Reduced Brillouin scattering from multiline CO_2 laser interaction with a plasma

R. Giles, R. Fedosejevs, and A. A. Offenberger
Department of Electrical Engineering, University of Alberta, Edmonton, Alberta, T6G 2G7 Canada
(Received 18 December 1981; revised manuscript received 8 March 1982)

Experimental verification of reduced stimulated Brillouin scattering (SBS) is reported for multiline CO_2 laser radiation interacting with high-density plasma. For long-pulse (40-nsec) irradiation SBS was observed to decrease from 15% to a negligible level when the spectrum of the incident laser pulse was changed from 1 to 2 or more well-separated frequencies. Results for both long- and short-pulse multiline laser conditions are in general accord with the expected behavior for varying $\Delta\omega/\gamma_0$, where $\Delta\omega$ is the frequency separation and γ_0 is the homogeneous growth rate.

Strong stimulated Brillouin scattering (SBS) of laser light is known to occur when high-intensity laser radiation interacts with high-density, long-scale-length plasma such as would be found in pellet coronas in laser-driven fusion.[1,2] Techniques which have been suggested for reducing the impact of parametric instabilities such as SBS include the use of broadband or multiline laser oscillators.[3] In previous related work, random-phase and comb amplitude modulation have been used at microwave frequencies on low-density plasma to produce similar effects to that expected for multiline oscillation,[4] but there have been no published results for laser irradiation experiments. We report here on laser-plasma interaction experiments in which multiline oscillation of a CO_2 laser has been successfully employed to demonstrate reduced plasma Brillouin backscatter as compared to that induced by single-line oscillation (with the same total focused intensity) for both long (40-nsec) and short (2-nsec) pulses.

The laser used in the experiments described here is a transversely excited atmosphere (TEA) CO_2 laser providing a 30-J, 40-nsec gain-switched pulse which when focused generates a peak intensity on target of 10^{13} W/cm^2. This laser could also be injection mode-locked by a pulse chopped from the output of a second oscillator to generate a train of 2-nsec pulses with peak focused intensities of 1.7×10^{13} W/cm^2 in the leading pulse. The target was a laminar oxygen gas jet which, when ionized, gave a long underdense shelf of density $n=0.3-0.4n_c$ with a nominal interaction length of 125 μm determined by the $f/2$ focusing optics and half-power SBS reflectivity.

Figure 1 shows the experimental arrangement which included input beam monitoring of energy, power, and spectral content. The SBS was temporally resolved using high-speed Ge:Au detectors (and various bandpass filters). Both the input beam and SBS were spectrally resolved with a monochromator (24-Å resolution) and detected with an infrared multichannel analyzer.

Multiline lasing was achieved by installing SF_6 cells in both the injection and slave oscillators. By adjusting the cell SF_6 fill pressure and buffering to 1 atm of helium, the laser cavity characteristics were modified to lower the gain at 10.59 μm and allow for competing lines to grow. In general, we observed a change from multiline lasing in the 10.6-μm band at low SF_6 fill pressure to multiline lasing in the 10.3-μm band with increased SF_6 to mixed 9.5- and 10.3-μm bands at yet higher SF_6 pressure and finally only 9.5-μm radiation at the highest SF_6 pressure. Details of the method will be published elsewhere. In both gain-switched and injection mode-locked multiline lasing, the peak power of the laser output was lower than for single-line lasing because of the additional losses introduced by the intracavity absorption cells. This, unfortunately, limited experimental comparison measurements to lower focused intensity.

The dramatic reduction in SBS reflectivity which can be achieved is summarized in Fig. 2 for long-pulse irradiation experiments in which the frequency

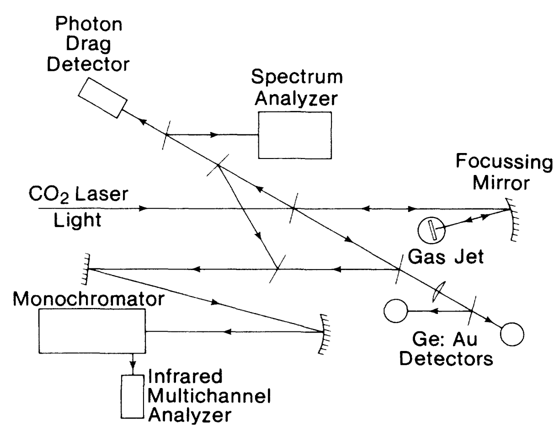

FIG. 1. Experimental layout. Both incident and reflected radiation are monitored simultaneously for power, energy, and spectral behavior.

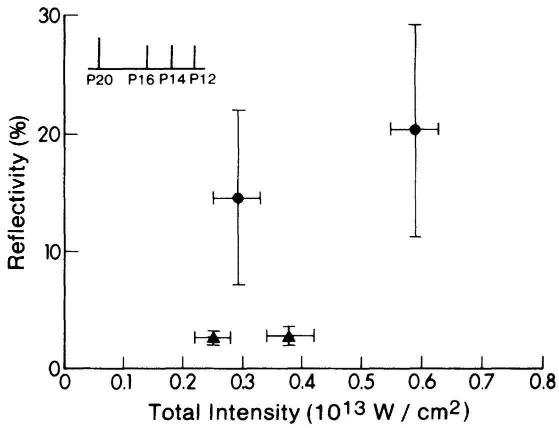

FIG. 2. Total power reflectivity (SBS plus specular) for 40-nsec laser-pulse incident on the oxygen target; single line (●), two-to-four line (▲). The 2% residual reflectivity is specular.

difference $\Delta\omega$ for the multiline case is greater than the SBS homogeneous growth rate γ_0. The measured reflectivity of 15% which obtains for single-line (10.59 μm) target irradiation at an incident intensity of 3×10^{12} W/cm^2 is reduced to 2% with two equal intensity lines at 10.59 and 10.55 μm (for the same total laser power on target). The frequency separation $\Delta\omega \simeq 6 \times 10^{11}$ sec^{-1} may be compared with $\gamma_0 = v_0/2c\,(\omega_0/\omega_s)^{1/2}\,\omega_{pi} \simeq 3.2 \times 10^{11}$ sec^{-1} for each line under our experimental conditions, where ω_0, ω_s and ω_{pi} are the frequency of pump wave, ion acoustic wave and ion fluctuation, respectively, and v_0 is the electron oscillating velocity in the pump wave.

The residual 2% reflected power did not change with three- or four-line oscillation in the 10.6-μm band. Furthermore, the remaining reflected light was predominantly specular, showing the long-pulse temporal features of the incident radiation as compared to the much shorter spike characteristic of SBS ($\lesssim 5$ nsec). This suggests that the backscatter process was nearly completely eliminated in the two-line pump and that the specular light resulted from some other mechanism such as critical layer reflection which depends only on the total incident intensity.

The overall trend in reflectivity (R) for single-line target irradiation can be accounted for by a model which includes convective gain (G) on the heavily damped ion waves[5,6] along with Kruer's ion heating model[7] for self-consistently relating reflectivity and damping (details to be published elsewhere). The convective growth of backscatter is given by $R(1-R) = \epsilon \exp[G(1-R)]$ where ϵ is an initial noise level and G varies linearly with the focused intensity I. Therefore dividing the input intensity into N independent (i.e., $\Delta\omega >> \gamma_0$) but equal lines should have a dramatic effect on R since the effective gain for each line is reduced to G/N. The observed reduction in SBS agrees well with the predictions of such a model.

In contradistinction to the substantial reduction in SBS noted above, when the laser was operated in the 10.3-μm band with adjacent line separation $\Delta\omega \simeq 2.7 \times 10^{11}$ sec^{-1} $\sim\gamma_0$, the observed reduction of SBS was considerably less than for the previous case of larger line separation. For roughly equal line intensity at 10.289 and 10.274 μm at a total irradiance of 5×10^{12} W/cm^2, the SBS reflectivity, shared equally between two lines, was reduced by a factor of $\sim$1.3 from single-line lasing at 10.289 μm. Spectral features of the two individual Brillouin components did not change with incident power, maintaining a characteristic 40–80-Å line shift and 30–65 Å full width at half maximum (FWHM) for the shot-to-shot variation in plasma conditions. The small effect of two-line irradiation on SBS in this case is attributed to the lack of wave decoupling when $\Delta\omega \simeq \gamma_0$.

Further evidence of anomalous behavior when $\Delta\omega$ did not significantly exceed γ_0 in the multiline case is shown in the spectral data of Fig. 3. When the laser output was adjusted so that one line was of much

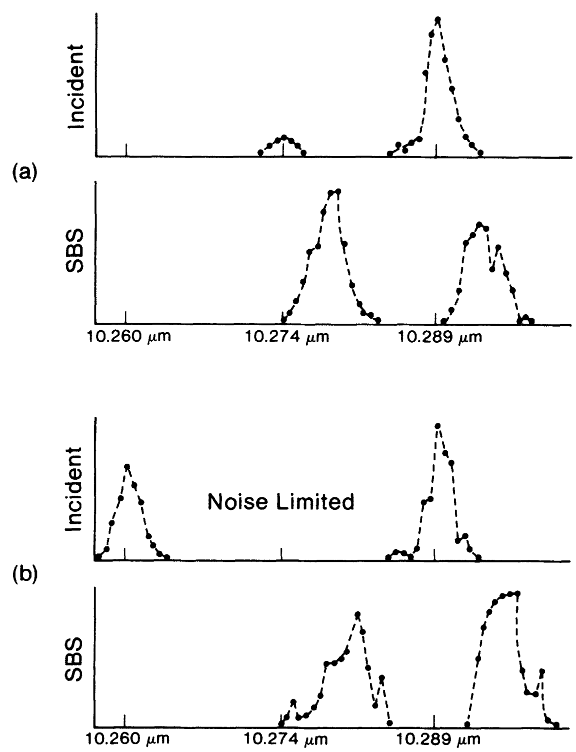

FIG. 3. Spectra of incident and reflected radiaton for two lines of unequal intensity (a) and for three lines of unequal intensity (b) where anomalous effects are observed. Note that the 10.274 μm, while small, is not zero in (b) and that a negligible level of SBS was found for the 10.26-μm line. The wavelength scale is 6.2 Å per point and the instrumental width has been deconvoluted in this data.

higher intensity than the adjacent line [Fig. 3(a)], the SBS reflectivity of the weaker line approached unity whereas the dominant line maintained approximately 9% reflectivity. For this particular shot, the line intensity ratio was 1:11 and the SBS ratio was 1.2:1, indicating that, within experimental error, the weak line is entirely Brillouin reflected. This suggests that the strong pump is driving up ion fluctuations from which the weaker line can scatter.

In addition, when a third line at 10.26 μm was introduced, the presence of the 10.274-μm line, though very weak, led to only moderate reduction in SBS reflectivity with anomalous spectral characteristics as shown in Fig. 3(b). While we might have expected significant reduction in SBS for the two strong lines only ($\Delta\omega > \gamma_0$), the presence of the weaker intermediate line closely coupled to the stronger lines ($\Delta\omega \simeq \gamma_0$) has altered the behavior dramatically. Indeed, as is clearly seen in Fig. 3(b), the reflectivity for the very weak line is greatly enhanced while the reflectivity for the strong line at 10.26 μm is greatly reduced. These spectra point out the complicated behavior that may arise for multiline irradiation when the separation $\Delta\omega$ does not significantly exceed the growth rate γ_0 and hence the reduction in SBS reflectivity is moderate.

In order to determine whether any significant temporal variations in SBS existed for multiline irradiation, the gain-switched laser was operated for convenience on lines at 10.28 and 9.55 μm for which separate filters and Ge:Au detectors could readily be used. As expected, for two widely separated lines ($\Delta\omega = 1.4 \times 10^{13}$ sec $\gg \gamma_0$) the reflectivity was greatly reduced. Within the instrumental resolution of 2 nsec, both lines exhibited identical characteristics in input and SBS reflection, thus precluding scattering from different lines at different times in the laser-plasma interaction. In addition, the fact that low-level SBS associated with two widely separated lines were temporally coincident suggests that the mechanism for terminating SBS is dependent more on rapidly changing plasma parameters than on pump characteristics.

Finally, SBS reflectivity measurements were made with the injection mode-locked laser system producing 2-nsec pulses in order to verify similar behavior for short-pulse irradiation. Unfortunately, the additional cavity losses referred to before when operating multiline limited the laser output power and hence focused intensity to a region for which the single-line reflectivity is low to start with. We note that for single-line, short-pulse irradiation at high intensities ($>10^{13}$ W/cm^2), SBS reflectivities of 85% have been measured. For our maximum available intensity of 2.8×10^{12} W/cm^2 in multiline operation, the single-line (10.289 μm) reflectivity was (2.0 ± 0.3)%, the two-line (10.289 and 10.274 μm) reflectivity was (1.2 ± 0.6)% and the three-line (10.289, 10.274, and 10.26 μm) reflectivity was (0.5 ± 0.1)%. Evidently the reduction in SBS reflectivity is not as dramatic as that found for the higher initial reflectivity, long-pulse case where $\Delta\omega > \gamma_0$. Nevertheless, the behavior is consistent with that expected for a smaller line separation and the predictions of the convective amplification model discussed earlier.

In conclusion, we have experimentally demonstrated that multiline laser irradiation indeed leads to reduced Brillouin backscatter in laser-plasma interaction. We find that the reduction is substantial for the case of line separation satisfying $\Delta\omega > \gamma_0$ (independent ion waves) and moderate for the case $\Delta\omega < \gamma_0$ (nonindependent ion waves). Such a reduction in SBS and in other parametric processes may be necessary in order to achieve efficient target coupling in large scale length, long-pulse laser fusion plasmas. The present results indicate that multiwavelength irradiation may be a valuable technique for reducing the undesirable effects of such parametric instabilities.

---

[1]K. Estabrook, H. Harte, E. M. Campbell, F. Ze, D. W. Phillion, M. D. Rosen, and J. T. Larsen, Phys. Rev. Lett. 46, 724 (1981), and references therein.

[2]A. Ng, L. Pitt, D. Salzmann, and A. A. Offenberger, Phys. Rev. Lett. 42, 307 (1979).

[3]J. J. Thomson, Nucl. Fusion 15, 237 (1975).

[4]A. Mase, N. C. Luhmann, J. Holt, H. Huey, M. Rhodes, W. F. Di-Vergilio, J. J. Thomson, and C. F. Randall, *Plasma Physics and Controlled Nuclear Fusion Research* (IAEA, Vienna, 1981).

[5]C. L. Tang, J. Appl. Phys. 37, 2945 (1966).

[6]D. W. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Fluids 18, 1002 (1975).

[7]D. W. Phillion, W. L. Kruer, and V. C. Rupert, Phys. Rev. Lett. 39, 1529 (1977).