Frequency upshift in the interaction of a high power microwave with an inhomogeneous plasma

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A frequency upshift of several megahertz is observed in the interaction of a high power microwave (f_0=9 GHz) with an unmagnetized inhomogeneous argon plasma. The dependencies of the frequency upshift on the plasma density, incident microwave power and space have been investigated. The induced frequency upshift is considered to be related to a rapidly expanding plasma created by the ponderomotive force of a strong standing wave. [S1063-651X(96)10011-8]

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The frequency shift of electromagnetic radiation is a very important phenomenon in laser (microwave)-plasma interaction because it reflects the coupling processes of the electromagnetic radiation and plasma. Such as within the interaction of a laser (microwave) with a plasma, a pump wave may couple to a plasma wave and an electromagnetic wave [stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS)] [1–5], or the pump wave may decay into two plasma waves (parametric decay, oscillating two-stream instability) [6–8]. These phenomena are significantly concerned with laser fusion applications, since the process can either decrease the amount of energy absorbed or decrease the implosion symmetry. Generally, when one of these instabilities occurs, the frequency downshift (redshift) can be observed because the pump wave gives its energy to plasma wave(s). However, the frequency upshift (blueshift) has also been observed in the laser-plasma interaction [9]. And, because the frequency upshift has the potentiality to develop different radiation sources, it has been studied extensively in laser-plasma interaction recently [10–12]. A dramatic frequency self-upshifted of an ionizing laser pulse has been observed as a result of the time-dependent decrease in the plasma's refractive index [13] , and the use of laser-produced ionization fronts has upshifted a microwave radiation from 30 GHz to over 150 GHz successfully [14].

In this paper, the first observation of the frequency upshift in the microwave-plasma interaction without any ionization front or time-dependent change in the plasma density is reported. When a high power electromagnetic wave (f_0=9 GHz, $P_i \leqslant 250$ kW, $\tau \simeq 1-3$ μs) is launched into an unmagnetized underdense argon plasma (plasma density is $n_0 \leqslant 1\times10^{12}$ cm^{-3}, corresponding ion plasma frequency is ω_i=33.2 MHz), the frequency upshift around 1–2 MHz and some other higher frequency components from 3 to 7 MHz have been observed. The clear dependencies of the frequency upshift and frequency components on the plasma density, incident power, and spatial position have been demonstrated in our experiments. Because neither an ionization front nor a further ionization has been observed in the plasma, this phenomenon is related to a rapidly expanding plasma which is created by the ponderomotive force arising from a strong standing wave. The incident microwave is partially reflected by a moving plasma and the frequency is upshifted due to the Doppler effect. This phenomenon is related to laser fusion directly and has potential applications in plasma based laser driven accelerators, tunable electromagnetic radiation sources.

In the present experiments, a cylindrical, azimuthally symmetric, unmagnetized argon plasma column was created in a vacuum chamber (32 cm in diameter, 60 cm in length). The outside surface of the vacuum chamber is covered with a large number of multidipole permanent magnets (cusp spacing $\simeq$ 4 cm) (see Fig. 1). The plasma is produced by a pulsed discharge between two directly heated LaB_6 cathodes and the chamber wall (grounded). After evacuating the chamber with a base pressure less than $P_0=2\times10^{-6}$ Torr, argon gas is fed with a typical pressure P_{Ar}=2.0$\times10^{-3}$ Torr. A typical plasma discharge pulse duration is t_w=2 ms with a repetition rate of 10 Hz. The typical plasma parameters are the following: the maximum electron density is $n_0 \leqslant 1.2\times10^{12}$ cm^{-3}, the electron temperature is $T_e \simeq 3-5$ eV, the estimated electron-ion collision frequency is $\nu_{ei} \simeq 4.5\times10^6$ sec^{-1}, and the ion neutral collision frequency is $\nu_{in} \simeq 10^5$ sec^{-1}. Within the experimental region of concern, there is a parabolic density profile $n_0 = n_{max}[1-(z-z_0)^2/L_z^2]$, here L_z is the half-width of the density profile along the chamber axis, n_{max} is the maximum plasma density during the experiments and z_0 is the position of the maximum density layer, while in the radial direction there is a quite weaker linear density gradient. In the present experiments, the L_z is around 25 cm and L_r, the gradient length in the radial direction, is around 300 cm. A pulsed microwave (f_0=9 GHz) with a rise time of $\tau_r \approx$ 100 ns, the maximum power of 250 kW and a typical pulse width of $\tau \simeq 1$ μs is irradiated synchronously with the discharge pulse through a rectangular horn antenna (aperture area$=13.5\times10.5$ cm^2) from the lower density side of the plasma along the chamber axis (z direction). The ratio of the electric field energy to the plasma energy is $\varepsilon_0 E_0^2/4n_c K T_e \approx 0.1$, where E_0 is the amplitude of the electric field of the incident microwave, $n_c = 1.0\times10^{12}$ cm^{-3} is the plasma density of critical layer and K is Boltzmann's constant. Because the pulse width of the microwave is shorter than the ionization or plasma heating time, and, furthermore, the increment of the plasma density has not been observed when the incident microwave pulse is interacting with the plasma, the effects of the ionization can be safely neglected. The perturbations of the plasma density and rf signals in the plasma are detected by a plane Langmuir probe and a cylindrical probe, respectively.

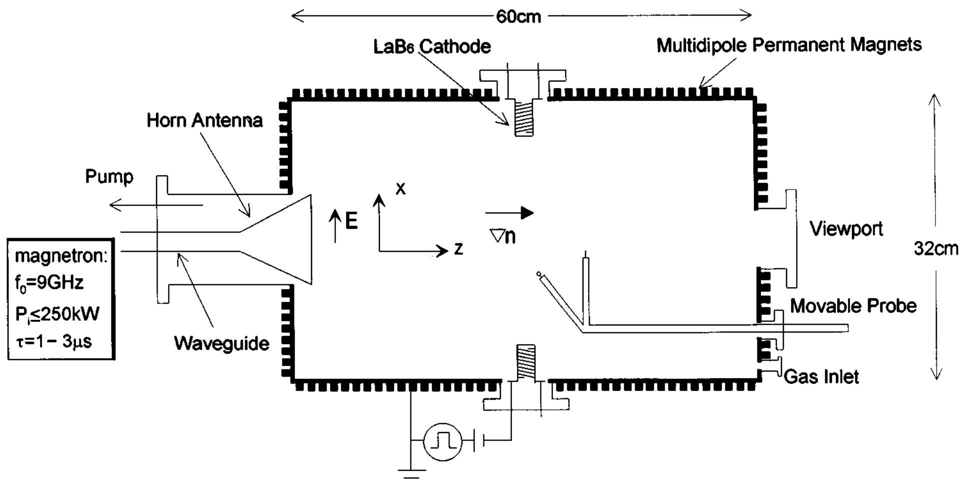

FIG. 1. Experimental setup. Typical parameters are $f_0 = 9$ GHz, $P_i \leqslant 250$ kW, $\tau \simeq 1 \sim 3$ μs, $\varepsilon_0 E_0^2/4n_{\rm cr}KT_e \approx 0.1$.

The spectra of the rf signals are observed along the axis of the chamber. The typical examples of the frequency spectra of the microwave pulses with and without plasma in the chamber at $z = 21$ cm are shown in Fig. 2. The dashed and solid lines represent the spectra of the rf signals in the vacuum and plasma, respectively. The incident microwave power P_i is 250 kW, the plasma density is $n_0 \approx 0.6 n_c$ at $z = 21$ cm, and there is no critical layer in the chamber. The frequency upshift around 1.5 MHz is clearly demonstrated. As shown in Fig. 2, besides the frequency upshift, some higher frequency components such as +3.5, +6.5 and +7 MHz have also been observed. But on the lower frequency side, the frequency component has not been observed. Here f_1 and f_m (m=2, 3, 4) represent the upshift from the center frequency ($f_0 =$ 9 GHz) and the components in the upper frequency range, respectively. From Fig. 2 a spectral broadening can also be seen besides the frequency upshift and the creation of higher frequency components. Because a rectangular microwave pulse is used in our experiments, each pulse segment experiences a slightly different frequency shift and the scan time of the spectrum analyzer is 50 seconds, each recorded spectrum represents an average sampling spectrum of 500 pulses. This is one of the reasons why continuous spectral broadening has been observed in our experiments.

Figure 3(a) shows the dependence of the frequency on the plasma density. It can be seen that when the plasma density n_0 is increased from $0.06 n_c$ ($n_c = 1 \times 10^{12}$ cm^{-3}) to $0.9 n_c$, the upshifted frequency increases slightly around 1.0 MHz while the higher frequency components increase proportionally to the plasma density. The frequency of f_2 shifts from 1.3 MHz to 4.5 MHz, and the frequency of f_3 shifts from 4.0 MHz to 6.5 MHz.

The relationship between the upper frequency components and the incident power is presented in Fig. 3(b). We found that as the incident power of the microwave P_i is increased from 0 to 250 kW, the frequency upshift (f_1) and the higher frequency components can only be observed when P_i is higher than 7.9 kW, i.e., the threshold power for the present phenomenon is around 7.9 kW.

The spatial dependence of the spectrum has been investigated when the plasma density is $n_0 = 0.5 n_c$ at $z = 11$ cm as shown in Fig. 4. It can be seen that the upshifted frequency and frequency components are quite sensitive to where they are observed.

The evidence of a local plasma flow or expansion is suspected. Therefore, the velocity of the plasma flow has also been investigated during the experiments. The examples of the plasma density perturbation are shown in Fig. 5(a) and the phase delay versus probe separation is plotted in Fig. 5(b). The numbers 1 and 2 represent the first and second peaks of the density perturbation after the turn off of the microwave pulse. It can be seen from Fig. 5(b) that the plasma expands towards two directions from $z \approx 21$ cm with a velocity of $v \approx 1.0 \times 10^6$ cm/s in these examples. This velocity is almost four times of $c_s \approx 2.5 \times 10^5$ cm/s, the velocity of ion acoustic wave in our case. In the experiments, the

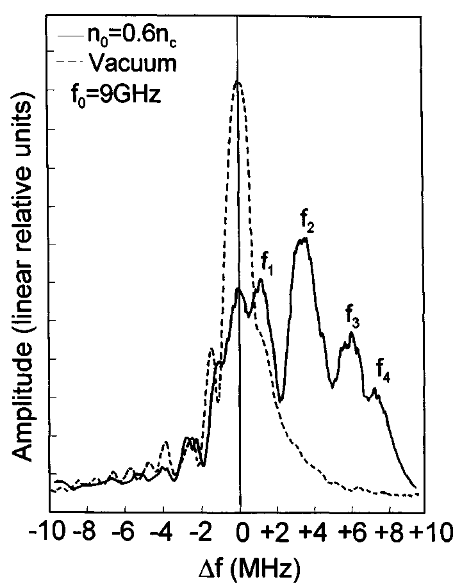

FIG. 2. Frequency spectra of rf signals observed inside the chamber. Dashed line represents the spectrum observed without plasma, solid line represents the spectrum with plasma. $n_0 \approx 0.6 n_c$, $n_c = 1 \times 10^{12}$ cm^{-3}, $P_i = 250$ kW, $\tau \simeq 1$ μs, $P_{\rm Ar} = 2 \times 10^{-3}$ Torr, $z = 21$ cm. Here f_1, f_2, and f_3 are denoted for convenience.

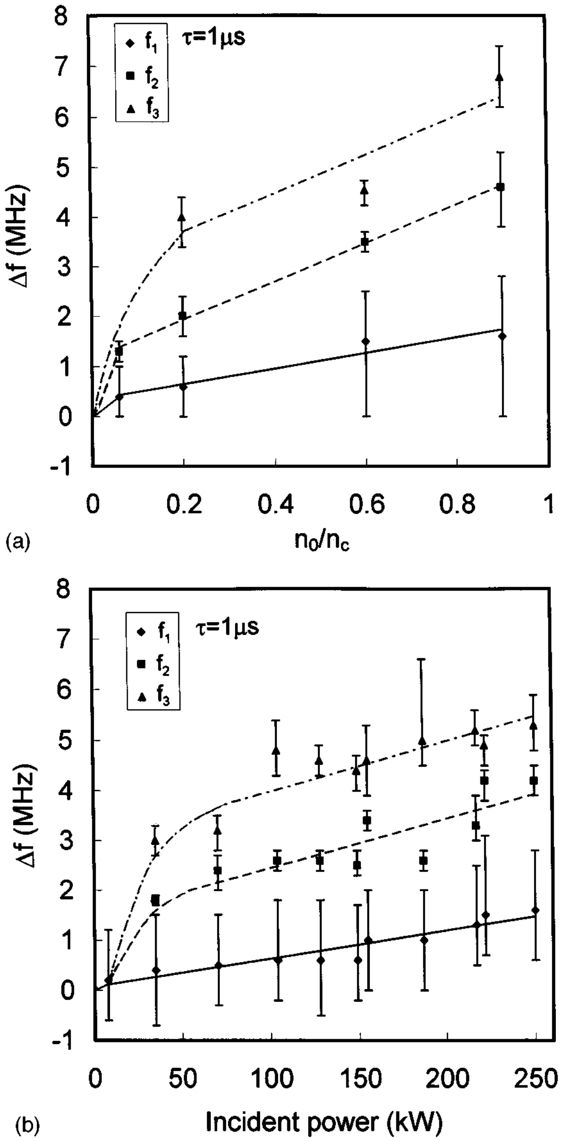

FIG. 3. (a) Frequency upshift and higher frequency components vs plasma density. $0.06n_c \leqslant n_0 \leqslant 0.9n_c$, $P_i = 250$ kW, $\tau \simeq 1$ μs, $P_{\mathrm{Ar}} = 2\times10^{-3}$ Torr, $z = 21$ cm. (b) Frequency upshift and higher components vs incident power. $P_i = 7.9$ kW $\sim$ 250 kW, $\tau \simeq 1$ μs, $n_0 \approx 0.6n_c$, $P_{\mathrm{Ar}} = 2\times10^{-3}$ Torr, $z = 21$ cm.

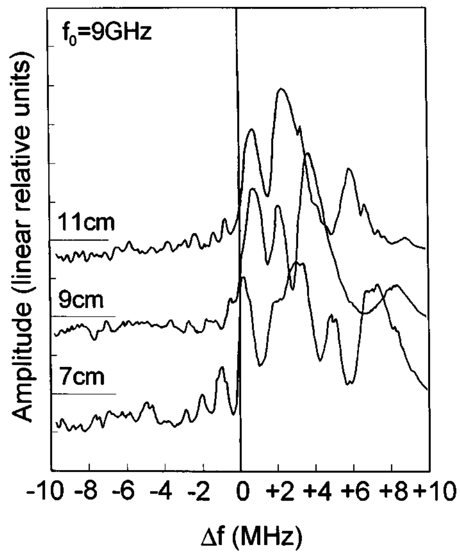

FIG. 4. Spectrum change vs position. $n_0 \approx 0.5n_c$ at $z = 11$ cm, $P_i = 250$ kW, $\tau \simeq 1$ μs, $P_{Ar} = 2\times10^{-3}$ Torr.

change of the effective temperature has not been observed, the density depletion length of 4 cm is estimated, and the maximum density depletion of 20% has been observed after the turn off of the incident microwave pulse. As the estimates of the density front speed are made after the turn off of the incident microwave, the obtained velocity may be smaller than that during the incident microwave pulse. The electric field intensity $|E|^2$ has a standing wave structure in space because of a strong reflection from the end wall of the chamber. In the present case, there is a high peak of the electric field at $z \approx 21$ cm as shown by the dotted line in Fig. 5(b). Because of this strong electric field the plasma is pushed away from this point towards two directions.

In a laser produced plasma, an upshifted scattered light can be resulted from the hydrodynamic expansion of the plasma due to the ablation of the target [15]. Nevertheless, the ablation of the target is impossible in our case. The parametric decay can generate frequency sidebands and broadening, and the upshifted frequency components have been observed when the oscillating two-stream instability occurs [8]. However, the threshold for the parametric decay is the following [1]: $(v_{os}/v_e)^2 \geqslant 12/k_0 L$, which results in a threshold incident power of 100 kW, where $v_e = (T_e/m_e)^{1/2}$ is the electron thermal velocity, $v_{os} = eE_0/m_e\omega_0$ is the electron quiver velocity. L is the scale length and k_0 is the wave number of the incident microwave. But, the threshold pump power of the upshift is quite low ($P_i \geqslant 7.9$ kW) in the present experiments as shown in Fig. 3(b). We also noted that this phenomenon could occur in the density range of $0.2n_c$ to $0.9n_c$ not only around $(1/4)n_c$. The parametric up conversion has been predicated theoretically [16]. However, a pump of large amplitude Langmuir wave is supposed to be necessary in that case. Recently, a frequency upshift about 1.5 MHz has been observed [17] when a microwave pulse interacts with a rapidly growing plasma in which there is a temporal growing plasma. But there is no ionization front or temporal plasma density growing during the interaction of the microwave and plasma in the present experiments. Consequently, neither the theories in Refs. [10–12] nor the parametric decay and two-stream instability can explain the phenomena in our experiments.

As mentioned above, it is obvious that the upshifted frequency and higher frequency components observed in our experiments depend not only on the incident power of the microwave and the plasma density but also on the spatial position. Another thing which should be also noted in the present experiments is that the plasma flow propagates at a very high speed. Because the strong standing wave is built in the chamber, the plasma is expanded at the very high speed by the pondermotive force of this standing wave. Consequently, the incident microwave wave is reflected by the moving plasma and the frequency is upshifted due to the Doppler effect. The ponderomotive force acting on the plasma can be written as

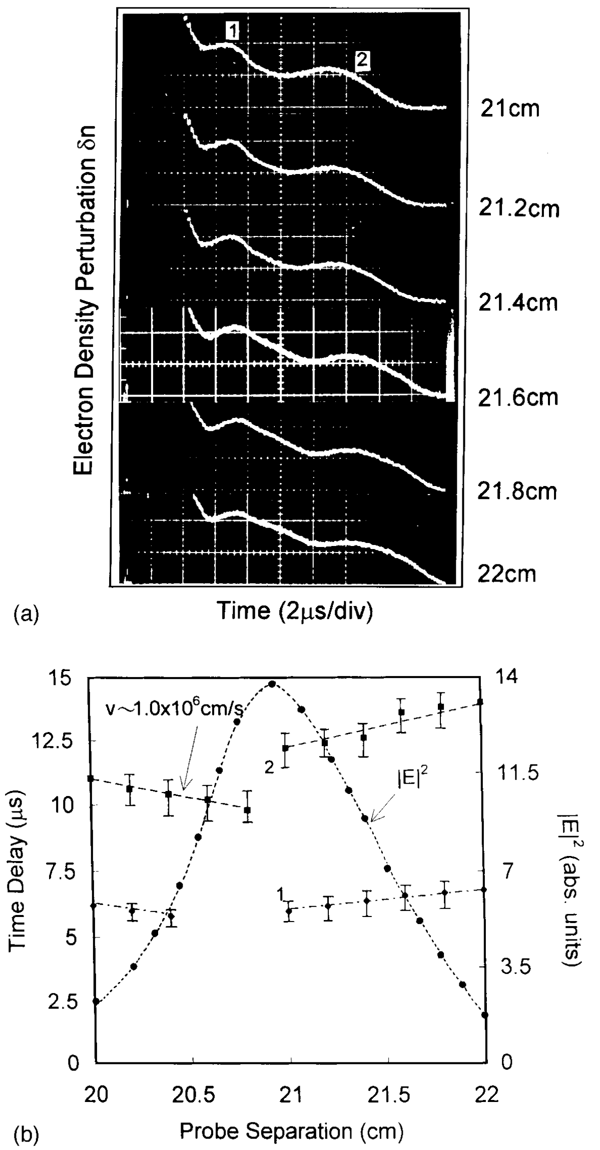

FIG. 5. (a) Examples of electron density perturbation observed around $z = 21$ cm. Here, a positive-going signal means a negative density perturbation. (b) Time-space display of the velocity of plasma flow and space scan of electric field intensity $|E|^2$. $n_0 \approx 0.6 n_c$ at $z = 21$ cm, $P_i = 250$ kW, $\tau \simeq 1$ μs, $P_{\mathrm{Ar}} = 2 \times 10^{-3}$ Torr.

$$F_{NL} = -\frac{\epsilon_0 \omega_p^2}{\omega_0^2} \nabla \frac{\langle E^2 \rangle}{2} = \frac{\omega_p^2}{\omega_0^2} \frac{\epsilon_0 \langle E^2 \rangle}{2l},$$

where $\omega_p = (n_0 e^2 / \epsilon_0 m_e)^{1/2}$, is the plasma frequency and l is the gradient length of $\langle E^2 \rangle$ [18]. The pressure-gradient force in the plasma is $F_{pressure} = -K(T_i + T_e) \nabla n_0$, where T_i and T_e are the ion temperature and electron temperature, respectively. Using these forces, the velocity of the expanding plasma is obtained as

$$v \approx \left[\frac{4P_i}{clA} \frac{\omega_p^2}{\omega_0^2} - K(T_i + T_e) \nabla n_0 \right] \tau / (m_i n_0), \tag{1}$$

where A is the irradiation area of the microwave, c is speed of light in vacuum, and m_i is the ion mass. If we take $P_i =$

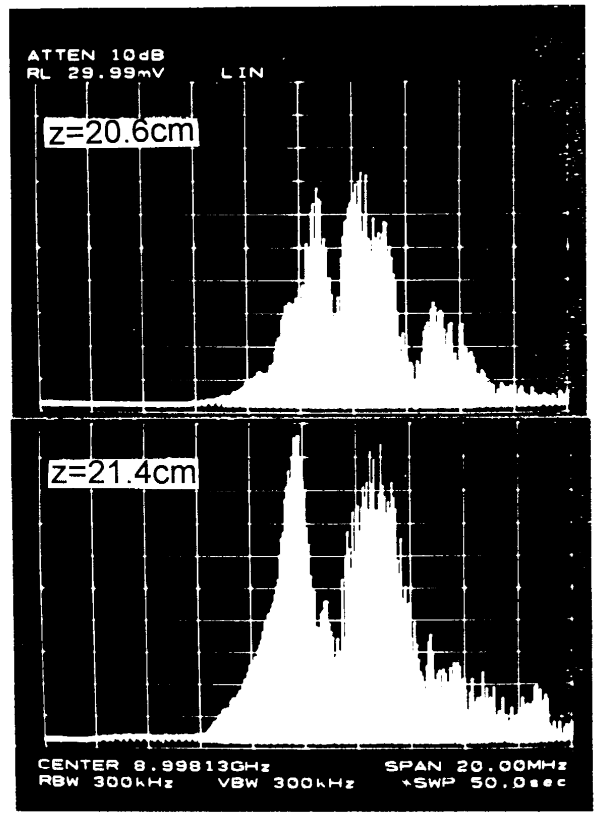

FIG. 6. Typical frequency spectra observed around the two sides of the high peak of electric field intensity $|E|^2$ at $z = 21$ cm. The frequency upshift is observed at $z = 20.6$ cm, the left side of the peak of $|E|^2$ while the downshift one at $z = 21.4$ cm, the other side. $P_i = 250$ kW, $\tau \simeq 1$ μs, $P_{\mathrm{Ar}} = 2 \times 10^{-3}$ Torr.

250 kW, $f_0 = 9$ GHz, $T_e = 3$ eV, $A = 6 \times 10^{-4}$ m^2, $\tau = 1$ μs, $l = 8 \times 10^{-3}$ m, the velocity of the expanding plasma is estimated to be $v \approx 1.1 \times 10^6$ cm/s. This result is in reasonable agreement with the experimental results.

When the incident wave encounters such a moving plasma, a part of it is reflected by the plasma and the rest transmitted through the moving plasma. In the frame of the moving plasma (the prime frame), the frequency of the incident wave is $\omega_0' = \gamma(1 + \beta)\omega_0$, where $\gamma = (1 - \beta^2)^{-1/2}$, $\beta = v/c$. Performing an inverse Lorentz transformation to get back to the lab frame, the wave frequencies for the reflected wave and transmitted wave are

$$\omega_r = \gamma^2 (1 + \beta)^2 \omega_0, \tag{2}$$

$$\omega_t = \gamma^2 (1 + \beta) \left\{ 1 - \beta \left[1 - \frac{\omega_p^2}{\omega_0^2 \gamma^2 (1 + \beta)^2} \right]^{1/2} \right\} \omega_0, \tag{3}$$

respectively. Substituting $v = 1.1 \times 10^6$ cm/s (experimental result) into Eqs.(2) and (3), the frequency upshifts due to the Doppler effect are obtained as $\Delta f_r = (2\beta f_0 / 1 - \beta) = 0.7$(MHz), $\Delta f_t = (2\beta f_0 / 1 - \beta) = 0.4$(MHz), respectively. These results agree fairly well with the experimental results. We noted that according to the above model, a frequency downshift should be observed because the plasma is expanded in two directions. The spectra are observed at the two sides of the high peak of the electric field intensity $|E|^2$ at

$z=21$ cm by moving the probe with a step of 2 mm, and the results are shown in Fig. 6. It can be seen that the frequency up- and down-shifts together with the higher frequency components have been observed at $z=20.6$ and 21.4 cm, respectively. These results provide further proof for the theoretical model given above.

In summary, the frequency upshift around 1 ~2 MHz and some other higher frequency components in the range of 3 MHz to 7 MHz have been observed. This is the first result that the frequency upshift (blue shift) being observed in the experiment of microwave-plasma interaction when there is no ionization front or temporal growing plasma. In the present case, because the strong standing wave is established in the chamber, the plasma is expanded rapidly by the collective ponderomotive force due to the electric field gradient of the standing wave. The incident wave is reflected by the moving plasma, and the upshifted frequency is resulted from the Doppler effect. If the velocity of the moving plasma is high enough, a large degree of the frequency upshift can be obtained. The observed phenomenon shows that not only an ionization front but also an underdense moving plasma can be used to upshift an electromagnetic radiation. The degree of the frequency upshift can be controlled by the incident microwave power, plasma density and the position where the signal is picked up. Therefore, it has the possibility to create a different kind of frequency tunable radiation source. This phenomenon is of relevance to the field of laser fusion and laser wakefield accelerators because it may happen in the experiments of the laser-plasma interaction also. Our results also show that in order to pinpoint the mechanism of the frequency shift, a careful diagnosis is necessary when the experiment of laser (microwave)-plasma interaction related to a frequency shift is carried out. Of course, the theoretical model in the present paper is only valid for the upshift of the center frequency of microwave. The explanation about the creation of the higher frequency components will be given in a following paper.

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