Experimental observation of short-pulse upshifted frequency microwaves from a laser-created overdense plasma

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(Received 30 July 2001; published 5 March 2002)

A short and frequency upshifted from a source microwave pulse is experimentally generated by the overdense plasma that is rapidly created by a laser. The source wave, whose frequency is 9 GHz, is propagating in the waveguide filled with tetrakis-dimethyl-amino-ethylene gas, which is to be converted to the overdense plasma by the laser. The detected frequency of the pulse is over 31.4 GHz and its duration is 10 ns. This technique has the potential for the generation of a tunable frequency source.

DOI: 10.1103/PhysRevE.65.036505 PACS number(s): 52.59.Ye, 52.25.Os, 52.50.Jm

In the last decade the interaction between a plasma and the electromagnetic (em) wave has been studied for plasma applications of short and tunable radiation source. Lampe *et al.* have studied the phenomena of the frequency upshift of the em wave using a relativistic, overdense ionization front with the speed of light [1]. The em wave reflects at the ionization front and the frequency is upshifted by the double Doppler effect. The creation of the ionization front is now easy to be realized by the intense short laser pulse through photoionization [2]. A frequency upshift and a radiation of the em wave have been studied by using photon acceleration [3] and relativistic underdense ionization front [4] in the plasma application in the 1990s. The frequency upshift of the em wave with the laser produced underdense ionization front having a speed of light was studied by Mori in 1991, when the em wave was incident on the underdense ionization front [4]. This phenomenon of the frequency upshift is the phase modulation of the incident wave by the ionization front. Savage *et al.* studied experimental frequency upshift of the microwave frequency from 35 GHz over 170 GHz by using the laser produced underdense ionization front [5].

The frequency upshift can also be expected from a periodic electrostatic field instead of the initial em wave, because the periodic electrostatic field is observed as the incident em wave with the frequency of $\omega' \neq 0$ in the frame moving with the ionization front. In the laboratory frame, the transmitted wave in the plasma behind the ionization front is directly observed as the em wave radiation pulse. The observed frequency, however, is upshifted from zero frequency, that is, this scheme can directly convert the dc field energy to the em wave radiation. This phenomenon is called dc to ac radiation converter [6–13].

Wilks and co-workers have investigated the effect of quickly creating a plasma around an em source wave, on the time scales in the order of a cycle of the wave [13,14]. They have found that this can generate upshifted em wave by changing the plasma density. Experimental works have been successfully performed [15,16]; however, this is the first time, to the best of our knowledge, that the phenomenon has been explored experimentally using laser-created overdense plasma.

In this paper we describe experimental results in which 9 GHz source is upshifted in frequency up to 31.4 GHz by the laser-created plasma. The mechanism that is called "flash ionization frequency upshift phenomena" can be explained as follows. The source em wave with an angular frequency $\omega_0(k_0)$ is propagating in the z direction. Suddenly, in a time interval much shorter than $2\pi/\omega_0$, a plasma is created around the em wave along the propagation direction keeping the wave number of this source wave, k_0, fixed at the initial value. But the em wave should obey the dispersion relation in the plasma given by

$$\omega_f^2 = k_0^2 c^2 + \omega_p^2 = \omega_0^2 + \omega_p^2 . \tag{1}$$

Therefore, the final frequency ω_f of the wave is represented to be $\sqrt{\omega_0^2+\omega_p^2}$, where ω_p is the plasma angular frequency and we can expect the frequency upshift that is represented by $\Delta\omega = \sqrt{\omega_0^2+\omega_p^2} - \omega_0$ (Fig. 1). When the length of the plasma, d, in the propagation direction of em wave is much longer than the wavelength of the em wave, λ_0, the pulse duration of the upshifted em wave is decided by the plasma length d. Therefore, this mechanism has a potential for the high frequency and the ultrashort pulse generation by changing the plasma density and length of plasma.

The upshifted wave has two components with the em wave propagation, i.e., copropagation and counterpropagation components. The maximum electric field of the wave is represented by

$$E_{\pm} = \frac{E_0}{2}\left(1 \pm \frac{\omega_0}{\sqrt{\omega_0^2+\omega_p^2}}\right), \tag{2}$$

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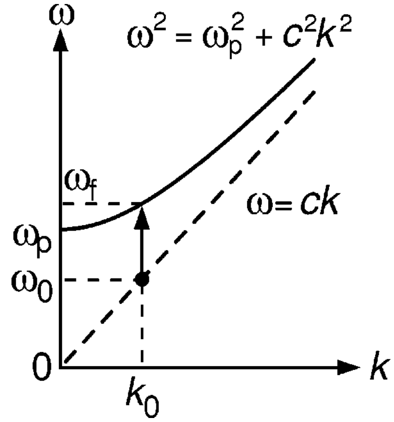

FIG. 1. Dispersion relationship of the em wave in an instantaneously created plasma. The wave number k_0 of the wave is fixed at the initial state, but the frequency should be upshifted to obey the dispersion relation of the em wave in the plasma. The frequency of the em wave is upshifted to ω_f.

where E_0 is the electric field of the em wave and the plus and minus signs denote copropagating and counterpropagating em wave, respectively.

By solving the initial-value problem on the theory, one can obtain the results that the periodic static, or zero-frequency, magnetic field remains in the plasma. This stationary magnetic field is generated by the transverse electron current, which is accelerated by the electric field of the initial em wave when the plasma is immediately created. The magnetic field B_s is given as

$$B_s = \frac{\omega_p^2 E_0}{\omega_p^2 + \omega_0^2}. \tag{3}$$

In our experiments, the electromagnetic wave propagating in the waveguide is irradiated into a thin plasma layer with slowly growing density in time, i.e., we must consider the electromagnetic wave of frequency ω_0 incident on a homogeneous plasma layer $0<x<d$ with plasma density $n(t)$. Here the plasma layer is assumed to be thin compared to the wavelength of the incident wave,

$$\frac{d}{\lambda_g} \ll 1,$$

where λ_g is the wavelength in the waveguide. We also assume the case of slow time variation of the plasma density, i.e., the rate of ionization $\mu = n_{\mathrm{cr}}^{-1}[dn(t)/dt]$, where $n_{\mathrm{cr}} = m\omega_0^2/4\pi e^2$ is the critical density for ω_0, is assumed much smaller than the wave frequency,

$$\mu \ll \omega_0 .$$

The analytic results of interaction between the incident wave and time varying plasma layer is given by Bakunov *et al.* [17],

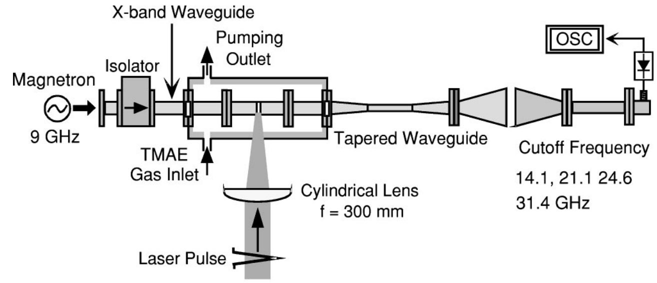

FIG. 2. Schematic of the experimental setup. The laser light is introduced through the tiny slit on the side of waveguide into the waveguide after focusing through a cylindrical lens.

$$B_L(t) = -\frac{i2G\,\delta_L(t)}{\sin\theta_0}\sqrt{\frac{\omega_0}{\omega_p(t)}} \times \exp\left\{-(\omega_0/2)\left[st + \int_0^t \delta_L(t')dt'\right]\right\}, \tag{4}$$

where

$$\delta_L(t) = \frac{\omega_0 d}{2c}\,\frac{\sin^2\theta_0}{\cos\theta(t)},$$

and θ is incident angle between plasma layer and radiation. This equation indicates that the frequency after the interaction is function of the rate of ionization μ, and the width of plasma layer d. We will present later the calculated spectrum by this equation by using experimental parameters.

Figure 2 shows the experimental setup. In the experiments, we used two microwave sources both with the frequency of 9 GHz. One is a Gunn diode (cw) with the maximum power of 5 mW and the other is pulse magnetron with the maximum power of 250 kW and a pulse duration of 2 μs. These microwave pulses initially propagate with TE_{10} mode in the *X* band waveguide whose cutoff frequency is 6.6 GHz. A tapered waveguide, whose cutoff frequency is 9.4 GHz, is inserted between the plasma and the horn antenna to prevent propagation from original microwave to the diagnostic region. Therefore, the detected microwave pulse is only upshifted microwave pulse. A working gas is TMAE (tetrakis-dimethyl-amino-ethylene, $C_{10}H_{24}N_4$) with the ionization potential of $U_i = 5.36$ eV, which can easily vaporize in the room temperature and is easy to be ionized by UV laser light. The gas is statically filled in the waveguide with the pressure of 20–100 mTorr after the evacuation by the turbo molecule pump. The ionizing laser pulse is fourth harmonic light ($\lambda = 266$ nm) of the yttrium aluminum garnet (YAG) laser, which has the maximum energy of 120 mJ and the pulse duration of $\sim$6 ns full width at half maximum (FWHM). TMAE gas is expected to be ionized by two-photon process. The laser light is introduced into the waveguide through the tiny slit (2 mm$\times$6 mm) on the side of waveguide using cylindrical lens whose focal length is 5 cm. The laser pulse is focused at the center of the waveguide and its focal size is 5 mm$\times$200 μm. The plasma density is controlled by varying the TMAE gas pressure. Before the pulse generation experiments, the plasma density was measured by

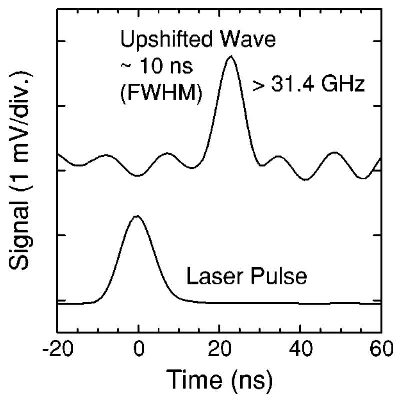

FIG. 3. The typical microwave signal detected by 31.4-GHz cutoff waveguide (upper trace) and the ionizing laser (lower curve).

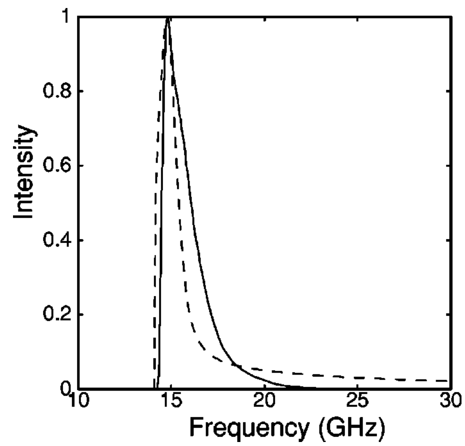

FIG. 4. Frequency spectrum of the upshifted microwave measured by the time of flight method. The steepness in the spectrum at 14.1 GHz is due to the cutoff frequency of the waveguide. The higher frequency component, for example, over 31.4 GHz, cannot be seen, because of the weakness of the signal intensity due to the strong attenuation from long propagation in the waveguide. The dotted line indicates the calculated results under the experimental condition.

the interferometry technique as a function of the TMAE gas pressure and the maximum plasma density ($n\sim 2\times 10^{13}$ cm^{-3}) is much larger than the critical density for 9 GHz radiation, $n_{\rm cr}=1\times 10^{12}$ cm^{-3}. When the plasma density is larger than n_c, the plasma acts as a mirror to the microwave and the microwave is reflected back by the plasma and cannot propagate in the initial direction.

In order to measure the upshifted radiation, we use the combination of the waveguide and horn antenna. The radiation is detected by a crystal detector. Four waveguides with specific cutoff frequencies are used, i.e., 14.1, 21.1, 24.6, and 31.4 GHz. The radiation frequency higher than the specific cutoff frequency is detected by the crystal detector.

The precise frequency spectrum of the emitted radiation is measured by the time of flight diagnostic method using a delay waveguide line. The radiation pulse propagates with a group velocity in the waveguide with length $L_{\rm d}$. The group velocity depends on the frequency of the radiation, i.e., $v_{\rm gw}=c(1-\omega_{\rm c}^2/\omega^2)^{1/2}$, where $\omega_{\rm c}$ is the cutoff frequency of the waveguide. When a delay time $t_{\rm d}=L_{\rm d}/v_{\rm gw}$ is estimated through the delay waveguide line, the frequency is given by $\omega=\omega_{\rm c}ct_{\rm d}/(c^2t_{\rm d}^2-L_{\rm d}^2)^{1/2}$. Note that broadening in the pulse width depends on the frequency broadening of the microwave pulse.

Figure 3 shows one of the typical oscilloscope traces of the upshifted microwave pulse observed in the waveguide of specific frequency of 31.4 GHz. The observed pulse duration is $\sim$10 ns (FWHM) and the maximum plasma density is estimated to be 2×10^{13} cm^{-3}. The delay time between laser pulse and microwave pulse depends on the cable length of the diagnostics, although the two signals are synchronous. The theory predicts that the pulse duration depends on the plasma length of the propagation direction. In the case of our experiments, however, the plasma length d is approximately as long as the focal thickness 200 μm and is much shorter than the microwave wavelength in the waveguide ($\lambda_g=4.8$ cm) and a skin depth ($\sim c/\omega_p$) of the order of millimeters. Even in the overdense plasma, the microwave can penetrate through the plasma and can be upshifted due to the increase of the plasma density in time. Therefore, the observed microwave pulse duration is on the order of the laser duration.

Solid line in Fig. 4 shows an example of frequency spectrum of the upshifted microwave measured by the time of flight method. The length of the delay line is 3.9 m. Steepness in the spectrum at 14.1 GHz is due to the cutoff frequency of the waveguide. Higher frequency component, for example, over 31.4 GHz, cannot be seen, because of the weak signal intensity due to the strong attenuation from long propagation in the waveguide. This spectrum broadening indicates the plasma density increases in finite time because the upshifted frequency is proportional to the time differential of the plasma density. In the case of our experiments, the ionizing laser pulse duration is 50 times longer than the cycle of the microwave pulse and the plasma is slowly produced during the laser pulse duration $\sim$6 ns. The frequency upshift takes place during the time when the plasma is produced, in other words, once the laser pulse is shut off, the increase of the plasma density stops and the upshift of the em wave does not occur anymore even if the steady plasma exists. Moreover, the frequency upshift is not expected when the plasma decays in long time scale, because the time differential of the density is negligibly small. Therefore, the short and monochromatic em wave cannot be generated as is expected in theory.

The dotted line in Fig. 4 shows the calculated frequency spectrum that is taken into account in the temporal evolution of plasma density, attenuation of rf by the waveguide wall, and cutoff by the waveguide. The plasma density $n(t)$ and the rate of μ is calculated as follows. We assumed that laser pulse has Gaussian profile such as

$$I(t)=I_0\exp\left(-\frac{t^2}{\sigma^2}\right),$$

where I_0 is the maximum intensity of the laser pulse. It is reasonable to assume that because the recombination time is long enough, the plasma density $n(t)$ is proportional to the accumulation within the laser pulse, and is given by

$$n(t)=\alpha\int_0^t I(t)dt,$$

where α is equal to the maximum density $n_{\max}$ at $t\rightarrow\infty$. We numerically calculated temporal plasma density $n(t)$ by this equation and obtained μ by its time differential. Finally, we obtained the calculated spectrum after the interaction with the plasma layer using Eq. (4) [17].

Furthermore, we have taken into account the loss of the em wave by the waveguide wall. The loss of the em wave in propagating the waveguide is due to the finite conductivity of the conductor surface, i.e., a conductivity of s is finite. The envelope of the amplitude of the emitted radiation is assumed an ideal Gaussian profile, i.e., $A(t)=A_{\max}\exp(-t^2\ln 2/\tau_L^2)$, where $A_{\max}$ is the peak amplitude of the emitted radiation. In general, the ratio of an input power $A_{\rm in}$ to an output power $A_{\rm out}$ can be written by $A_{\rm out}/A_{\rm in}=\exp(-\gamma L)$ with

$$\gamma=(4/abZ_0\sigma\delta)(1-f_c^2/f^2)^{-1/2}[(f_c/f)^2(a+2b)+(\lambda_c^2-\lambda^2)/4a],$$

where a is a damping rate of the em wave power and other parameters are $Z_0=377\ \Omega$, $\sigma=6\times10^7$ S/m, $f_c=14.1$ GHz, $a=10.7$ mm, $b=4.3$ mm, and $\delta=(\omega\sigma\mu_0/2)^{-1/2}$. The em wave is strongly damped when the frequency of the wave is close to the cutoff frequency ω_c. The wave form of the em wave after propagating the delay waveguide line is calculated by using these conditions. The typical observed wave form of the delayed signal (corresponding to the frequency spectrum) and the calculated one are shown at the plasma density of 2.0×10^{13} cm^{-3}. The calculated spectrum is narrower than the experimental data. The detailed simulation will be required for the explanation of experimental data.

Figure 5(a) shows the amplitude of the detected signals measured by four different waveguide and detector combinations as a function of the plasma density. The amplitude of each signal is normalized to the maximum signal intensity in the same waveguide. Note that the microwave pulse suffers from strong attenuation when its frequency is close to the cutoff frequency. When the plasma density is increased, higher frequency microwave pulse is observed. The vertical arrows indicate the plasma density at which the onset of the upshifted frequency starts. We plot the onset frequency of the onset vs the plasma density in Fig. 5(b). The solid line represents the theoretically predicted line given by Eq. (1). The data show excellent agreement with the theory.

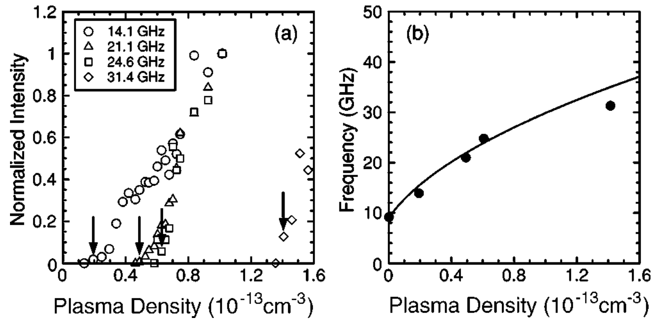

FIG. 5. (a) Signals on the cutoff frequency $f_c=14.1$, 21.1, 24.6, and 31.4 GHz vs plasma density; (b) output frequency vs plasma density. The solid line stands for the theoretical prediction given by Eq. (1).

The theory treated here assumed the infinite length of the plasma, that is, the plasma length is much longer than the wavelength of the em wave, and thus the plasma contains a large number of wavelengths. In our experiments, however, the length of plasma is as long as focal size of 200 μm, which is much shorter than the wavelength of the microwave in the waveguide. Therefore, the higher frequency component of the microwave could be excited by the finite size effect from the discontinuity of the electric field of microwave at the plasma edge. The computer simulation is needed for the explanation for our experimental data.

The theory estimates the power of the upshifted em wave as Eq. (2). In our experiments, however, we could not measure the absolute power, because the microwave detector is not calibrated yet. Furthermore, the poor coupling between the waveguide and diagnostic cannot give us precise microwave power. In this paper, therefore, all signal intensities were given in arbitrary units. Precise power measurement should be required in our future works.

In conclusion, we have demonstrated the frequency upshifted short microwave pulse generation from 9 GHz to 31.4 GHz by rapidly created plasma. The observed pulse duration of the upshifted microwave could be explained by the increase of plasma density resulting from the finite ionization time during the laser pulse irradiation. The present mechanism will give us a unique short and coherent em source.

A part of the present work was supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports, and Culture, Japan. One of the authors (T.H.) is also grateful to the JSPS for financial support. We also are grateful to Cooperative Research Center and Satellite Venture Business Laboratory (SVBL) of Utsunomiya University for providing the laser system.

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