Intense Terahertz Wave Generation from Gases

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***Abstract*—Terahertz generation from gaseous media was further investigated by a gas jet system. The experimental results reveal that the terahertz radiation amplitude is correlated with the third order nonlinear susceptibility.**

I. Introduction And Background

Terahertz wave generation from gaseous media has attracted considerable attention in recent years.[1-6] Early in the 1990s, Hamster *et al*. first reported terahertz generation by focusing intense laser pulses into air.[2] They demonstrated that THz radiation is from the motion of electron driven by the laser's pondermotive force. After that, Loffler *et al*. reported that the emission process can be enhanced and steered to the forward direction by applying a static bias field to the plasma.[3] Later, Cook and Hochstrasser have demonstrated intense Terahertz generation by mixing the fundamental laser pulse and a second-harmonic pulse together.[4] After that, searching for a higher efficiency and better performance gaseous media plays an important role both for fundamental research and technological application. Recently, investigations of THz generation from other gaseous media have been reported by Chen *et al*.[5] They demonstrated that the terahertz generation efficiency of noble gases increases with decreasing ionization potential, which may provide a direction for searching for high efficiency gas-based THz emitter.

In this letter, we further test the generation mechanism with various gases. Most of the gases demonstrated here (He, Ne, Kr, Xe) are chemically inert and structurally simple; hence, vibrational structures and photoinduced fragmentation can be ignored.

The experimental setup is similar to the one mentioned in [5].The optical source is a Spectra-Physics Hurricane amplified laser with a central wavelength of 800 nm, ~80 fs pulse duration, 750 μJ pulse energy and 1 kHz repetition rate. The THz wave is generated through a process which is similar to four wave mixing (FWM).[6] Instead of using a gas cell, in order to minimize the effects of dispersion, the measurements were performed using a pulsed gas jet. The fundamental and second harmonic beams focus together in front of the outlet of the gas jet (Figure 1). The gas jet is synchronized with the laser, delivering 400 μs pulses at a repetition rate of 100 Hz. The timing between the gas and laser pulses is adjusted electronically with a digital delay generator. All the optics are put inside a vacuum chamber and pump down to below 20 mtorr. The emitted THz wave was detected by standard electro-optic sampling with a 0.5 mm-thick electro-optic crystal ZnTe[7].

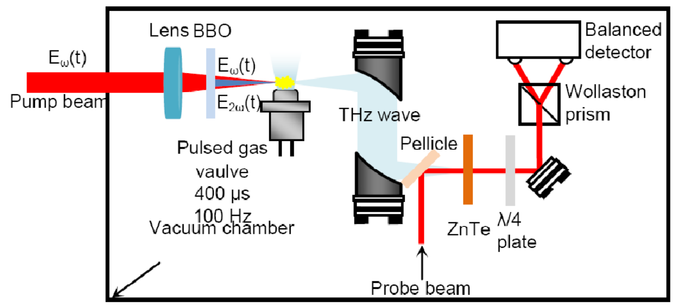

Figure 1 Schematic illustration of experiment setup.

II. Results

In the four-wave rectification model[6], the terahertz wave is generated by the third order nonlinear process, which can be interpreted as

$$E_{THz} \propto \chi^{(3)} E_{2\omega}(t) E_\omega^*(t) E_\omega^*(t) \cos(\theta)$$

where $E_{2\omega}(t)=E_{400}\exp(i2\omega t)$, $E_\omega(t)=E_{800}\exp(i\omega t)$, and θ is the relative phase difference between the ω and 2ω beams, . $\chi^{(3)}$ is the third order nonlinear susceptibility.

A pressure gauge is connected to the feedthough of the gas jet to measure the pressure dependent behavior of THz wave generation process. Figure 2 shows the relation between THz field amplitude and gas pressure for different gases. The inset figure is the zooming in of helium data. As expected, at the low pressure regime (below 100 torr), the plasma region at the focus is almost fully ionized.[9]Hence, increasing molecule density will enhance plasma density, which is responsible for the almost linear dependence of THz field at this regime. Our results show that for helium and neon, the generated THz fields follow linear dependence on pressure. However, for gases with relatively high index of refraction and lower ionization potential, above 200 torr, Nitrogen, Krypton and especially Xenon show a saturation phenomenon. Since there is no absorption for monatomic gases at THz frequency, the saturation is mainly from the intensity clamping effect [10], which results from defocusing of intense laser pulses during and after plasma formation. Thus, intensity clamping will affect the pulse width and peak intensity, limiting the plasma density above certain pressure. Chen et al. have reported that the Terahertz wave generation efficiency is related to the ionization potential of gas medium [5]. However, for the gases with low ionization potential, the intensity clamping effect is easy to encounter. For a gas with lower ionization potential and higher

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dispersion, such as Xenon, the phenomenon is more severe.

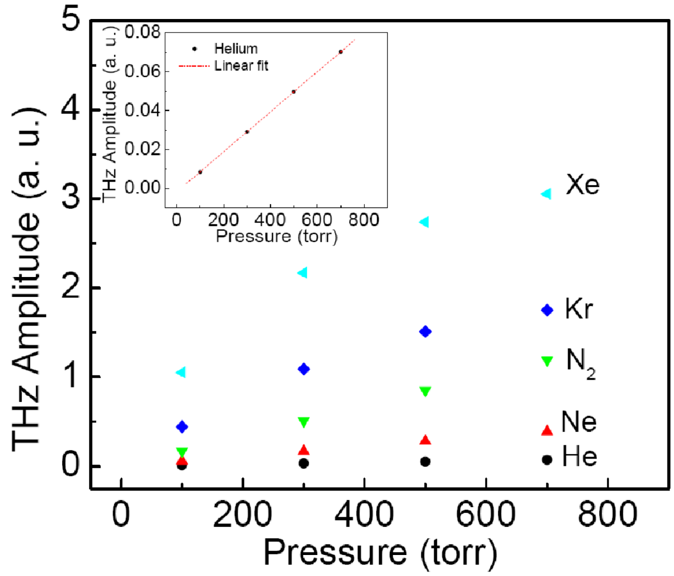

Figure 2 The pressure dependence of the Terahertz field amplitude of xenon, krypton, nitrogen, neon and helium. The inset is zooming in of helium.

Figure 3 shows a relationship between generated THz amplitude and $\chi^{(3)}$ of that gas under a series of pressures. Since $\chi^{(3)} \propto N$[11], where N is the molecular number, at the same pressure, the ratios between $\chi^{(3)}$ of other noble gases to that of helium stay constant. At the lower pressure (less than 100 torr), the inset of figure 1 shows a linear dependence of THz amplitude versus $\chi^{(3)}$ which is consistent with four-wave rectification model. The off-trend point of Helium gas is due to the experimental error due to the small signal to noise ratio. With increasing pressure, the trend starts to change and shows a saturation effect at high pressure, which is the result of intensity clamping as discussed above.

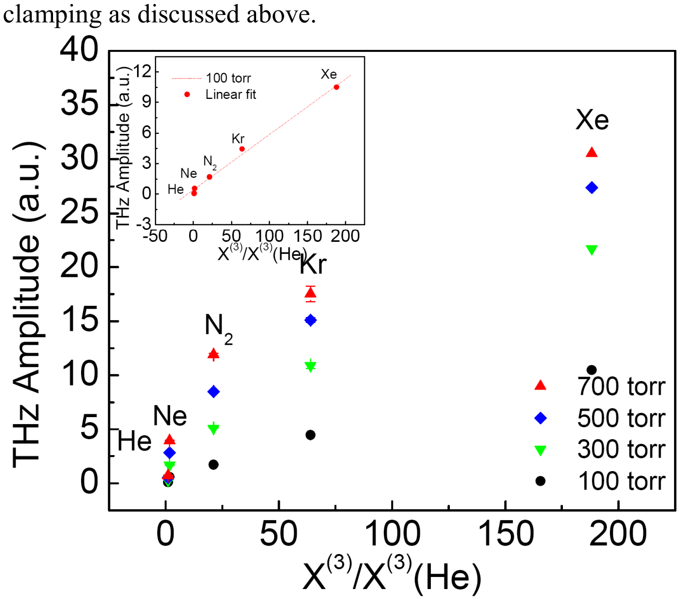

Figure 3 The relationship between Terahertz amplitude and the nonlinear susceptibility $\chi^{(3)}$ at different gas pressures.

From Figure 3, xenon shows relatively high THz wave generation efficiency, which is 1.7 times higher than nitrogen at 700 torr. Based on our measurement, the THz field generated from xenon is nearly twice than that from ambient air at atmosphere pressure, which reveals that xenon is a potentially useful gas emitter for pulsed terahertz radiation.

In conclusion, we reported a systematic study of the generation of subpicosecond terahertz radiation from noble gases as an emitter medium with two-color excitation by amplified femtosecond laser pulses using a pulsed gas jet. The strongest terahertz wave radiation has been observed from xenon. The terahertz amplitude from gases is proportional to the third order nonlinear susceptibility, which is consistent with four wave mixing rectification.

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