Studies of terahertz discharge in noble gases using a Michelson interferometer

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Abstract. The measurements of the spatial-time evolution of the discharge in argon and krypton at a wide range of pressures were performed. The gyrotron was used for plasma ignition. The radiation was 40 kW with frequency 0.67 THz. The pulse duration was 20 µs. A Michelson interferometer has been exploited for investigation of the discharge in the noble gases in a focused beam of terahertz waves. The diameter of the laser beam near the plasma cloud was 25 mm at $1/e^2$ level, $\lambda = 532$ nm. The rectangle area (about 20 × 15 mm) near the focus of THz beam was examined synchronously by the interferometer and a CCD camera. The spatial-time evolution of laser beam phase-shift of THz discharge in Kr and Ar from atmospheric pressure down to a few torrs was obtained. The intensity of the discharge glow in optical range correlates with the phase shift map. Previous measurements of plasma density made in Ar under a background gas pressure at a level of a few torrs, based on the Stark effect, are in good agreement with the gained results.

1. Introduction

The studies of gas discharge sustained by the powerful radiation of the terahertz frequency range have been of benefit in fundamental and applied physics. Nevertheless, it is still less studied area mainly because of the lack of high-power terahertz radiation sources. The recent appearance of such a sources: powerful gyrotrons [1-4] and free-electron lasers [5] brings one the opportunity to investigate the gas discharge phenomenon in THz band.

Some time ago, when studies of a microwave discharge and a laser spark in the optical and infrared bands were just launched, it was noticed that the discharge often tends to propagate towards the heating electromagnetic radiation. A review of papers on the propagation of a laser spark can be found in [6]. Studies on the propagation of a microwave discharge in their mass were carried out in air (see, for example, [78]). Although there have been a couple of works devoted to the propagation of a microwave discharge in noble gases [9-10]. Since studies in the microwave and infrared ranges showed that the distribution of the discharge at different frequencies of the heating radiation has its own specifics, it can be concluded that the propagation of the THz discharge will have its own characteristics. This work is one of the first devoted to the investigation of the propagation of a THz discharge in noble gases.

Gas discharge propagation was investigated by using laser interferometry. It is one of well known methods of plasma diagnostics [11]. This technique gives a large body of information for studying the spatial distribution of the electron density in plasma discharge. Usually
interferometers with the field visualization are used for the plasma diagnostics with electron density about $10^{21} \text{cm}^{-3}$. This paper considers plasma with electron density about $10^{16} \text{cm}^{-3}$. The 2D maps of electron density of the gas discharge plasma with spatial resolution above tenths of a millimeter were obtained.

2. Experimental setup

![Figure 1. Scheme of the experiment. 1 - gyrotron, 2-3 - quasi-optical converter, 4 - focusing mirror, 5 - vacuum chamber input window, 6 - vacuum chamber, 7 - turbo molecular pump, 8 - gas-intake pipe, 9 - parabolic mirror.](image)

A pulsed gyrotron\cite{1} with a maximum radiation power of up to 40 $kW$ at a frequency of 670 $GHz$ was used for plasma ignition. The pulse duration was 20 $\mu s$. The vacuum chamber was pre-pumped to a pressure of $10^{-6}$ Torr to avoid the effect of the residual gas, and then filled with argon or krypton up to a certain pressure. The pressure range was from 4 Torr to 760 Torr. The gyrotron radiation was transformed to the Gaussian beam by a quasi-optical converter and focused in the center of the discharge chamber (fig.1). An additional parabolic mirror with focal length of 0.8 $mm$, was placed in the beam waist. The gases come to vacuum chamber through narrow pipe. The end of the gas-intake pipe located in the vertex of the additional parabolic mirror. The gas discharge spreads from the focal spot of the additional parabolic mirror toward to the THz beam. The glow of the discharge was studied with a CCD camera. The camera was synchronized with the start of the terahertz pulse. The minimal exposure time was 4 $\mu m$. Figure 2 shows the path of the laser beam. Continuous wave diode laser with $\lambda = 532$ nm was used. Laser beam went through a spatial filter with pinhole 20 $\mu m$. The spatial filter was used to alter the phase structure of the beam. The diameter of the laser beam near the plasma cloud was 25 $mm$ at $1/e^2$ level. During the experiment, the size of plasma cloud was less than 1 $mm$. The half of the laser beam went through the plasma, the other half of the beam was used as a reference for interferometric image formation. The beam was split into two parts in a Michelson interferometer. Interferometric image was formed on the CCD camera placed in one of the arms of the interferometer.

The rectangle area (about 20x15mm) near the focus of THz beam was examined synchronously by the interferometer and a CCD-camera.

3. Experimental results: measurements of plasma density

The integral of the electron density along the probe direction can be obtained by measuring the phase shift. When a electromagnetic wave crosses the plasma cloud, its phase is shifted with compare to the phase of the wave propagating through vacuum. The phase shift $\Delta \varphi$ is
determined by the concentration of free electrons $N_e$:

$$\Delta \varphi \approx \frac{2\pi}{\lambda} \frac{N_e}{N_{cr}} L,$$

where $N_{cr} = \frac{1.1 \times 10^{13}}{\lambda}$ - critical frequency, $L$ - size of the plasma along the probe laser beam direction. Typical gas discharge plasma density ($10^{15} - 10^{17} \text{ cm}^3$) lead to small shifts (0.1 rad) of interference fringes. For each measurements the two interferometric images with THz pulse(signal) and without THz pulse (background) were obtained. For both images the two-dimensional Fast Fourier Transformation (2D FFT) [12] were applied to get the phase maps. The two-dimensional Fast Fourier Transformation is a powerful and popular tool for evaluation of phase distributions from interferograms with implied carrier fringes. The spatial intensity distribution of the fringe pattern, determined by objects phase shift $\Phi$ and the spatial carrier phase, can be written as

$$i(\vec{r}) = i_0(\vec{r}_0) + c(\vec{r})e^{2\pi\nu_0\vec{r}} + c^*(\vec{r})e^{-2\pi\nu_0\vec{r}}$$

where $c(\vec{r}) = \frac{1}{2}m(\vec{r})e^{i\Phi}$, $i_0$ and $m$ are the background and contrast functions, $\nu_0$ is the carrier frequency vector, $c^*$ - complex conjugate of $c$. Fourier transforming $i(x, y)$ gives

$$\hat{i}(\vec{\nu}) = \hat{i}(\vec{\nu}_0) + \hat{c}(\vec{\nu} - \vec{\nu}_0) + \hat{c}^*(-\vec{\nu} - \vec{\nu}_0)$$

Separation in the Fourier domain between the information of the fringe system and disturbing low frequencies allowed to calculate the phase distribution $\Phi(\vec{r})$. First of all, determinate the domain $\hat{c}(\vec{\nu} - \vec{\nu}_0)$ of the interferogram around the carrier frequency. Second, set all frequencies outside this domain to zero. The third step, get $c(\vec{r})$ by applying inverse Fourie transform. And calculate phase

$$\Phi(\vec{r}) = \arctan \frac{\text{Im}(c(\vec{r}))}{\text{Re}(c(\vec{r}))}$$

To gain the resulting phase map the background phase map was subtracted from the signal phase map.

The rectangle area (about 20x15mm) near the focus of THz beam was examined synchronously by the Michelson interferometer and a CCD-camera. The typical phase map of gas discharge was introduced on figure 3. Terahertz radiation falls from the left to right. Time delay was counting from start of terahertz pulse. At early times in evolution of the gas discharge the intensity map of discharge match the area with a negative phase, as shown on figures 3 and 4. The mean plasma density in Argon and Krypton were $2 \cdot 10^{16} \text{ cm}^{-3}$ at background gas pressure 7 Torr. Previous experiments of plasma density measurements[13] gives us an integral value for plasma density for Ar $10^{16} \text{ cm}^{-3}$ at background pressure about 7 torr. This value is in good agreement with the gained results.

Figure 2. Set-up for plasma density measurement using Michelson Interferometer.
Figure 3. Phase map of discharge in Ar. Background pressure 0.5 atm, time delay after beginning of the gyrotron pulse 10 mks. Red for $\Delta \varphi = +3\text{ rad}$, blue for $\Delta \varphi = -3\text{ rad}$.

Figure 4. Intensity of discharge in Ar. Background pressure 0.5 atm, time delay after beginning of the gyrotron pulse 10 mks. The exposure time was $4\text{ \mu m}$.

4. Conclusion

This work presents the results of studying a pulsed discharge in noble gases, which is produced by a focused beam of THz radiation. For plasma density measurements the interferometric techniques was used. Experiments were made at a wide range of background gas pressures. The results of experiments are in good agreement with previous experimental measurements and theoretical calculations. The dynamics of the phase map had been studied at the pressure range from 4 Torr to 760 Torr.

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