PHYSICAL REVIEW E **80**, 025402(R) (2009)

Generation of terahertz radiation via an electromagnetically induced transparency at ion acoustic frequency region in laser-produced dense plasmas

Makoto Nakagawa,[1] Ryosuke Kodama,[1,2,3,*] Takeshi Higashiguchi,[3,4,†] and Noboru Yugami[3,4,‡]
[1]*Graduate School of Engineering, Osaka University, Yamada-oka 2-1, Suita, Osaka 565-0871, Japan*
[2]*Institute of Laser Engineering, Osaka University, Yamada-oka 2-6, Suita, Osaka 565-0871, Japan*
[3]*Japan Science and Technology Agency, CREST, 4-1-8 Honcho, Kanagawa, Saitama 332-0012, Japan*
[4]*Department of Advanced Interdisciplinary Sciences and Center for Optical Research & Education (CORE), Utsunomiya University, Yoto 7-1-2, Utsunomiya, Tochigi 321-8585, Japan*
(Received 1 June 2009; published 14 August 2009)

Electromagnetically induced transparency is a well-known quantum phenomena that electromagnetic wave controls the refractive index of medium. It enables us to create a passband for low-frequency electromagnetic wave in a dense plasma even if the plasma is opaque for the electromagnetic wave. This technique can be used to prove the ion acoustic wave because the ion acoustic frequency is lower than the plasma frequency. We have investigated a feasibility of electromagnetic radiation at THz region corresponding to the ion acoustic frequency from a dense plasma. We confirmed that the passband is created at about 7.5 THz corresponding to the ion acoustic frequency in the electron plasma density of 10^{21} cm^{-3} with a Ti:Sapphire laser with the wavelength of 800 nm and the laser intensity of 10^{17} W/cm^2. The estimated radiation power is around 1 MW, which is expected to be useful for nonlinear THz science and applications.

DOI: 10.1103/PhysRevE.80.025402 PACS number(s): 52.25.Os, 52.59.Ye, 42.65.Ky

Recently, there has been increasing interest in the electromagnetically induced transparency (EIT) which can control the refractive index of the electromagnetic waves in a medium. The EIT was originally investigated in atoms as a quantum mechanism and is the technique that the complex refractive index of the probe beam can be modified by coupling an additional coherent wave with another atomic transition [1,2]. In 1996, Harris pointed out that the EIT is achieved not only in atoms but also in plasmas as a classical mechanism [3]. He found the electromagnetic wave with frequency lower than the plasma frequency can propagate in the plasma. On the other hand, the generation of terahertz radiation has been extensively studied by laser-plasma interaction experiments [4–10] and formation of filaments by intense laser propagating in air or gas [11–14]. The THz radiation has a lot of applications in imaging, biological sensing, surface investigation, and condensed-matter studies. High-power radiation sources are required for these applications because the power of the conventional THz sources, for example, the photoconductive antenna or the device based on optical rectification phenomena excited by the femtosecond laser pulse, are ranged in μW–mW level.

In this Rapid Communication, we investigate the feasibility of the generation of terahertz radiation at the ion acoustic frequency region from a laser-created dense plasma by using the EIT technique. Note that the coupling between acoustic mode and nonlinear laser field has been theoretically predicted as an optical bistability [15]. We analyze requirements for the laser frequency, intensity, and the plasma density and estimate the frequency of the generated THz radiation.

The electromagnetic (EM) wave propagates with the displacement current J_d, which is defined as $(1/c)(\partial E/\partial t)$ and is proportional to the electric field of EM wave, in a vacuum. On the other hand, in a plasma, the EM wave propagates with not only the displacement current but also the real electric current J_e which is excited by the electric field of the EM wave. In the case of the overdense plasma $(\omega > \omega_p)$, where ω is the frequency of the EM wave and ω_p is the plasma frequency, because the induced electric current shields out the displaced current of the EM wave, this results in the interruption of the propagation for the EM waves. It is suggested that the EM wave can propagate with the phased electric current even in the overdense plasma $(\omega > \omega_p)$.

The frequency, which is initially below cutoff and around which a passband is to be created, is denoted as ω_s and referred to as the stokes frequency. Here, the passband is frequency region where the EM wave can propagate even in the overdense situation. The frequency of the pump laser is denoted as ω_a, which is higher than the plasma frequency $(\omega_a > \omega_p)$. These two waves drive the longitudinal plasma oscillation at the difference of these frequencies $\omega_a - \omega_p$ by the $V\times B$ force, where V and B denote the velocity of plasma oscillation and the magnetic field of the EM wave, respectively. It is phased such that the current associated with the pump wave and the plasma oscillation tends to cancel the current associated with the stokes wave. This reduces the amplitude of the current at the stokes frequency which allows the stokes wave to propagate.

Taking the electron current of plasma wave, $V\times B$ term and electron current excited by the EM wave into account, the dispersion relation for a stokes wave could be expressed as (see Ref. [3] for the derivation of following equations)

$$k_s = \frac{-\omega_{pole}k_{a0} \pm k_{s0}[\delta\omega_s(\delta\omega_s - \omega_{crit})]^{1/2}}{(\delta\omega_s - \omega_{pole})}, \qquad (1)$$

*ryo@ile.osaka-u.ac.jp
†higashi@cc.utsunomiya-u.ac.jp
‡yugami@cc.utsunomiya-u.ac.jp

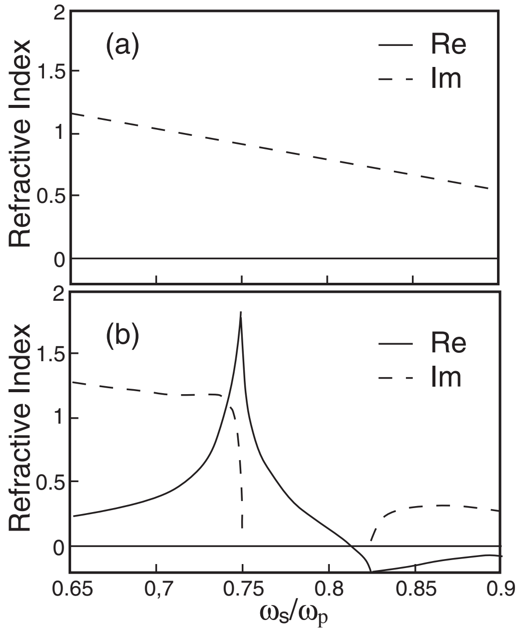

FIG. 1. Refractive index ($N=ck/\omega$) of the stokes wave vs ω_s/ω_p. (a) Without the pump laser. (b) With the pump laser ($\omega_a/\omega_p=1.75$). In the case of no pump laser, the imaginary part of refractive index (Im N) which is indicated by the dashed line, is negative, therefore, the EM wave is strongly damped in the plasma. On the other hand, in the case of pump laser, the passband is created between $\omega_s/\omega_p=0.75$ and 0.82. The EM wave with frequency in this range can propagate even in the overdense plasma.

$$\omega_{pole}=\frac{1}{2}\left(\frac{1}{mc^2}\frac{q^2|E_a|^2}{4m\omega_a^2}\right)\omega_p, \tag{2}$$

$$\omega_{crit}=\frac{(\omega_a^2-\omega_s^2)}{(\omega_p^2-\omega_s^2)}\omega_{pole}, \tag{3}$$

where $\delta\omega=\omega_p-(\omega_a-\omega_s)$ is the frequency detuning of the plasma frequency from the longitudinal plasma oscillation frequency and E_a is the electric field of pump wave. The symbols k_{a0} and k_{s0} are the propagation constants of either of the waves if alone. The electron current that is excited by the $V\times B$ term has nonlinearity and modifies the usual dispersion relation $\omega^2=\omega_p^2+c^2k^2$.

According to Eqs. (1)–(3), the passband strongly depends on the plasma density, pump frequency, and its intensity. This means that the electromagnetic waves with frequency lower than the plasma frequency with the plasma can be emitted by creating the passband which is equal to the electromagnetic wave frequency.

Figure 1 shows the refractive index as the function of ω_s/ω_p with the pump wave when $\omega_a/\omega_p=1.75$ and $q^2|E_a|^2/4m^2c^2\omega_a^2=0.02$. When the pump wave exists, the imaginary part of the refractive index vanishes between 0.75 and 0.82 of ω_a/ω_p. At this region, the electromagnetic wave can propagate without damping. The passband strongly depend on the parameters ω_a/ω_p and $|E_a|^2$. Because the plasma frequency and ponderomotive potential are proportional to

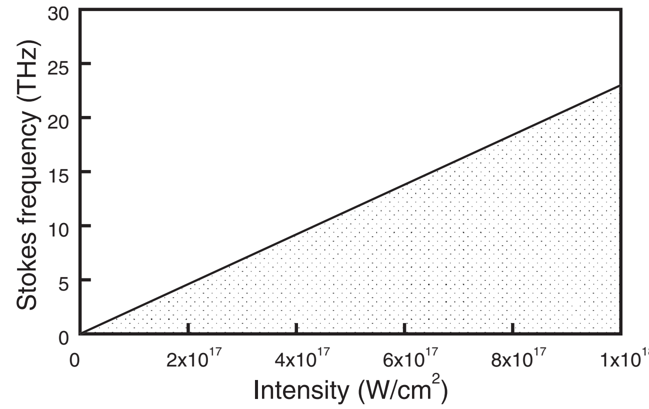

FIG. 2. The stokes frequency vs the pump laser intensity. Passband is created in painted area. The plasma density is 1.7×10^{21} cm^{-3}. The pump laser wavelength is 800 nm.

$\sqrt{n_e}$ and the pump intensity, respectively, the passband can be created at arbitrary frequencies.

Figure 2 shows the passband width as the function of the pump intensity with pump wavelength of 800 nm. The passband is proportional to the pump intensity. We considered the THz generation by the EIT with a Ti:Sapphire (Ti:S) laser as pump laser. In this discussion, we consider the ion acoustic wave in the plasma, instead of the plasma wave. Although the ion acoustic wave has slow propagation velocity and slow oscillation, we can tune it in the terahertz range by controlling the plasma density and expect the strong terahertz emitter. Figure 3 shows the diagram of the propagation of the radiation by changing the plasma density. The calculation parameters are pump laser wavelength $\lambda=800$ nm and pump laser intensity $I=2.0\times10^{17}$ W/cm^2, and we assumed the ion density n_i is equal to the electron

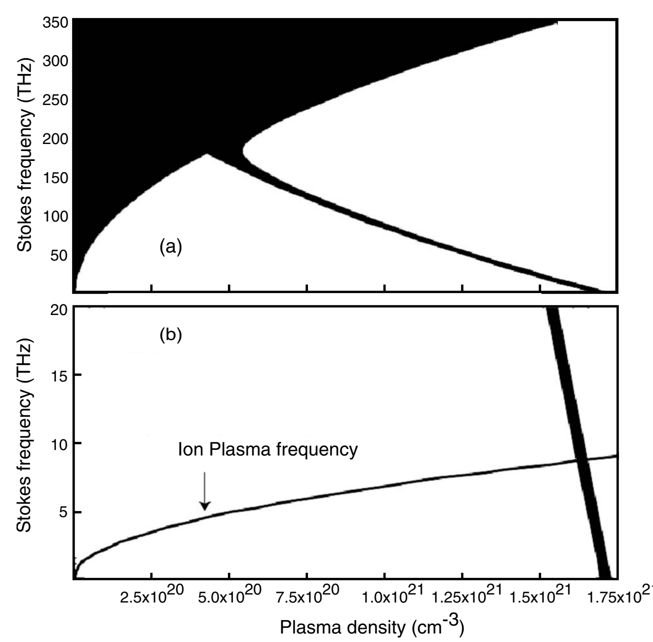

FIG. 3. The stokes frequency vs the plasma density. Passband is created in painted area. Ti:Sapphire laser (800 nm, 2.0×10^{17} W/cm^2) is applied as the pump laser.

plasma density ($n_i = n_e$). At the plasma density, $n = (1.70 \pm 0.05) \times 10^{21}$ cm^{-3}, the ion acoustic frequency is identical to the passband frequency and the resonantly excited radiation with ion plasma frequency can propagate in the plasma.

Because the ion acoustic frequency is lower than the ion plasma frequency, it is necessary to create the passband below the ion plasma frequency for electromagnetic radiation at the ion acoustic frequency. Figure 3(b) shows that the passband is created below the ion plasma frequency around 7.5 THz when the plasma density is about 1.7×10^{21} cm^{-3}. This indicates that the terahertz emission is expected to operate around 7.5 THz, and we can control the frequency of the emission by changing plasma density and the pump laser power.

As stated above, the THz wave can propagate in the plasma by the EIT. In actual plasma experiments, however, the plasma density is not uniform. When the radiation emits to the vacuum, it must propagate lower-density region where the EIT condition is not satisfied and the radiation decays at the region between the EIT and vacuum. Before the actual experiment, the damping of the terahertz wave should be considered, that is, we should calculate the damping factor Γ. When the plasma is created by the high power laser by the irradiation to the plane solid target, the spatial profile of the plasma density decays as the function of the distance from the target surface and can be expressed as

$$n_e(x) = n_0 \exp\left(-\frac{x}{L}\right), \tag{4}$$

where x denotes the distance from the target surface, n_0 is the plasma density at the target surface, and L is the scale length of the plasma density. When $n_0 = 1.0 \times 10^{21}$ cm^{-3} and $L = 1$ μm, the dumping factor is estimated to be $\Gamma = e^{-2.5} = 8\%$, which is defined as

$$\Gamma = \exp\left(-\int k_i dx\right),$$

where k_i is the imaginary part of the wave number.

When the transmission coefficient and the decay factor are known, the average power density radiated in vacuum is finally given as

$$p \approx \Gamma^2 \frac{cE_x^2}{8\pi}, \tag{5}$$

where E_x is the amplitude of the ion acoustic wave. The longitudinal ion acoustic wave field E_x can be estimated from the fluctuation of ion density δn_i. With small amplitude $\delta n_i / n_i = 0.1\%$, the power p is estimated to be 1 MW. The precise estimation for ion acoustic wave amplitude is needed by the computer simulation, taking the wave breaking and the boundary condition between plasma and vacuum into account [16,17].

In the above discussion, we did not state the excitation of initial ion acoustic wave because we assumed that small amplitude ion acoustic wave exists in the plasma. If insufficient acoustic wave is excited in the experiments, we must prepare the method for it, for example, the excitation via stimulated Brillouin scattering before main laser pulse irradiation [18].

In summary, we have indicated the feasibility of the electromagnetic radiation at THz region corresponding to the ion plasma frequency at the dense plasma by the EIT phenomena. The calculation shows that the passband is created at around 7.5 THz corresponding to the ion acoustic frequency from the plasma (1.7×10^{21} cm^{-3}) with a Ti:Sapphire laser (800 nm, 2×10^{17} W/cm^2). The average power of the radiation is estimated to be MW level by taking into account the decay at the plasma surface. This technique would give a high-power THz radiation source in the future.

The authors are deeply indebted to Professor Hitoki Yoneda for fruitful discussions. A part of this work was performed under the CREST and supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology. We also are grateful to the Center for Optical Research and Education of Utsunomiya University. One of the authors (T.H.) also acknowledges support from the Takahashi Industrial and Economic Research Foundation and the Research Foundation for Opto-Science and Technology.

[1] K. J. Boller, A. Imamoglu, and S. E. Harris, Phys. Rev. Lett. **66**, 2593 (1991).
[2] D. F. Phillips, A. Fleischhauer, A. Mair, R. L. Walsworth, and M. D. Lukin, Phys. Rev. Lett. **86**, 783 (2001).
[3] S. E. Harris, Phys. Rev. Lett. **77**, 5357 (1996).
[4] X. G. Dong, Z. M. Sheng, H. C. Wu, W. M. Wang, and J. Zhang, Phys. Rev. E **79**, 046411 (2009).
[5] C. B. Schroeder, E. Esarey, J. van Tilborg, and W. P. Leemans, Phys. Rev. E **69**, 016501 (2004).
[6] M. Abo-Bakr, J. Feikes, K. Holldack, P. Kuske, W. B. Peatman, U. Schade, G. Wustefeld, and H.-W. Hubers, Phys. Rev. Lett. **90**, 094801 (2003).
[7] J. Yoshii, C. H. Lai, T. Katsouleas, C. Joshi, and W. B. Mori, Phys. Rev. Lett. **79**, 4194 (1997).
[8] N. Yugami, T. Higashiguchi, H. Gao, S. Sakai, K. Takahashi, H. Ito, Y. Nishida, and T. Katsouleas, Phys. Rev. Lett. **89**, 065003 (2002).
[9] H. Hamster, A. Sullivan, S. Gordon, W. White, and R. W. Falcone, Phys. Rev. Lett. **71**, 2725 (1993).
[10] H. Hamster, A. Sullivan, S. Gordon, and R. W. Falcone, Phys. Rev. E **49**, 671 (1994).
[11] P. Sprangle, J. R. Penano, B. Hafizi, and C. A. Kapetanakos, Phys. Rev. E **69**, 066415 (2004).
[12] X. Xie, J. M. Dai, and X. C. Zhang, Phys. Rev. Lett. **96**, 075005 (2006).
[13] N. Yugami, K. Ninomiya, K. Kobayashi, and H. Noda, Jpn. J. Appl. Phys. **45**, L1051 (2006).
[14] C. D'Amico, A. Houard, M. Franco, B. Prade, A. Mysyrowicz,

A. Couairon, and V. T. Tikhonchuk, Phys. Rev. Lett. **98**, 235002 (2007).
[15] K. Morawetz and D. Kremp, Phys. Plasmas **1**, 225 (1994).
[16] D. F. Gordon, W. Mori, and C. Joshi, Phys. Plasmas **7**, 3145 (2000).
[17] D. F. Gordon, W. Mori, and C. Joshi, Phys. Plasmas **7**, 3156 (2000).
[18] W. L. Kruer, *The Physics of Laser Plasma Interaction* (Addison-Wesley Publishing Co., Redwood City, 1988).