PHYSICAL REVIEW A VOLUME 11, NUMBER 6 JUNE 1975

# Self–phase modulation of laser light in a laser-produced plasma

C. Yamanaka
*Institute of Laser Engineering, Osaka University, Suita, Osaka 565, Japan*

T. Yamanaka, J. Mizui, and N. Yamaguchi
*Institute of Plasma Physics, Nagoya University, Nagoya 464, Japan*
(Received 10 February 1975)

A spectrum broadening due to the self–phase modulation of laser light was observed in a laser-produced deuterium and hydrogen plasma. Qualitative treatments of the density modulation due to the self-focusing process and the modulational instability are discussed. The theoretical estimation of spectrum broadening agrees fairly well with the experimental results.

The mechanisms responsible for absorption and reflection of laser light in a plasma are very important problems in laser-fusion research. The scattered light from a plasma yields information on the nonlinear phenomena in a plasma. There have been a number of recent experimental[1–8] and theoretical[9–13] works on the light-scattering problems in plasmas. In this paper we describe the angular distribution of scattered light from a plasma and the backscattered spectrum which shows the broadening due to the self–phase modulation[14–16] of laser light in a plasma.

The laser system was composed of a yttrium aluminum garnet oscillator and glass amplifiers. The output energy was 25 J in 2 nsec. The spectral width and the beam divergence were 3 Å and less than 1 mrad, respectively. The laser beam was focused onto a solid deuterium and hydrogen target, whose dimensions were $2\times2\times10$ mm, by an aspherical lens, $f=50$ mm. The image of the target was magnified 20 times to check the focal condition. The accuracy of the focal adjustment was 25 $\mu$m. The incident laser light and the reflected light through the focusing lens were monitored by a HTV-R317 biplanar photodiode with an IR-80 filter. The time-integrated scattered spectra were observed using an infrared vidicon, the photocathode of which was PbS, through a Czerny-Turner grating spectrometer with a mean dispersion of 8 Å/mm in the first order. The intensity profile was recorded by a video recorder to be reproduced on an oscilloscope. The time-resolved spectroscopy of the backscattered light was performed using two channels of the optical fibers connected to the HTV-R317 photodiode, the spectral resolution of which was 6 Å at 1.06 $\mu$m.

We performed measurements of the angular distribution and the spectra of the scattered light around the wavelength of the incident laser, 1.06 $\mu$m, and its second harmonics, 5300 Å. Table I summarizes the results for the scattered light at the directions of 0° (backward), 45°, and 90° from the laser beam. The second harmonic and its satellites on the red side were observed in all directions when the electric-field vector of the incident laser light was perpendicular to the plane including the vector $\vec{k}$ of the incident laser light and the scattered light. But they were only observed in the backward direction when the electric-field direction was in that plane. The detailed behavior of the second harmonic and the satellites was reported elsewhere.[5]

The spectrum of the scattered light around the incident wavelength was dependent upon the focal position of the laser beam as shown in Fig. 1. The backscattered spectrum had two peaks above the laser intensity of $5\times10^{13}$ W/cm$^2$ when the focal point was in the ranges of 50–150 $\mu$m and 100–200 $\mu$m beneath the surface of the hydrogen and deuterium targets, respectively. One was at the red side of the incident wavelength and another was at the blue side as shown in Figs. 1(a) and 1(b). However, the backscattered spectrum showed one peak at the red side of the incident wavelength in the 5–10 Å range when the focal point was out of

TABLE I. Angular dependence of scattered light. Case A is for $\vec{E}$ (for the incident laser light) perpendicular to the plane of $\vec{k}$ (for incident and scattered light). Case B is for $\vec{E}$ in the $\vec{k}$ plane.

| Frequency | | Measurement location: Backscatter (0°) | 45° | 90° |
|---|---|---|---|---|
| $\omega_0-\Delta\omega$ | A | yes | yes | yes |
| | B | yes | yes | yes |
| $\omega_0+\Delta\omega$ | A | yes | no | no |
| | B | yes | no | no |
| $2\omega_0$ | A | yes | yes | yes |
| | B | yes | no | no |
| $2\omega_0-\Delta\omega$ | A | yes | yes | yes |
| | B | yes | no | no |

the above-mentioned region as shown in Figs. 1(c) and 1(d). And also the blue-shifted peak was not observed at the direction of 45° and 90° from the laser beam even at the laser intensity of $10^{14}$ W/cm$^2$ as shown in Fig. 2(a). The frequency shift of the blue-shifted peak from the center of the incident spectrum was 17 Å for the deuterium plasma at the laser intensity of $1\times10^{14}$ W/cm$^2$, and it increased slightly with the laser intensity. The onset time of the blue peak was near the time of the maximum intensity of the incident pulse. The maximum of its intensity appeared after 1.5 nsec from that of the incident pulse. On the other hand, the onset of the red peak was delayed 1 nsec from that of the incident pulse, and the time of the maximum intensity coincided with that of the incident pulse as shown in Fig. 2(b).

This spectrum broadening could be explained by the self-phase modulation of the incident laser light in the plasma. According to the theory[14] of a self-phase modulation, the phase shift $\phi(x, t)$ of a plane wave propagating in the $x$ direction through a medium with instantaneous nonlinearity is

$$\phi(x, t) = -\frac{\omega_0}{c}\int [n_0 + n_2 I(x, t)]\,dx\,, \tag{1}$$

where $\omega_0$ is the frequency of the incident plane wave, $c$ is the light velocity in a vacuum, $n_0$ and $n_2$ are the linear and nonlinear refractive indices, respectively, and $I(x, t) = I_0(x)F(t)$ is the time-dependent intensity with the peak intensity $I_0(x)$. The frequency change $\Delta\omega$ due to the nonlinearity is

$$\Delta\omega = -k_0\int \frac{n_2}{n_0} I_0(x)\frac{\partial F(t)}{\partial t}\,dx\,, \tag{2}$$

where $k_0$ is the wave number in a vacuum. The frequency broadening is proportional to $\int I_0(x)[\partial F(t)/\partial t]dx$. In plasmas $n_0$ and $n_2$ are functions of the density and the density change inside the propagating beam, respectively. The density change is induced by the self-focusing[17-22] of the laser beam or the modulational instability[23-26] due to the resonance absorption[27] in the region of the cutoff density.

In the case of self-focusing, the nonlinear refractive index $n_2$ is given by the following equation[20] in the equilibrium condition when the absorption is neglected and the laser field is low compared with $I_{nl}$:

$$n_2 = (1 - n_0)/I_{nl}\,, \tag{3}$$

$$I_{nl} \simeq 2\left(\frac{\epsilon_0}{\mu}\right)^{1/2}\frac{m\omega_0^2}{e^2}\kappa T_e\left(1 + \frac{T_i}{ZT_e}\right), \tag{4}$$

where $\epsilon_0$, $\mu$, $m$, $e$, $T_e$, $T_i$, and $Z$ are the dielectric constant of vacuum, the permeability, the electron

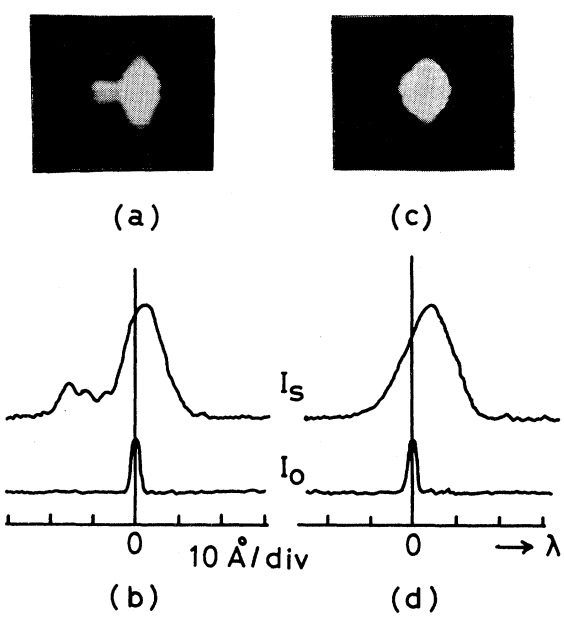


FIG. 1. Backscattered spectrum around incident wavelength: (a) spectrum when focusing position is at 100 μm inside target; (b) intensity profile of central part of (a); (c) spectrum when focusing position is at surface of target; (d) intensity profile of central part of (c).

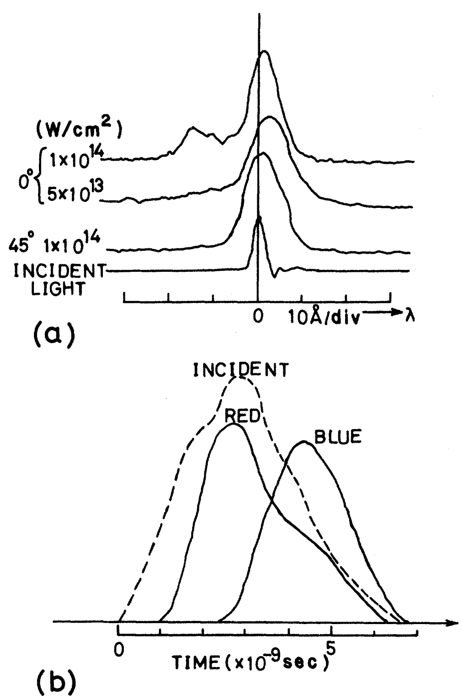


FIG. 2. (a) Power dependence and angular dependence of scattered light around incident wavelength. Whole profile of spectrum was shifted to the blue by the Doppler effect. (b) Time sequence of the backscattered light.

mass, the electron charge, the electron temperature, the ion temperature, and the ion charge number, respectively. $I_{nl}$ is the laser intensity where the electron quivering energy is comparable to the mean thermal energy of the plasma. Using Eq. (3), Eq. (2) becomes

$$\Delta\omega \simeq -k_0 \frac{\partial F(t)}{\partial t}\frac{1}{I_{nl}}\left[\int\left(\frac{I_0(x)}{n_0(x)} - I_0(x)\right)dx\right]$$

$$\simeq -k_0 \frac{\partial F(t)}{\partial t}\frac{1}{I_{nl}}\int \frac{I_0(x)}{n_0(x)}dx \quad (n_0 \ll 1)\ . \qquad (5)$$

The broadening width due to the self–phase modulation is generally symmetric to the spectrum of the incident light unless any irreversible process exists. In the case of the laser-produced plasma, the medium expands toward the laser beam. Then the whole spectrum of the broadening was shifted about 10 Å to the blue side[28] as a result of the Doppler effect due to the expanding velocity, $\approx 3 \times 10^7$ cm/sec which was reported before.[29] The center of the broadened spectrum shifted to the blue side as shown in Fig. 2(a) can be explained by this effect. Figure 2(b) shows the right sequential time response of the red and the blue shifts as indicated by Eq. (5). But the red peak can be observed below the threshold laser power of the self–phase modulation because most of the red-shifted spectrum seems to be Brillouin scattering.[7,8] As the experimental laser power is much larger than the threshold laser power for the self-focusing, which is $4\times 10^9$ W at $n_0 = 10^{-2}$ (cutoff density), the self-focusing takes place in the cutoff region and the laser intensity could be increased by more than one order to $10^{15}$ W/cm$^2$. From Eq. (5) the frequency broadening to the blue $\Delta\omega(\Delta\lambda)$ becomes $1\times 10^{12}$ rad/sec (5 Å) putting $\lambda = 1.06$ m, $n_0 = 10^{-2}$, $x = 10\ \mu$m, $\kappa T_e = 300$ eV, and $I_0 = 10^{15}$ W/cm$^2$. This estimation agreed well with the experimental values. In this case the density depression increases to 4%.

If the focal point is too shallow beneath the surface, we cannot expect enough plasma to undergo self-focusing. And if the focal point is too deep beneath the surface, the laser intensity is not sufficient to focus. This is the reason why the suitable focusing range is necessary for spectrum broadening.

As well as the self-focusing process, the modulational instability introduces the density depression in the cutoff region due to the resonance absorption by the linear conversion of the laser field in the case of the oblique incidence of the laser light. This modulational instability takes place within a certain angle of the incidence, so the self–phase modulation can be introduced in a certain focusing range. The threshold[23] of the modulational instability is as follows:

$$\left(\frac{E_0^2}{4\pi N\kappa T_e}\right)^{1/2} \geqslant \frac{\Gamma_i}{\Omega_i}\ , \qquad (6)$$

where $\Gamma_i$ and $\Omega_i$ are the damping rate and the frequency of the ion acoustic wave, $E_0^2/4\pi$ and $N\kappa T_e$ are the energy density of the laser beam and the electron thermal energy, respectively. The threshold laser intensity is $6\times 10^{13}$ W/cm$^2$ in our experimental condition of $\kappa T_e = 300$ eV and $N = 10^{21}$ cm$^{-3}$. The results indicate that the modulational instability is also responsible for the spectrum broadening. We believe that these two treatments show the different approaches to the process of cavity formation in the plasma. A more detailed experiment will clarify the contribution of these mechanisms.


[1]N. G. Basov, A. R. Zaritskii, S. D. Zakharov, O. N. Krokhin, P. G. Kryukov, Yu. A. Matveets, Yu. V. Senatskii, and A. I. Fedosimov, Kvant. Elektron. 5, 63 (1973) [Sov. J. Quant. Electron. 2, 439 (1973)].

[2]J. L. Bobin, M. Decroisette, B. Meyer, and Y. Vitel, Phys. Rev. Lett. 30, 594 (1973).

[3]L. M. Goldman, J. Soures, and M. J. Lubin, Phys. Rev. Lett. 31, 1184 (1973).

[4]M. Decroisette, B. Meyer, and Y. Vitel, Phys. Lett. 45A, 443 (1973).

[5]C. Yamanaka, T. Yamanaka, T. Sasaki, J. Mizui, and H. B. Kang, Phys. Rev. Lett. 32, 1038 (1974).

[6]P. Lee, D. V. Giovanielli, R. P. Godwin, and G. H. MaCall, Appl. Phys. Lett. 24, 406 (1974).

[7]B. H. Ripin, J. M. MacMahon, E. A. McLean, W. M. Manheimer, and J. P. Stamper, Phys. Rev. Lett. 33, 634 (1974).

[8]For reviews of work at several laboratories see the contributions of C. Yamanaka, J. L. Bobin, M. Lubin, R. Sigel, and J. Stamper, in *Laser Interaction and Related Plasma Phenomena*, edited by H. Schwarz and H. Hora (Plenum, New York, 1974), Vol. 3.

[9]D. W. Forslund, J. M. Kindel, and E. L. Lindmann, Phys. Rev. Lett. 30, 739 (1973).

[10]M. N. Rosenbluth, R. B. White, and C. S. Liu, Phys. Rev. Lett. 31, 1190 (1973).

[11]H. H. Klein, W. M. Manheimer, and E. Ott, Phys. Rev. Lett. 31, 1187 (1973).

[12]W. L. Kruer, K. G. Estabrook, and K. H. Sinz, Nucl. Fusion 13, 952 (1973).

[13]C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974).

[14]S. A. Akhmanov, R. V. Khokhlov, and A. P. Sukhorukov, in *Laser Handbook*, edited by F. T. Arecchi and E. O. Schulz-Dubois (North-Holland, Amsterdam, 1972), Vol. 2, p. 1209.

[15]E. Yablonovitch, Phys. Rev. Lett. 32, 1101 (1974).
[16]C. Yamanaka, T. Yamanaka, T. Sasaki, J. Mizui, K. Yoshida, N. Yamaguchi, K. Suzuki, K. Tanaka, and T. Tschudi, Japan. J. Appl. Phys. Suppl. 14, 87 (1975).
[17]H. Hora, Phys. Fluids 12, 182 (1969).
[18]J. Lindl and P. K. Kaw, Phys. Fluids 14, 371 (1971).
[19]A. J. Palmer, Phys. Fluids 14, 2714 (1971).
[20]J. W. Shearer and J. L. Eddleman, Phys. Fluids 16, 1753 (1973).
[21]L. C. Johnson and T. K. Chu, Phys. Rev. Lett. 32, 517 (1974).
[22]D. R. Cohn, G. J. Raff, R. L. Brooks, N. G. Leter, and W. Halverson, Phys. Lett. 49A, 95 (1974).
[23]H. Ikezi, K. Nishikawa, and K. Mima, J. Phys. Soc. Jpn. 37, 766 (1974).
[24]C. E. Max, J. Arons, and A. B. Langdon, Phys. Rev. Lett. 33, 209 (1974).
[25]E. Ott, W. M. Manheimer, and H. H. Klein, Phys. Fluids 17, 1757 (1974).
[26]A. B. Langdon and B. Lasinski (unpublished).
[27]V. L. Ginzburg, *The Propagation of Electromagnetic Waves in Plasma* (Pergamon, New York, 1970), p. 260.
[28]C. Yamanaka *et al.*, IAEA Fifth Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, 1974, paper No. F3-5; Proceedings of the Fuji Seminar on Laser Interaction with Plasma, Review of Laser Engineering 2, No. 3 (1974).
[29]C. Yamanaka, T. Yamanaka, T. Sasaki, K. Yoshida, and M. Waki, Phys. Rev. A 6, 2335 (1972).

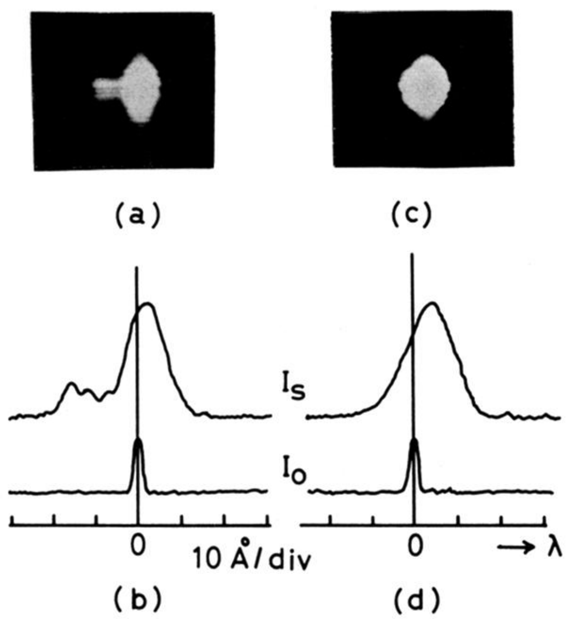


FIG. 1. Backscattered spectrum around incident wavelength: (a) spectrum when focusing position is at 100 $\mu$m inside target; (b) intensity profile of central part of (a); (c) spectrum when focusing position is at surface of target; (d) intensity profile of central part of (c).