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Laser Pulse Chirping Dependence of Terahertz Emission from Laser-Induced Plasma in Air

レーザー誘起大気プラズマからのテラヘルツ放射の
レーザーパルスチャーピング依存性

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Plasma induced by femtosecond laser pulses of fundamental and second harmonic waves of Ti:sapphire laser in air is expected as a high-intense and broadband terahertz source with table top size. We measured the dependence of terahertz intensity on the laser pulse duration, and observed the strong dependence near the shortest pulse duration. We also measured the dependence of the emission of N_2 and N_2^+ on the laser pulse duration. The experimental results suggested that the terahertz radiation was absorbed by plasma with high density.

1. Introduction

Terahertz radiation is of great interest owing to the possibility of applications in various fields. Plasma induced by femtosecond and high-intense laser pulses in air is expected for a new terahertz wave source. High-power (several μJ) and broadband (<300 THz) terahertz radiation was obtained from plasma induced by femtosecond laser pulses of fundamental (800 nm) and second harmonic (400 nm) waves of Ti:sapphire laser in air [1].

In this study, we measured the dependence of the terahertz intensity and emission intensities of N_2 and N_2^+ on the laser pulse duration, and considered the optimum plasma conditions for the high intense terahertz radiation.

2. Experimental Setup

The experimental setup is shown in Fig.1. A Ti:sapphire laser pulses with >40 fs duration and 15 mJ energy were used at a 10 Hz repetition rate. The laser pulses were focused by a plane-convex lens with a focal length of 100 cm. A β-BBO crystal was placed after the lens to generate a second harmonic wave (SHW). The fundamental and SHW pulses co-propagated and generated plasma in air.

The fundamental and SHW laser pulses after the plasma were blocked by a low-pass Teflon filter (<23.3 THz). Terahertz waves radiated by plasma were collected by parabolic mirrors, passing through another low-pass Teflon filter (<10.9 THz), and detected by a golay cell.

The emission of plasma was collected by a cylindrical lens and a plane-convex lens located in a direction perpendicular to laser axis. The emissions of 337 nm and 391 nm from nitrogen molecules ($C^3\Pi_u - B^3\Pi_u\ (0-0)$) and the nitrogen molecular ions ($B^2\Sigma_u^+ - X^2\Sigma_g^+\ (0-0)$), respectively, were detected.

When the SHW energy of laser pulses was measured, a dichroic mirror was placed after the β-BBO crystal to divide the wavelengths of 800 nm and 400 nm.

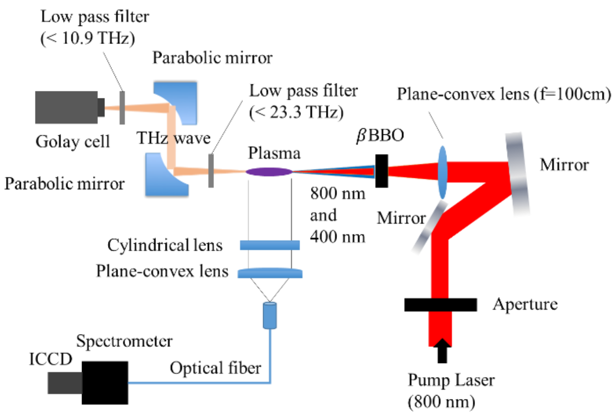

Fig.1. Experimental setup

3. Result and Discussion

The laser pulse duration dependence of the terahertz intensity and the emission intensity of 391 nm from plasma is shown in Fig.2. The plus or minus signs in the horizontal axis indicates the positive or negative chirp, respectively. The experimental results show that the dependence of the terahertz intensity on the laser pulse duration in the negative chirp region is different from that in the positive chirp region. In the negative chirp region, the terahertz intensity increased when the laser pulse duration is shorter; it had a strong dependence on the pulse duration in the vicinity of the shortest pulse duration. In the positive chirp region, when the pulse duration was longer, the terahertz intensity was constant after drastically decrease, and slowly increased.

On the other hand, the dependence of the emission of 391 nm from plasma on the laser pulse duration was different from that of terahertz intensity. In the negative chirp region, the dependence of 391 nm emission indicated the same trend as the terahertz intensity. However, in the positive chirp region, when the pulse duration is longer, the intensity of 391 nm emission was constant after increase. It started to decrease when the pulse duration was longer than 64 fs, at which the terahertz intensity started to increase.

The intensities of the 337nm and 391 nm emission are proportional to the numbers of $\mathrm{N_2}$ at the neutral excited state ($\mathrm{C^3\Pi_u}$) and $\mathrm{N_2^+}$ at the ionic excited state ($\mathrm{B^2\Sigma_u^+}$), respectively. The number of $\mathrm{N_2}$ ($\mathrm{C^3\Pi_u}$) is proportional to the number of the excited nitrogen molecule ions [2]. The excitation of the molecular ion to the vibrational levels of the $\mathrm{B^2\Sigma_u^+}$ electric state of $\mathrm{N_2^+}$ is mainly accomplished through multi-photon ionization of the inner valence electrons from the $\mathrm{N_2}$ molecule [3].

The measurements of the emission from plasma contain the variation in plasma volume. Therefore, we considered the emission intensity ratio R for 391 nm and 337 nm ($\mathrm{R = I_{391\,nm}/I_{337\,nm}}$). Then, the variation in plasma volume can be excluded. The value of R indicates the ratio of the number of $\mathrm{N_2^+}$ at ionic excited state ($\mathrm{B^2\Sigma_u^+}$) to the total number of $\mathrm{N_2^+}$. When the number of $\mathrm{N_2^+}$ ($\mathrm{B^2\Sigma_u^+}$) increases, it is considered that the air is easy to be ionized. Therefore, in case of the value of R is high, it is assumed that the plasma density is increased.

The laser pulse chirping dependence of the SHW energy indicated that same trend as the dependence of the value of R. These results suggest that the multi-photon ionization efficiency was enhanced when the ratio of the SHW energy to the fundamental wave energy was high. Therefore, it is considered that the plasma density depends on the SHW energy.

These results suggest that strong terahertz wave is not radiated when the plasma density is low. On the other hand, when the plasma density is too high, terahertz intensity is greatly reduced owing to the strong absorption of the terahertz wave in plasma.

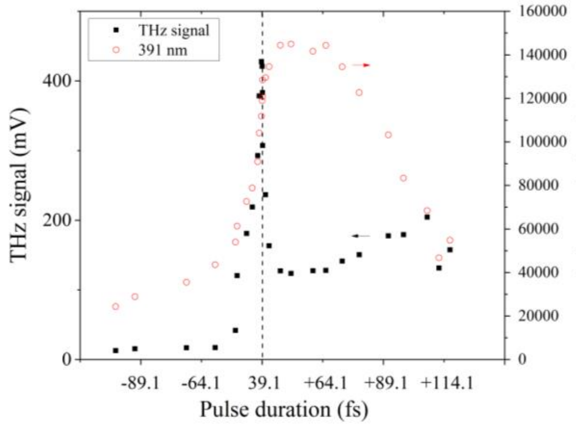

Fig.2. Dependence of terahertz intensity and emission intensity of 391 nm on the laser pulse duration. (“+” and ”-” signs in the horizontal axis represent the positive and negative chirp, respectively.)

References

[1] T.-J. Wang, J.-F. Daigle, S. Yuan, F. Théberge, M. Châteauneuf, J. Dubois, G. Roy, H. Zeng, and S.L. Chin : Phys. Rev. A **83**, 053801 (2011)

[2] H. L. Xu, A. Azarm, J. Bernhardt, Y. Kamali, and S.L. Chin : Chem. Phys. vol.360, issues 1-3, p.171-175 (2009)

[3] A. Talebpour, S. Petit, S.L. Chin : Opt. Commun. 171 p285-290 (1999)