1) competition from other nonlinear effects such as self-focusing and forward SRS for high power laser applications, especially if a long light pipe is to be used; (2) appropriate SBS materials; and (3) in cases where a pressurized gas is to be used as the SBS medium, the fabrication of high reflectance hollow cells to serve as low-loss light pipes.

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References

1. Hon, D. T., Opt. Lett. 5, 516 (1980).
2. Kaiser, W., and Maier, M., in Laser Handbook, edited by F. T. Arecchi and E. O. Schulz-Dubois (North-Holland, New York, 1972), vol. 2.
3. Hill, K. O., Johnson, D. C., and Kawasaki, B. S., Appl. Phys. Lett. 29, 185 (1976).