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Observation of Energy Transfer between Frequency-Mismatched Laser Beams in a Large-Scale Plasma

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The observation of energy transfer between two frequency-mismatched laser beams crossing in a low-density, large-scale plasma is described. The beams cross at an angle of 53° from parallel, with the average intensity in the blue beam equal to 2×10^{15} W/cm^2. A redshifted probe beam is amplified by interaction with the blue beam and a stimulated ion acoustic wave. Significant energy is transferred to the probe when the difference in the frequencies of the two beams is comparable to the frequency of the acoustic wave. As much as 52% of the pump energy is transferred to the probe.

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The interaction of two intersecting laser beams is a rich topic for the study of nonlinear wave processes in plasmas. Early theoretical work [1] predicted that electron plasma waves could be generated by two crossing laser beams with frequencies separated by the frequency of the resonant plasma wave. This was soon confirmed experimentally in a plasma jet illuminated with dye lasers [2]. While the excitation of electron plasma waves with frequency-mismatched lasers has found application in particle accelerator [3–5], the same principles have also been applied to the excitation of ion acoustic waves in microwave experiments [6,7] and to the creation of stationary density perturbations in laser experiments [8]. Experiments using intersecting microwave beams with mismatched frequencies have demonstrated many of the fundamental properties of resonant three-wave and four-wave interactions in plasmas and have successfully produced a phase-conjugated electromagnetic wave [7]. Recently, interest has increased in the interaction of multiple, frequency-mismatched, laser beams and ion acoustic waves because such conditions occur in inertial confinement fusion (ICF) experiments. Marsh, Joshi, and McKinstrie [9] have demonstrated with CO$_2$ lasers that crossing beams of identical frequency can cause oscillations in the beam intensities on the time scale of the ion wave frequency by driving ion waves nonresonantly. Kruer *et al.* [10] have shown theoretically that the intensity and frequency separation of the beams in the baseline proposal for the National Ignition Facility (NIF) [11] are such that ion waves will be driven resonantly, causing a significant energy transfer between beams.

In this Letter we report the measurement of the amplification of a laser beam in a plasma by interaction with a second frequency shifted beam and a stimulated ion acoustic wave. We observe a maximum amplification of the long wavelength (probe) laser beam of 2.8 when the frequency difference $\Delta\omega$ of the two beams is in the vicinity of the ion acoustic resonance ($\Delta\omega = c_s|\Delta\mathbf{k}|$, where c_s is the acoustic speed and $\Delta\mathbf{k}$ the difference in wave vectors between the two beams). The amplification is steady state in that it persists for many ($\sim 10^3$) ion acoustic periods, and is resonant in that it is largest at a particular frequency difference. Further, in the large, mixed species plasmas that are used in these experiments, we find that the amplification of the probe beam is independent of its intensity up to a maximum average scattered intensity of 1.0×10^{15} W/cm^2. This indicates that the ion response n_1 remains unsaturated up to $n_1/n_0 \sim 1\%$.

The experiments were performed in an approximately spherical plasma [12] produced by eight $f/4.3$, $\lambda = 351$ nm beams of the Nova laser facility. These heater beams have a 1 ns, square pulse shape with a total power of 20 TW (2.5 TW each beam) and pass through a 1 atm C$_5$H$_{12}$ gas contained in a 500 nm thick spherical polyimide shell with radius $r_0 = 1.3$ mm. Each heater beam is centered at the target center with a converging focus. The beam spot size at the target center is approximately equal to the target diameter allowing spatially uniform heating. Two-dimensional numerical simulations using LASNEX [13] indicate that after $t = 400$ ps a plasma is formed which is stationary ($v \leq 0.15c_s$), with a uniform density plateau ($\Delta n/n \leq 0.1$) in the region $r = 250$ to 900 μm. By $t = 1.4$ ns, the outer radius of the density plateau is reduced to approximately $r = 450$ μm by an incoming shock wave created by the ablation of the polyimide shell. The plasma parameters calculated by the simulation, and in agreement with measurements [12], are a density of $n_e = 10^{21}$ cm^{-3} ($0.1n_{\rm cr}$ where $n_{\rm cr}$ is the critical density for $\lambda = 351$ nm light) and electron temperature $T_e = 3.0$ keV. The high intensity pump beam and low intensity probe beam are also $f/4.3$ and $\lambda_0 = 351$ nm, and are aligned to cross at $r = 400$ μm near the best focus for both beams. As a result, the interaction between the two electromagnetic waves and an ion acoustic wave occurs in the plateau region of the plasma as shown in Fig. 1. The interaction beams have random phase plates (RPPs) which smooth the intensity profile and limit the spot size to 177 μm

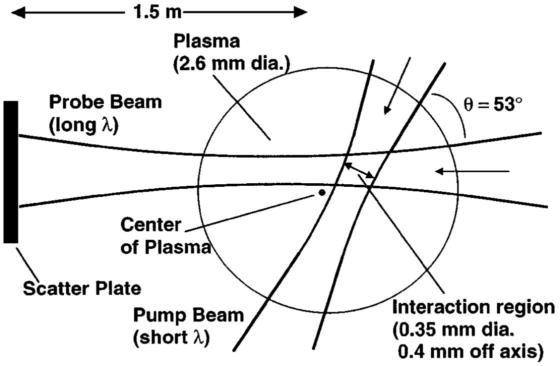

FIG. 1. Experimental configuration showing an approximately spherical plasma and two interaction beams crossing in a homogeneous region off the plasma center. The two beams are detuned by $\Delta\lambda = 0.0$ to 0.73 nm to excite the ion acoustic resonance. The transmitted power vs time of the long wavelength probe beam is measured.

FWHM (345 μm between first Airy minima) and the peak pump intensity to 1×10^{16} W/cm^2 (2×10^{15} W/cm^2 average inside the Airy minima) in vacuum. The beams have their polarizations aligned within 25° of parallel. The simulations indicate that the presence of the focused probe beam increases the temperature only slightly ($\sim$6%) in the vicinity of best focus. The probe beam is adjusted to have a wavelength slightly longer than that of the pump with the wavelength separation ranging between 0.0 and 0.73 nm. The probe beam has a square pulse shape lasting 2.0 ns which begins at the same time as the heaters ($t = 0$). The pump beam has a 1.0 ns square pulse shape that is delayed 0.4 ns so that the plasma in the interaction region is relatively homogeneous during the interaction period. The transmitted power of the probe beam is collected by a fused silica plate 1.5 m from the target, which is roughened to scatter the light over a broad angle [14]. This scattered light is imaged onto a fast photodiode and a gated optical imager. The photodiode is calibrated to provide a histogram of the probe beam power which is transmitted through the plasma and onto the scatter plate. The imager captures a 2D image of the light on the scatter plate during the 0.6 ns period when all beams are on and provides a measure of the directionality of the transmitted power during the period of the interaction.

The interaction of the beams creates an ion wave in the plasma that scatters energy from the pump so that it propagates parallel to the probe beam. The ion wave forms in response to the interference of the two beams, which generates a ponderomotive force that is periodic in space and proportional to the product of the amplitude of the two beams. The initial ion wave amplitude is then proportional to the probe beam incident amplitude. As a result, the energy scattered from the pump is also proportional to the probe intensity, and an amplification of the probe results. This amplification is defined to be the ratio of the transmitted power measured in an experiment with the pump beam to that measured in an essentially identical experiment without the pump beam. The transmitted power wave forms with and without a pump beam are shown in Fig. 2, for the case of $\Delta\lambda = 0.43$ nm, and a normalized probe intensity of $I_{\mathrm{probe}}/I_{\mathrm{pump}} = 0.06$. The total transmitted energy without a pump beam is (49 ± 7)% of the indicent energy which is in agreement with a calculation of inverse bremsstrahlung absorption and refraction by the plasma [14]. This transmission is reproducible within $\pm 15\%$. The shape of the wave form in the pump-off case in Fig. 2 shows that the transmission first increases in time when the plasma temperature is increasing and then decreases in time after the heaters turn off at 1.0 ns and the plasma radiatively cools. Comparing the "pump-on" wave form in Fig. 2 to the "pump-off" shows an increase in the probe's transmitted power during the time the pump beam is on ($0.4 \leq t \leq 1.4$ ns). The pump-on wave form is corrected to account for a small variation in the energy of the probe beam between the two shots. The transmitted probe power is nearly the same in the two experiments before the arrival of the pump. After $t = 0.4$ ns, the transmitted probe power rises in about 150 ps to nearly 1.7 times the level observed without the pump indicating amplification of the probe by the pump. After the pump turns off the probe power drops rapidly to equal the value observed without the pump. The amplification is determined from the ratio of the two traces and is found to vary between 1.6 and 1.8 during the 1 ns duration of the pump pulse. The average amplification A is determined by averaging over the 1 ns that the pump is on plus an additional 0.3 ns to include signal delayed by the response of the detector, and is found to be 1.7 in this case.

The amplification observed in Fig. 2 can be explained by scattering from an ion wave produced by the beating of the incident and pump beams. Resonant interaction requires that this ion wave have a wave vector $\mathbf{k}_{ia}$ which satisfies wave vector matching $\mathbf{k}_{ia} = \Delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$, where $\mathbf{k}_1$ is the wave vector of the pump and $\mathbf{k}_2$ is the wave vector of the probe. An ion wave with this wave vector will cause energy to be scattered in the direction

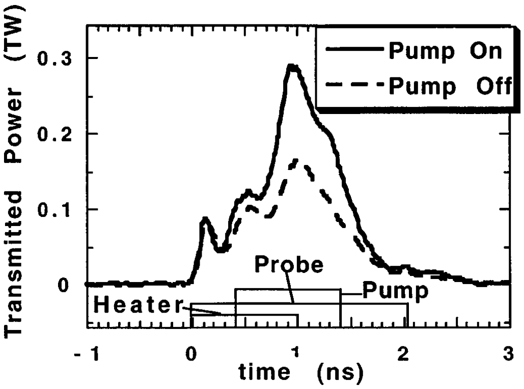

FIG. 2. Measurement of the probe beam power transmitted through the plasma for $\Delta\lambda = 0.45$ nm and $I_{\mathrm{probe}}/I_{\mathrm{pump}} = 0.06$. In the pump-on case a 2×10^{15} W/cm^2 pump beam intersects the probe between 0.4 and 1.4 ns causing the probe to be amplified by a factor of 1.7 above the pump-off case.

of the probe beam. Experimental evidence of the wave number matching is obtained from the 2D image of the transmitted probe beam on the scatter plate. To eliminate the spatial structure in the transmitted beam that is due to the inhomogeneity of the incident beam the 2D image is averaged over the azimuthal angle to obtain a measure of the beam intensity as a function of the angle from the beam axis as shown in Fig. 3. The amplified beam has an azimuthally averaged angular profile which is largest inside the $f/4.3$ cone of the incident beam ($\pm 6.6°$) and similar to the profile of the probe beam obtained when it is transmitted through the plasma with the pump beam off. The fact that the intensity of the amplified beam falls rapidly outside of the $f/4.3$ cone (FWHM $= 12°$) indicates that the scattering is caused by ion waves with wave numbers near the matched value $\Delta\mathbf{k}$. The profile of the unamplified beam intensity outside the cone is similar to that for the amplified case, indicating that in these experiments the observed spreading of the beam is not caused by the two beam interaction but rather by refraction and scattering from the unperturbed plasma.

Experiments to determine the average energy amplification as a function of the frequency mismatch were performed for six different wavelength separations between 0.0 and 0.73 nm with the normalized probe intensity $I_{\text{probe}}/I_{\text{pump}}$ between 0.06 and 0.32. The amplifications for these cases are shown in Fig. 4 and exhibit significant gain only when there is a frequency separation between the two beams. The largest amplification is 2.8 when the wavelength separation is $\Delta\lambda = 0.58$ nm. The resonant ion wave frequency is calculated as $\omega_{ia} = c_s|\Delta\mathbf{k}|$ and the half-width of the resonance as $\nu_i/2$, where ν_i is the intensity damping rate of the ion wave [10,15,16]. The predicted position of the resonance is $\Delta\lambda = 0.46$ nm with a width of ± 0.04 nm for the plasma parameters found in the vicinity of the focused beam. This indicates that the observed maximum measured gain is near the ion wave resonance, but may be Doppler shifted by weak plasma flows produced by heater beam and target inhomogeneities that are not included in the 2D simulations. The observation of a maximum amplification near the ion wave frequency combined with the observation of reduced amplification at both larger and smaller frequencies ($\Delta\lambda =$ 0.3 and 0.73 nm) indicates that resonant excitation of an ion acoustic wave is necessary for amplification.

To compare with theory, we adopt the model of a steady state, convective instability which leads to the amplification A of the probe by a gain G such that $G = \ln(A)$. This interpretation is applied in this case because the beam crossing angle is less then 90° (forward scattering) so that the instability cannot be absolute, and because the duration of the experiment (1 ns) is long compared to the time to reach a steady state, which in the strong damping limit is the ion wave damping time (~ 1.0 ps). In this limit the gain exponent in a homogeneous plasma scales as $nLI_{\text{pump}}/T_e\nu_i$ [10], where L is the length of the interaction region. The effect of the pump wave is to scatter its power in the direction of the probe wave such that the transmitted probe wave amplitude is proportional to the exponential of G. The measured amplification is also affected by small scale inhomogeneities both in the incident beam and in the plasma, for which accurate characterization and analysis is outside the scope of this Letter and is presented elsewhere [10,17]. These inhomogeneities make a calculation of the gain of the instability based on the simple model of coherent laser beams in uniform plasmas an overestimate of the actual gain. In fact, under the conditions of this experiment, the ideal model indicates a gain of $G \sim 20$ when the probe beam is perfectly tuned [10,15,16], while the maximum observed gain is $G = 1.0$. These values can be substantially reconciled by considering calculations including the two types of inhomogeneities and recognizing that the set of discrete measurements in Fig. 4 may miss the exact resonance and underestimate the peak gain. First, because the shape of the resonance is $G \propto 1/[1 + 4(\Delta\omega/\nu_i)^2]$ [10], a frequency detuning of

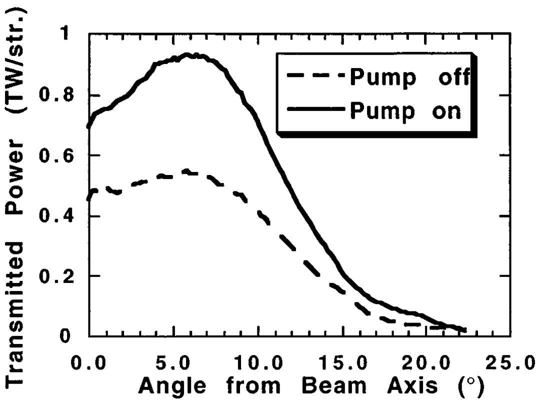

FIG. 3. The angular distribution of the transmitted power of the probe beam is shown for the experiment in Fig. 2. The similar profiles in the two cases indicate that the amplified light is collimated and coincident with incident laser beam.

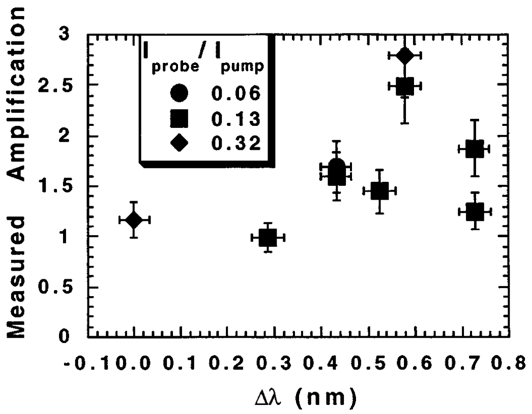

FIG. 4. A series of experiments measured the amplification of the probe beam as a function of the wavelength separation of the two beams as shown. The amplification is greatest when the frequency separation is in the vicinity of the unshifted ion wave resonance, $\Delta\lambda = 0.45 \pm 0.04$ nm.

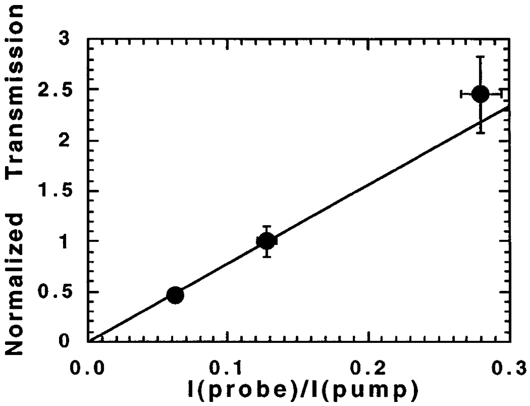

FIG. 5. The measured transmitted power is shown to be proportional to the probe intensity over the range of $I_{\text{probe}}/I_{\text{pump}} = 0.06$ to 0.32 using data obtained at disparate separation frequencies by normalizing to the amplification measured with $I_{\text{probe}}/I_{\text{pump}} = 0.13$.

as little as $\Delta\omega = \nu_i$ (or $\Delta\omega \sim 0.2\omega_{ia}$) can decrease G locally by a factor of 5. This frequency detuning can result from Doppler shifting by small amplitude velocity fluctuations in the plasma or by inhomogeneous steady flows, both of which are produced by structure in the laser beam and target. For example, a velocity fluctuation as small as $\delta v/c_s \sim 0.2$ rms in the interaction region reduces the gain at resonance by a factor of 3 by Doppler shifting the resonance to different frequencies in different regions of space as discussed in Ref. [10]. As shown in Ref. [17], the combination of a spectrum of velocity fluctuations and linear gradients lead to reductions in G by a factor greater than 5. Second, the gain of two intersecting beams with RPPs is substantially affected by the overlap of the spatial profiles of the two beams. Similarly, interaction with other waves, such as those produced by stimulated Raman scattering, may further reduce the gain.

To investigate the dependence of the scattered power on the incident probe power, experiments were performed at both high and low scattered power at the frequency separation of maximum observed gain, $\Delta\lambda = 0.58$ nm. The high probe intensity was $I_{\text{probe}}/I_{\text{pump}} = 0.32$, and the low intensity was $I_{\text{probe}}/I_{\text{pump}} = 0.13$. The measured amplification of the probe at high intensity was 2.8 ± 0.42 and at low intensity was 2.5 ± 0.37, indicating that the gain is nearly independent of the probe intensity up to this level and that the ion wave is unsaturated. Under these conditions a maximum of (52 ± 12)% of the pump energy was transferred to the probe. This large an energy transfer should lead to a 23% reduction in the spatially averaged amplification due to pump depletion. This effect was not observed but it is comparable to the combined shot to shot variation in the transmission coefficient (±15%) and amplification in these measurements. The amplitude of the ion wave is estimated by considering the amplitude necessary to scatter 1/2 the probe energy in a volume of dimension L, according to $n_1/n_0 = 8\pi(2)^{1/2}(\omega/\omega_p)^2(L/\lambda_0)$. A lower limit to the maximum ion wave amplitude observed in this experiment is $n_1/n_0 = 1\%$, assuming the scattering occurs uniformly over the region in which the beams intersect ($L = 345\ \mu$m). The actual wave amplitude may be higher if inhomogeneities localize the scatter to a region smaller than L. The data in Fig. 4 also indicate a linear dependence of transmitted power on the incident probe power. To show this the transmitted power measured with values of $I_{\text{probe}}/I_{\text{pump}}$ different than 0.13 is normalized to the transmitted power measured at the same $\Delta\lambda$ but with $I_{\text{probe}}/I_{\text{pump}} = 0.13$. These normalized values are plotted in Fig. 5 and show that the transmitted power is proportional to the incident probe power over a range of 5:1, in good agreement with Ref. [10].

In conclusion, we have reported the first observation of energy transfer between frequency-mismatched laser beams and a stimulated ion acoustic wave.

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