Applications of wavefront reversal by stimulated Brillouin scattering

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Abstract. Wavefront reversal (WFR) via stimulated Brillouin scattering (SBS) is shown to possess the capability to compensate for phase aberrations in laser media and also to temporally compress long laser pulses. Such techniques, which involve passive and lightweight conjugator elements, are believed to be simple and practical.

Keywords: optical phase conjugation; nonlinear optical phase conjugation; wavefront reversal; stimulated Brillouin scattering; pulse compression; master-oscillator/power-amplifiers; light guides.

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CONTENTS

I. INTRODUCTION

In laser engineering, several well-known problems continue to limit the usefulness of many lasers. Among them are (1) large beam divergence, which can result from optical inhomogeneities in highly pumped or turbulent gain media; (2) alignment instability, which can be a function of temperature, vibration, and/or time; and (3) long pulse width, which results in low peak powers. Nonlinear optical phase conjugation has been proposed to circumvent the first pair of the above problems. Of the various nonlinear optical techniques that can be utilized as phase conjugators, stimulated Brillouin scattering (SBS) has received a great deal of attention since it is perhaps the simplest and most efficient interaction. Moreover, it offers a convenient means to solve the third above-stated problem.

In this paper, two classes of SBS experiments will be discussed: the correction of laser medium inhomogeneities, and the temporal compression of laser pulses.

II. GENERAL BACKGROUND

In this section, we briefly review some basic facts about SBS and its relationship to wavefront reversal (WFR). Stimulated Brillouin scattering[1] involves the scattering of light by sound waves (i.e., acoustic phonons, or pressure/density waves), which results from optically induced electrostriction. This effect can occur in almost any solid, liquid, or gaseous medium. The resultant Stokes scattered light is down-shifted in frequency by a relatively small amount ($\sim 10^9$ to 10^{10} Hz). Stimulated Brillouin scattering, which is a threshold process, is rather easily generated, since SBS enjoys one of the largest cross sections[1] among the many known stimulated nonlinear optical effects. This is the case, provided that the coherence time ($1/\Delta\omega$) of the incident light is long compared to the response time τ of the acoustic phonon. Typically, τ 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.

Since the SBS gain depends on the incident optical intensity, one can utilize a guided-wave structure (e.g., a light pipe or an optical waveguide) to minimize the required input powers necessary to realize the onset of the stimulated scattering process.[2-5] 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-switched, 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.[4] We note that the single-mode fiber used in Ref. 4, although demonstrating SBS on a cw basis, cannot be directly applied to wavefront inversion; indeed, practical compensation schemes necessarily require multimode guided-wave structures to process the incident spatial information.

The efficiency of the SBS process (defined as the ratio of the Stokes-shifted, backward-going energy or power, to the incident optical energy or power) has been measured[5,6] to be as large as 90%. However, due to the possibility of optically induced damage effects, efficiencies in the range of 30 to 50% are typically used in system design considerations. As we will show below, these high efficiencies enable SBS conjugators to be of practical use in high power laser systems.

It is well known that the gain of the Stokes-shifted wave is

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generally the greatest in a direction opposite to that of the incident field[1] (i.e., in the backward direction). However, it was not until the work of Zel'dovich and collaborators[2] and Nosach et al.[7] that precision wavefront reversal (or phase conjugation) of the Stokes wave was demonstrated.[8] In general, most of the amplitude of the backward-going SBS field is wavefront reversed. Moreover, the degree of WFR has been predicted[3] and measured[14,6] to be nearly complete if the Fresnel number is small (i.e., <1), and if the incident optical field has a large angular spectrum. Thus, optical waveguides or light pipes appear to provide the most ideal interaction geometry, both from an input optical power threshold standpoint as well as from conjugation efficiency considerations.

We note that although SBS can give rise to wavefront inversion, the polarization state of the backward-going field is *not* conjugated,[9] thereby precluding perfect (vector) field phase conjugation. Thus, a left-handed circularly polarized incident beam would, as a result of the SBS interaction, emerge as a right-handed circularly polarized Stokes wave. This is in contrast to certain classes of (degenerate) four-wave mixing interactions[10] where the conjugate wave can be "time-reversed" both in terms of its spatial and polarization[11] nature. In many applications, this mirror-like response (via SBS) to the field polarization can be beneficial, as we describe below.

III. CORRECTION OF MEDIUM INHOMOGENEITIES

Phase aberrations (or inhomogeneities) in laser media often arise from a variety of mechanisms, such as thermally induced strain and nonuniform flows (in gaseous or liquid media). These aberrations can result in appreciable degradation of the wavefront quality of the optical system, yielding a nondiffraction-limited output.

It has been shown in recent years that WFR by SBS can correct for most classes of optical inhomogeneities in laser media by employing a double-pass master-oscillator/power-amplifier (MOPA) configuration. Most of the work has been performed with high power glass lasers in the Soviet Union.[12] More recently, this technique was used at Hughes Research Laboratories[13a] in the configuration shown in Fig. 1. The inclusion of a SBS conjugator greatly improved the beam quality and extraction efficiency of a highly distorted Nd:YAG laser system.

In one experiment,[13a] an output pulse of 5 mJ from a 10 Hz Q-switched, single-mode Nd:YAG laser is first amplified to 200 mJ by two Nd:YAG amplifier rods. Since this system was limited to low repetition rates, we have simulated the optical distortion that would result from the amplifiers at high repetition rates by passing the beam through yet another Nd:YAG rod which is cw-pumped to 4.5 kW (the single-pass phase aberration induced by this rod was measured to be >30 times the diffraction limit). After passing through this aberrating rod and diagnostic elements, the pulse impinges on a SBS conjugator consisting of a light pipe filled with either CS_2 or pressurized CH_4. Typically, the SBS return is 50% to 80% of the input. The phase-conjugate nature of the backward-going Stokes wave is then seen to compensate for the induced optical aberrations (due to the strongly pumped rod) after its return trip through the rod. Approximately 730 mJ of diffraction-limited output has been observed in this MOPA configuration; the total energy stored in the system was estimated to be about 880 mJ. These experiments have revealed several features of SBS phase conjugation that have important systems implications:

(1) If an ordinary mirror is substituted for the SBS cell (and no optical isolator is used), the noise photons "see" a total of four highly pumped rods. Consequently, superradiance prevents any substantial population inversion buildup; this inversion is necessary to achieve high power, Q-switched MOPA operation. This problem is circumvented by employing the SBS cell since the SBS does not occur until a high intensity threshold is reached. Thus, the SBS cell serves as a passive optical isolator as well as a WFR device. This combination of effects results in a greater MOPA output pulse energy (at higher efficiency), along with an improved output beam quality.

(2) From studies of SBS in bulk media and in guided-wave geometries, we have found that the polarization state of the backward-wave behaves similarly to that of a conventional mirror (even though the spatial wavefront is time-reversed).[9] This property of the SBS interaction permits one to configure a MOPA system with efficient input/output beam splitters by using a $\lambda/4$-plate and a Glan prism, as shown in Fig. 1. However, the large pump powers used in our experiments resulted in thermally-induced birefringence within the Nd:YAG amplifier rods, degrading the performance of this geometry. Since this scheme requires the maintenance of a given polarization state for its success, amplifier birefringence can be a major problem. If a 90° rotator is placed between two identically pumped rods, as shown in Fig. 2, the amplifier birefringence can be largely compensated.[16] Figure 3 shows the measured[17] percentage of depolarization in a single pass through the two YAG rods as a function of total pump power with and without the birefringence compensation scheme. The small residual depolarization is a reflection of the practical difficulty of "balancing" the two rods exactly. Assuming a nominal efficiency of 2% for YAG systems, the uncom-

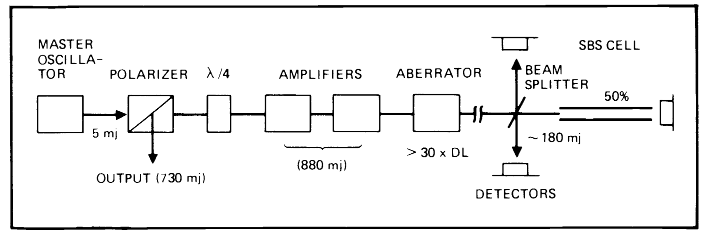

Fig. 1. Schematic of a double-pass master-oscillator/power-amplifier (MOPA) using SBS as the "wavefront reversal" reflecting mirror. The 730 mJ output is in a single transverse and single longitudinal mode, signifying a complete correction of the severe aberration imposed. A polarizer and $\lambda/4$ system is used to extract the backward-traveling beam efficiently. [After Ref. 13a.]

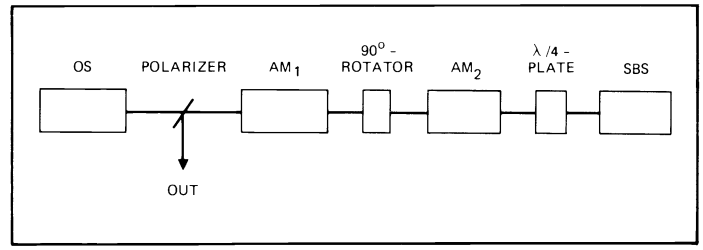

Fig. 2. Compensation technique to circumvent the thermally induced birefringence in the two laser amplifier rods ($AM_{1,2}$), using a 90° polarization rotator.

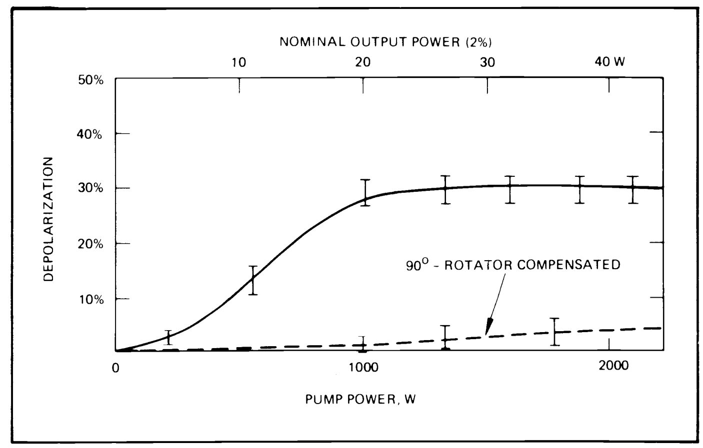

Fig. 3. Measured depolarization of two YAG rods as a function of the pump power. Nominal output powers are also given. A 90° polarization rotator placed between the two rods (as illustrated in Fig. 2) compensates for the birefringence and greatly reduces the total depolarization. [After Ref. 17.]

pensated geometry (solid line) shows that this extraction scheme can be applied to a system with an average output of 10 W, with ~80% coupling efficiency. However, at higher pump powers, the output coupling (resulting from the birefringence effect) becomes prohibitively high; this problem is circumvented by employing the 90° rotator, resulting in a reduction of the depolarization (dashed line). Hence, much higher average output powers can be realized.

(3) Based on our demonstrated energy extraction of 83%, a 2% pump-to-output efficiency is reasonable for our YAG system. Since we have also demonstrated the phase-distortion compensation of an aberrator (which was a YAG rod pumped at 4.5 kW), we have essentially demonstrated the feasibility of a YAG system with at least 90 W of diffraction-limited (average) output power. For Nd:YAG lasers, this scheme is considered suitable for use in systems whose output energy ranges from approximately 200 mJ, using small rods, to tens of joules using a chain of large rods. Basov et al.[12] have demonstrated a similar scheme using a 100 J Nd:glass system.

(4) Only 1 to 5 mJ pulse energy output is required from the single-mode master oscillator. This low energy requirement would allow the oscillator to operate at up to several hundred Hz before experiencing thermally induced birefringence and cooling problems in either the YAG rod or the Q-switching crystal.

The Nd:YAG laser is but one of *many* laser systems, from low-power dye and alexandrite lasers to high-power excimer lasers, that can benefit from this SBS scheme. However, there are several basic system requirements that one must consider in constructing such MOPA schemes: first, a single longitudinal mode oscillator/driver must be available with an output linewidth comparable to or smaller than that of the Brillouin linewidth, which is typically 10^7 to 10^9 Hz. Secondly, the gain of the amplifier medium must be high enough so that a double-pass MOPA scheme can extract a sufficient portion of the stored energy, even though some of it is bound to be "lost" by the SBS interaction. Thirdly, a SBS medium and a (light guide) cell must be configured to provide a reliable, high efficiency phase conjugator. Finally, the SBS frequency downshift still must fall within the gain linewidth of the amplifier media. To circumvent the latter constraint, schemes employing fortuitous isotopic shifts may be employed. One such scheme would involve the use of an isotopically shifted laser amplifier, whose gain profile is downshifted in frequency (relative to the driver oscillator) by an amount equal to the Stokes frequency downshift of the SBS conjugated wave.

Generally speaking, short-pulsed lasers appear to be particularly suitable candidates for such SBS/MOPA schemes. Long-pulsed or cw lasers may face temporal instability problems associated with such nonlinear processes as SBS, especially when a long light guide is to be used in an attempt to lower the SBS threshold.

IV. PULSE COMPRESSION BY SBS

SBS can be used to compress[13b] a long laser pulse into a short pulse several nanoseconds long with high energy efficiencies. This has been accomplished by using a *tapered* light guide. A typical pulse time sequence is illustrated in Fig. 4. The compression mechanism can be understood by the following qualitative argument. The threshold of SBS is reached by the leading edge of the pulse at the far end of the tapered light pipe, where the smaller diameter results in a local increase of power density. As the SBS pulse sweeps backwards, it beats with the remainder of the incident wave to create a strong acoustic wave, which in turn acts as a bulk grating to reflect the incident wave further, coherently amplifying the SBS wave. The pulse compression results from strong pump depletion at the leading edge of the SBS pulse. Ideally, the length L of the tapered guide should be at least half that of the incident pulse length, i.e.

$$\mathrm{Ln} \gtrsim c\Delta T/2 \ , \tag{1}$$

where n is the linear refractive index of the SBS medium, c is the velocity of light, and ΔT is the laser pulse length. Figure 5 is a schematic diagram of our experiment[13b] (which, aside from the tapered light pipe, is similar to that of Fig. 1). A 20 nsec output pulse

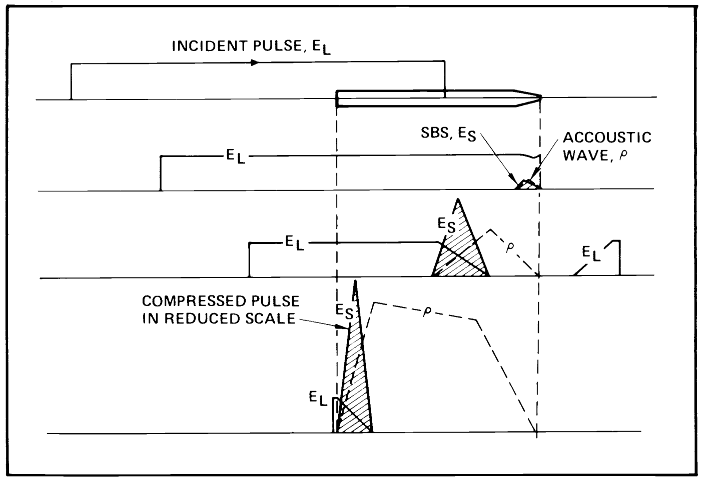

Fig. 4. Temporal sequence of pulse compression by SBS using a tapered waveguide. Time increases from the upper to the lower traces. The leading edge of the incident pulse (E_L) reaches the SBS threshold first because of the reduced diameter at the far end of the waveguide. The SBS-generated Stokes wave (E_s) sweeps backward and is amplified by the remainder of the incident pulse. Pulse compression comes about because of a rapid depletion of the SBS gain.

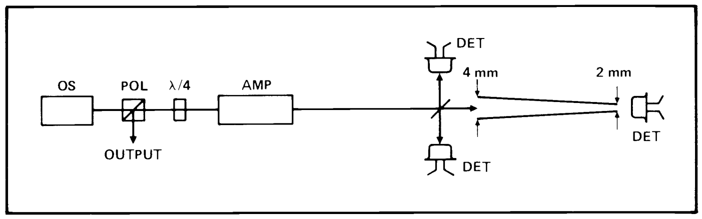

Fig. 5. Schematic diagram of the experimental setup used to achieve pulse compression via SBS in tapered waveguide: OS, oscillator; POL, polarizer; Q, λ/4 plate; AMP, amplifier; and DET's, detectors.

from a single longitudinal mode Nd:YAG oscillator traverses a polarizer (i.e., a laser Glan prism), a quarter-waveplate, and two laser amplifiers. This highly amplified, circularly polarized pulse is then coupled into a tapered light guide. The resultant SBS-generated, temporally compressed output pulse, which is WFR, and is 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. In our experiments, the energy of incident pulses was varied continuously up to 430 mJ.

Using this scheme, we have demonstrated pulse compression via SBS in methane at 120 atm in a (hollow) tapered glass tube whose i.d. varied from 4 mm to 2 mm over the guide's length of 1.2 m. The minimum compressed pulse width that can be achieved without damage to the glass window was measured to be consistently one nanosecond. A typical oscillograph of the output is shown in Fig. 6. The first pulse, which is detected near the exit window of the cell, shows a sharp compressed pulse at the leading edge, followed by a relatively long tail that resulted from the short length of the compression cell (see Ref. 13b for details). The second pulse in the same trace is the amplified output where the leading spike has grown disproportionately due to gain depletion in the amplifiers. These results reasonably agree with our theory[13b,c] which predicts ~1.0 nsec as the smallest compressed pulse width for our system.

Since, in this case, the SBS-generated conjugate wave possessed a polarization state that behaved analogously to that of an ordinary mirror,[9] the energy in the backward-traveling wave (700 mJ) was completely extracted by the polarizer. Along with the phase-conjugation nature of SBS, this scheme suggests many possibilities around the general theme of an efficient short-pulsed MOPA (master-oscillator/power-amplifier) system that can tolerate optical distortions.

To compress the entire energy of a 20 nsec pulse in a gaseous

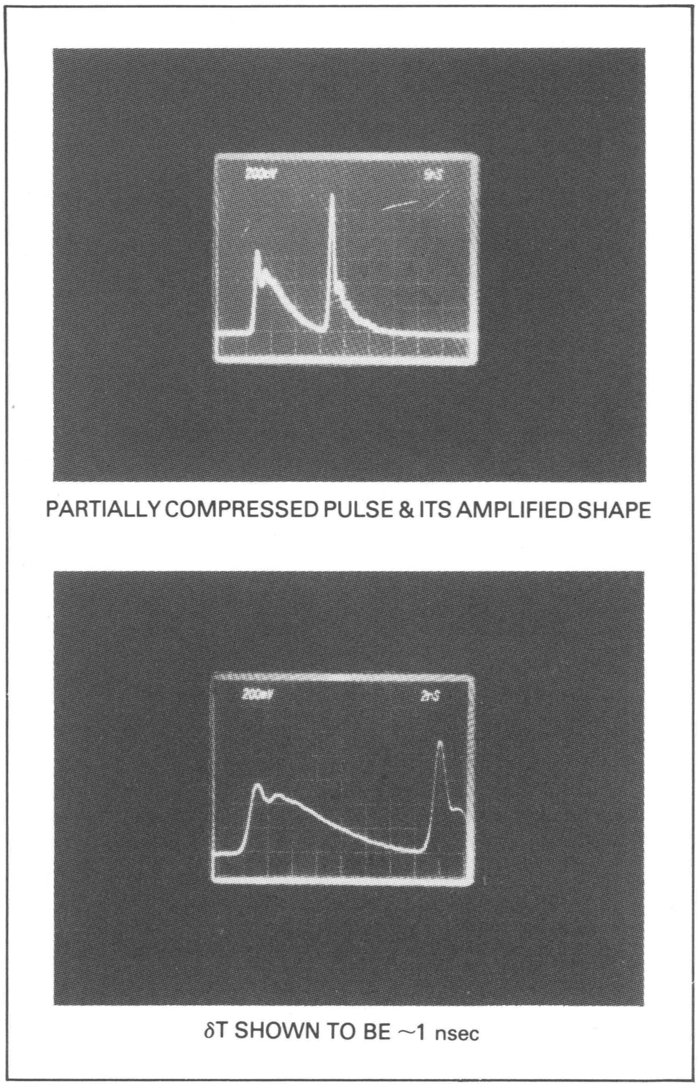

Fig. 6. Oscillographs of SBS pulse compression. The theoretical limit of ~1 nsec for pressurized (120 atm) methane was observed. The experimental setup used here is shown in Fig. 5, and is similar to Fig. 1, except that a tapered light pipe was employed for these measurements. [After Ref. 13b.]

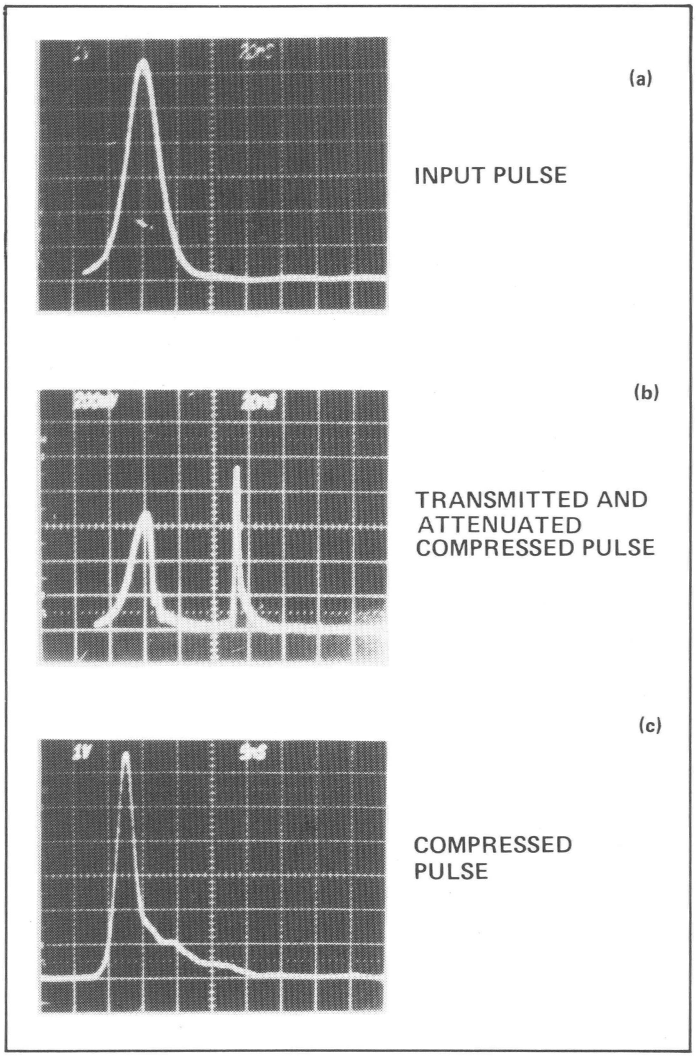

Fig. 7. Experimental studies of SBS pulse compression using a 2 m tapered solid glass fiber. The three oscilloscope traces show the (a) temporal evolution of the input pulse; (b) the pulse transmitted through the tapered guide, and the (attenuated) backward-going, compressed output pulse; and (c) the compressed output pulse of (b), but on an expanded scale. [After Ref. 13b.]

medium, a cell length of 3 m is necessary.[13b] Partly due to the difficulties encountered in fabricating such a hollow guide, we tried a solid glass fiber in which SBS is known to occur very easily.[1] We used a *tapered* solid glass fiber, which is a natural biproduct at the beginning of a fiber pulling "run." Because of the larger refractive index, a fiber length of 2 m is nominally sufficient for a 20 nsec pulse. 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. Typical experimental results using these solid, tapered fibers are shown in Fig. 7. Figure 7(a) shows the 20 mJ input pulse; Fig. 7(b) 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 7(c) is a display of the compressed pulse, using an expanded temporal scale. In contrast to the multiple pulse sequence 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 pulse width of 3 nsec is in approximate agreement with the "phonon mirror" theory given in Ref. 13b; it can be shown that the compressed pulse width δT is given by

$$\delta T \sim (\lambda / 2\, n^3 p_{12}) \sqrt{\rho_o v_o / P}\ , \qquad (2)$$

where p_{12} = piezo-optic constant, ρ_o = density, v_o = velocity of sound, and P = power density. 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.

Considerable progress has been made in the theory of SBS pulse compression. The details of that work, which are based on a self-consistent solution of the Maxwell's and Navier-Stokes' equations, will be published shortly in another article.[13c] Computer simulations of SBS pulse compression based on this theory and using various boundary conditions have been made. For example, Fig. 8 shows what happens to a 20 nsec Gaussian pulse (E_{L0}^2) incident from the left into a light guide when it is met with a counterpropagating weak SBS signal (E_{L0}^2) at the center (at time zero). The 5 nsec time sequence shows that the SBS output is amplified and compressed, while the incident pulse is quickly depleted. The last (lowest) set of curves may be compared with Fig. 7, which shows the input, transmitted, and compressed pulses using a tapered glass fiber (L = 2 m) where the SBS is initiated by a taper at the far end; there is reasonable qualitative agreement with the experiment. The theory also predicts that the minimum pulse width that can be obtained by SBS is approximately $(1/\omega)$, where ω is the angular frequency of the sound

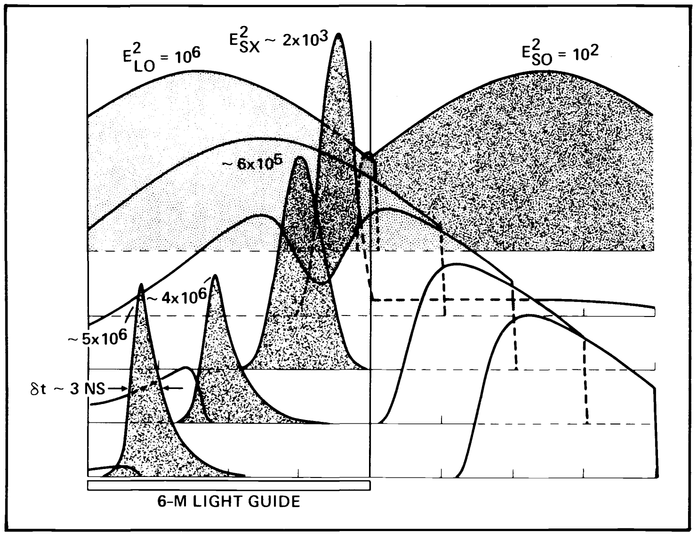

Fig. 8. Theoretical calculations showing the temporal evolution of the input transmitted, and output (compressed pulses for the experimental conditions of Fig. 7 (assuming a lossless nonlinear medium). The lower trace is to be qualitatively compared with the experimental results (see Fig. 7). [After Ref. 13c.]

wave involved. As noted above, this pulse width, which is ~1.0 nsec for methane at 120 atm, has also been verified experimentally.[13b]

V. 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 (WFR);
- Pulse compression can occur;
- It has a very small frequency shift, relative to other stimulated processes (e.g., stimulated Raman scattering, SRS);
- It has negligible forward scattering, thus eliminating the greatest cause of multiple scattering (e.g., SRS);
- The polarization state of the conjugated field 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 material, the fabrication of high reflectance, hollow cells to serve as low-loss light pipes.

VI. ACKNOWLEDGMENTS

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