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Frequency upshift via flash ionization phenomena using semiconductor plasma

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Abstract. We have demonstrated frequency upshift in the terahertz region by flash ionization. The magnitude of upshift frequency is tuned by the laser intensity. A proof of principle experiment has been performed with a plasma creation time scale much shorter than the period of the electromagnetic wave and a plasma length longer than its wavelength. Frequency upshifted from 0.35 to 3.5 THz by irradiating a ZnSe crystal with a ultra-short laser pulse has been observed.

1. INTRODUCTION

Over-dense plasma can be easily created by ultra-short intense laser pulse. Electromagnetic (em) wave generated from such plasmas has a broad range of frequency which includes terahertz (THz) whose frequency is between traditional photonics and microwave. The THz region has many applications i.e, imaging, security, information-communication [1, 2]. Most recent advances have been achieved by employing free electron lasers (FELs) to generate THz radiation [3]. FELs can generate pulse energies of the order of μJ and operate over a wide frequency range. However, since they are large-scale systems they are not suitable for many applications.

A novel technique for tuning the frequency is flash ionization, which was predicted by S. C. Wilks et al [4, 5]. The source em wave with an angular frequency ω_0 is propagating in the z direction. Plasmas are created in a much shorter time than the period of the source em wave along the propagation direction. The wave number of this source wave k_0 is fixed at the initial value. The angular frequency of the transmitted em wave adjusts to satisfy the dispersion relation in the plasma. The upshifted frequency ω_f is given by

$$\omega_f^2 = k_0^2 c^2 + \omega_f^2 = \omega_0^2 + \omega_P^2, \tag{1}$$

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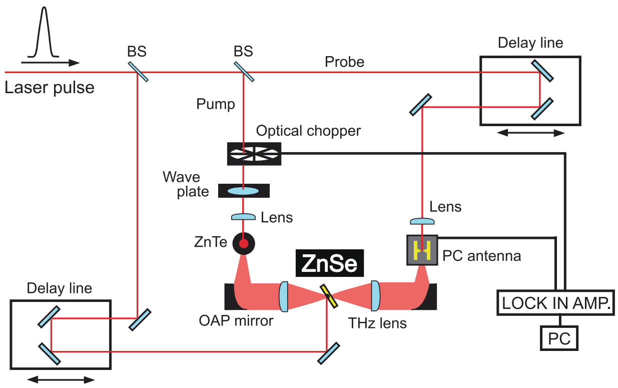

Figure 1. Experimental setup.

where c is the speed of light and ω_P is the plasma frequency. Therefore, the magnitude of frequency upshift $\triangle\omega$ is expressed by

$$\triangle\,\omega = \sqrt{\omega_0^2 + \omega_P^2} - \omega_0^2. \tag{2}$$

Thus, the output frequency can be tuned by adjusting the plasma density.

Following the publication of these theoretical predictions, several experiments were performed using microwaves and optical waves as sources [6–8]. However, these experiments do not fulfil the theory requirements. One is that the plasma creation time should be much shorter than the oscillation period of the em wave. The other is the plasma length is much longer than a wavelength to neglect the edge effect. In this paper, we have demonstrated the proof of principle experiment of flash ionization, which meets the requirements of the above two conditions.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. The Ti:sapphire chirped-pulse amplification laser system delivered an maximum energy of 1 mJ at a center wavelength of 800 nm, and 1 kHz repetition rate. The laser beam was split into three beams. One beam is a pumping pulse to create electron carrier in a ZnSe crystal. The second beam is the chopped pump beam that was passed through the half wave plate and focused on a ZnTe crystal to generate the source THz wave. The third beam is used to detect the THz wave using a bow-tie photoconductive (PC) antenna. The source THz pulse is focused in the ZnSe crystal by the off-axis parabola (OAP) mirror and lens pair whose effective focal length is 76.2 mm and 150 mm, respectively. The output THz pulse is collected by another OAP and lens pair, and finally focused on the PC antenna to detect the THz signal. We measured this small current by chopping the 0.5 kHz optical pulse train that triggers the emitter and using a lock-in-amplifier.

A dashed red line in Fig. 2 indicates the waveform spectrum of the source THz wave. The central frequency of source wave is 0.35 THz. The laser pulse duration is 100 fs that is much shorter than the source THz wave. Furthermore, the source THz wave has a wavelength of 0.85 mm, which is shorter than the laser focal diameter (10 mm). Thus, the two theoretical requirements are perfectly satisfied in the present experiment.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The solid line in Fig. 2 shows a typical upshifted spectrum. The upshifted spectrum is observed at 3.4 THz with a frequency width of 0.3 THz.

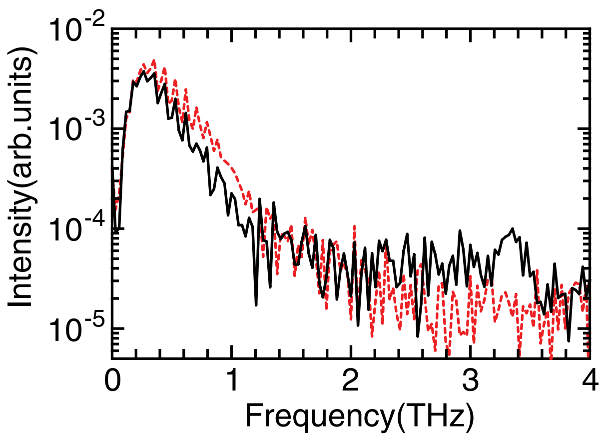

Figure 2. Measured upshifted frequency of THz pulses.

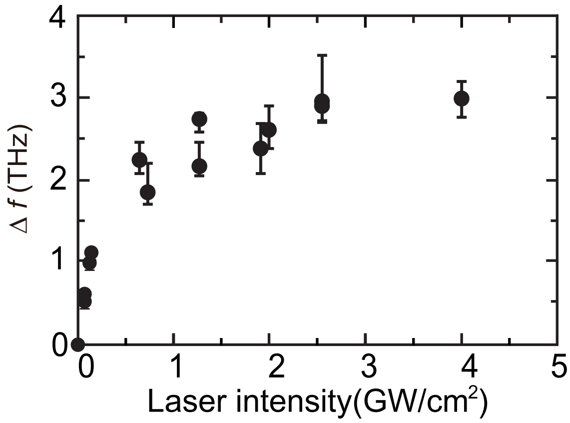

Figure 3. Observed frequency upshift as a function of the laser intensity.

Figure 3 shows the magnitude of upshift frequency Δf changing by the pump laser intensity irradiated on the ZnSe crystal. The upshifted spectrum is observed up to 3.5 THz, when the laser intensity is 4.2 GW/cm^2. The maximum frequency upshifted about 10 times as large as the seed THz pulse. The upper frequency limit of the measurement is due to the frequency response of the bow-tie type PC antenna as the detector.

Reference 5 indicates the relationship of energy conversion of the THz pulse. The maximum electric field of the upshifted wave is represented by

$$E_{f\pm} = \frac{E_0}{2}\left(1 \pm \frac{\omega_0}{\omega_f}\right). \tag{3}$$

The plus and minus signs denote copropagating and counterpropagating em waves, respectively. A proportional relationship between electric field and frequency is given by

$$\frac{I_f}{I_0} \propto \left(\frac{E_f}{E_0}\right)^2 \propto \left(\frac{\omega_0}{\omega_f}\right)^2, \tag{4}$$

The intensity of THz pulse I is proportional to the square of the electric field strength E which is detected by the PC antenna. The normalized ratio of the intensity of the THz pulse I_f/I_0 is plotted as

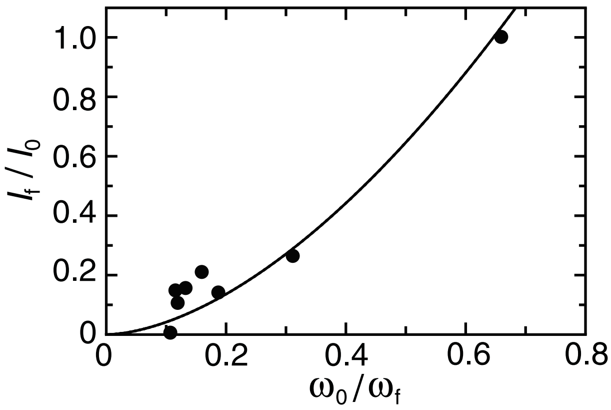

Figure 4. Nomarized intensity of THz pulse against angular frequency.

a function of the normalized frequency ω_0/ω_f. The fitting curve in Fig. 4 indicates $\propto (\omega_0/\omega_f)^{1.7}$. This experimental data is lower than the values given by Eq. (4) because the source THz pulse interacts not only with the surface of the ZnSe carrier plasma but also its interior.

4. CONCLUSION

In conclusion, we have demonstrated the proof of principle experiment of the flash ionization with the ZnSe crystal. The plasma creation time is much shorter than the period of the source EM wave and plasma size is much larger than a cycle of THz wave. We upshifted the frequency from 0.35 to 3.5 THz. Various frequencies can be observed by changing pumping laser intensity irradiated on the ZnSe crystal. We confirmed relationship between the electric field strength of upshifted THz pulse and its intensity. This result has possibilities of tunable high power radiation source in the THz region.

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References

[1] B. Ferguson, X.-C. Zhang, Nature Mat. **1**, 26 (2002)
[2] M. Tonouchi, Nature Photo. **1**, 97 (2007)
[3] G. M. H. Knippels, X. Yan, A. M. MacLeod, et al., Phys. Rev. Lett. **83**, 1578 (1999)
[4] C. Lai, T. Katsouleas, W. Mori, et al., Plasma Science, IEEE Transactions. **21**, 45 (1993)
[5] S. Wilks, J. Dawson, W. Mori, Phys. Rev. Lett. **61**, 337 (1988)
[6] S. Kuo, Phys. Rev. Lett. **65**, 1000 (1990)
[7] C. Joshi, C. Clayton, K. Marsh, et al., Plasma Science, IEEE Transactions. **18**, 814 (1990)
[8] N. Yugami, T. Niiyama, T. Higashiguchi, et al., Phys. Rev. E **65**, 1(2002)