Increase in the compression factor in stimulated-Brillouin-scattering compression of nonmonochromatic light pulses

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An increase in the compression factor, i.e., in the ratio of the length of the pump pulse to that of the Stokes pulse, $H = T_p / T_S$, has been observed during stimulated-Brillouin-scattering compression of nonmonochromatic laser light. An interpretation of the effect is offered. The value of H can reach values $H_{max} = 60–100$ at the "optimum" spectral width of the pump pulse.

The compression in which we are interested here (a contraction of pulses along the time scale) is that which occurs during stimulated Brillouin scattering (SBS) in focused beams. In this process the Stokes pulse is formed from the spontaneous-scattering noise which is distributed over a length $l \gtrsim T_p c/2$ (c is the velocity of light in the medium) in a nonlinear medium.

At first glance, the physical mechanism for the compression would seem to require that the pump be extremely monochromatic, i.e., that the condition $\Delta T_p c \sim 1$ (Δ is the width of the spectrum in reciprocal centimeters), since the Stokes pulse must effectively collect energy over the entire length of the pump pulse. This assertion also corresponds to the results of Refs. 1 and 2 on the SBS compression of nonmonochromatic pulses from excimer lasers. In those experiments it was not possible to achieve high conversion efficiencies and high values of H simultaneously.

The theoretical and experimental research[3–8] on the case of a monochromatic pump shows that an upper bound is imposed on H_{max} by the threshold growth rate for the SBS: $M_t = 20–30$. The value H_{max} can be reached only in the optimum focusing geometry, with $l / z_f = M_t$ (z_f is the length of the focal neck), and only at the optimum pump energy. This optimum pump energy is determined by the hypersound attenuation time T_a and by the gain g (in units of centimeters per megawatt) of the medium. These conditions were not satisfied in Refs. 1 and 2. Furthermore, there was a significant amount of absorption of the light in the medium. For this reason, the small values of H could not be unambiguously linked with the nonmonochromatic nature of the pump.

The analysis below shows that H_{max} will in fact increase, rather than decrease, as the width of the spectrum is increased. This analysis is based on a development of the model of Ref. 3 regarding the formation of the compressed pulse from distribution of spontaneous noise under the condition $\Delta z_f / M_t \ll 1$. Under this condition, according to Ref. 8, the efficiency of the SBS of focused nonmonochromatic light is high. Our experimental results (discussed below) show that the latter condition is also a sufficient condition for an efficient use of pump energy in SBS compression.

The approach of Ref. 3 can be summarized as a determination of the temporal

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positions of the leading and trailing edges of the Stokes pulse from the threshold conditions for stimulated scattering. The position of the leading edge is determined by the noise which starts from the point z_1 and which acquires the threshold growth rate over the path $l - z_1$. (The distance z is reckoned from the focus, $z = 0$, to the entrance to the nonlinear medium, $z = l$.) The quantity z_1 is calculated from the expression for the growth rate of the noise in the field of the focused pump beam:

$$\int_{z_1}^{l} \Gamma(z)dz = M_t, \tag{1}$$

where $\Gamma(z) = gI(z)$ (Ref. 3), and $I(z)$ is the distribution of the pump intensity along the z axis.

The position of the trailing edge is set by the noise which starts from the point z_2 and which is the first to acquire the threshold growth rate over the path $z_3 - z_2$. (The time is reckoned from the time at which the leading edge of the pump pulse crosses the $z = l$ plane.) The quantities z_2 and z_3 are calculated from the system of equations

$$\left.\begin{aligned} \frac{dt}{dz_2} &= \frac{d}{dz_2}[(l + z_3 - 2z_2)/c] = 0, \\ \int_{z_2}^{z_3} \Gamma(z)dz &= M_t \end{aligned}\right\} \tag{2}$$

We see that the length of the Stokes pulse is $T_S = 2(z_1 - z_2)/c$, and we see that its minimum value is found from (2) at the optimum pump energy, $T_{S_0} = \sqrt{2}z_f/c$ (Ref. 3). In this case we have $z_1 = 0$ and $z_2 = -z_f/\sqrt{2}$. In the case of a nonmonochromatic pump, the growth rate per unit length, $\Gamma(z)$, is given by[8]

$$\Gamma(z) \approx \begin{cases} gI(z) - 2\Delta, & \text{for } gI(z) > 2\Delta \\ gI(z)(1 + \Delta T_p c/2)^{-1}, & \text{for } gI(z) < 2\Delta. \end{cases} \tag{3}$$

We see from (3) that in the case of a nonmonochromatic pump, in which there is an even more pronounced localization of the growth rate near the focus in the focused beam, the point z_1 must shift slightly into the region of negative z, i.e., along the direction toward z_2. It is easy to show that the position of the latter does not depend on the width of the spectrum. Using (3), we can calculate the position z_1 from Eq. (1) for the case of a nonmonochromatic pump. Working by analogy with Ref. 3, we can then find the minimum length of the Stokes pulse as a function of the spectral width of the pump:

$$T_C(\Delta)/T_{C0} \approx 1 - 2\sqrt{2\pi\Delta z_f/M_p} + 3\pi\Delta z_f/M_p. \tag{4}$$

We see from (4) that in the case $\Delta z_f/M_t = 2/9\pi = 0.07$ (with optimum focusing, this condition is equivalent to $\Delta T_p c \approx 50$) the degree of compression can be increased by a factor of three; i.e., we can achieve $H_{max} = 3M_t$.

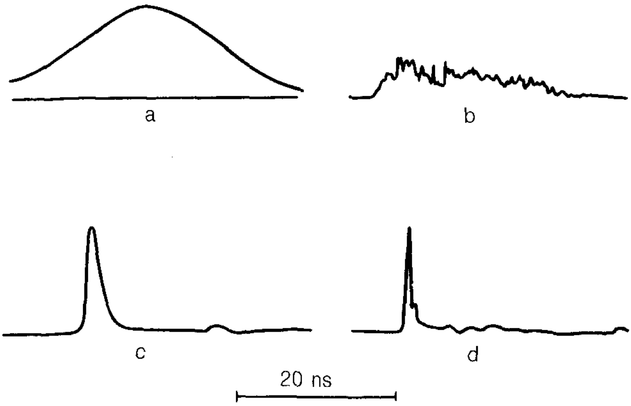

FIG. 1. Oscilloscope traces of pulses. a, b—Pump pulses; c, d—SBS pulses; a, c—with a narrow spectrum, $\lambda_{p1} = 0.53$ μm, and $\Delta \approx 0.001$ cm^{-1}; b, d—with a broad spectrum, $\lambda_{p2} = 0.47$ μm and $\Delta \approx 0.04$ cm^{-1}.

We have carried out an experimental study of the effect of a finite spectral width in experiments on the SBS compression of pulses with various spectral widths, under otherwise essentially identical conditions.

The pump laser used in the apparatus had an output beam with a divergence close to the diffraction level and an energy of 25 mJ. This beam was focused by a lens with $f = 300$ cm into a cell 400 cm long filled with argon ($p = 120$ atm). The lens was pressed directly against the entrance window. As pumps we used the second-harmonic pulse from a neodymium laser with $T_{p1} = 20$ ns and $\Delta \approx 0.001$ cm^{-1} (Fig. 1a) and the pulse from a laser using the dye coumarin-102 as active medium with $T_{p2} = 20$ ns, $\Delta \approx 0.04$ cm^{-1}, and $\lambda_{p2} = 0.47$ μm (Figs. 1b, 2a, and 2b). The shape of the pulses was measured by an FK-26 photocell and an S7-15 oscilloscope with a time resolution of 0.25 ns; the spectral width was determined with the help of Fabry-Perot interferometers with baselines of 15 and 3 cm. The transverse intensity distribution of each beam

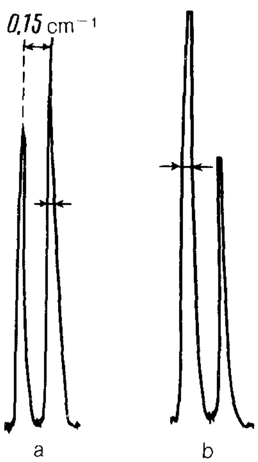

FIG. 2. Densitometer traces of spectra. a—Spectrum of the pulse from the dye laser; b—spectrum of the corresponding Stokes pulse. The free-dispersion region of the Fabry-Perot interferometer is 0.15 cm^{-1}.

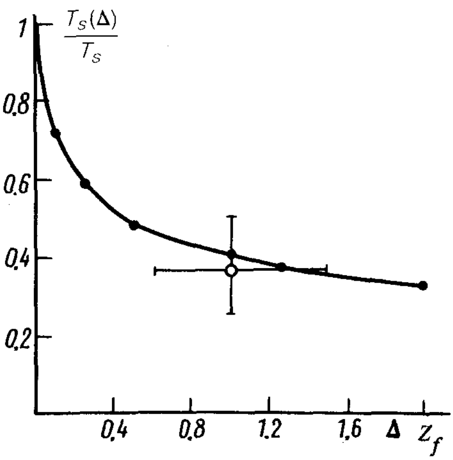

FIG. 3. Minimum length of the compressed Stokes pulse versus the spectral width of the pump. Solid line—Calculated from expression (4); point—experiment with a dye laser.

was formed by an apodizing aperture with a transmission $T(r) = \exp[-(r/r_0)^6]$, where $r_0 = 0.4$ cm.

Under these conditions, the energy efficiency of the SBS was essentially the same, reaching 50%. We obtained Stokes pulses, with $T_{S1} = 1.2$–1.3 ns in the case of a pump with a narrow spectrum and with $T_{S2} = 0.3$–0.4 ns in the case of a pump with a broad spectrum (Fig. 1, c and d). Consequently, the length of the compressed Stokes pulses is shorter by a factor of three for the nonmonochromatic pump, under otherwise identical conditions. The results of the experiment with the dye laser are shown in Fig. 3. They demonstrate a good agreement with the results calculated from expression (4).

In summary, these experiments have brought us up to the "next limit" on the compression factor. We believe that these results are of significant interest in connection with the problems of forming subnanosecond pulses in lasers of various types which are used for plasma production and plasma diagnostics. With some reservations, these results can be extended[9] to the case of stimulated-Raman-scattering compression. It thus becomes possible to formulate requirements on the pump spectrum in order to achieve the direct conversion of "standard" 10-ps pulses into the range ~100 fs, without the power limitations which are characteristic of optical-fiber compressors.

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