

Experimental Study of Radio-Frequency Cherenkov Radiation by a Line Focused Laser Pulse Obliquely Incident on a Wire Target

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(Received July 21, 2010)

The generation of radio-frequency radiation by oblique incidence of a picosecond laser pulse cylindrically focused on a line on a copper wire has been experimentally investigated in this work. By fairly accurately measuring the radiation pattern using one movable antenna and two fixed reference antennas, it was found that the radiation is directed in the direction corresponding to the specular reflection of the incident pulse, which identifies the radiation mechanism as the Cherenkov effect by a superluminal electron emission current source propagating along the target surface.

PACS numbers: 41.60.Bq, 42.62.Cf

I. INTRODUCTION

The generation of a broadband directional electromagnetic pulse (EMP) by means of a superluminal macroscopic source of the electron emission current has long been studied [1]. This generally happens when a metal surface is illuminated by an obliquely incident beam, i.e., laser light or X-ray, with photoelectrons struck out forming an emission current propagating at a phase velocity $v_{ph} = c/\sin\theta > c$ along the target surface, where c is the speed of light and θ the angle of incidence of the radiation with respect to the surface normal. Then the superluminal electron emission current acts as a pointlike macroscopic source which generates electromagnetic radiation via the Vavilov-Cherenkov effect. The characteristic of this radiation is the sharp directionality: the electromagnetic pulse is emitted in the direction corresponding to specular reflection of the incident beam. The basic radiation mechanisms were theoretically analyzed by Ginzburg in Ref. [2]. Carron and Longmire performed the theory of electromagnetic radiation generation by obliquely incident X-ray flux on a plate [1, 3]. Lazarev *et al.* carried forward the studies to generate a high-power directed wideband microwave using a diode-based scheme operating in a high voltage external electrostatic field to amplify the emission [4–7]. However, direct measurement of the spatial angular distribution of such electromagnetic radiation is rare to our knowledge. The lack of stability of the radiation source has been one of the obstacles. This is due to the different generation parameters, such as the drift of the incident laser pulse energy in different shots.

In this work, we present a simple method for measuring the spatial pattern of the radio-frequency (rf) radiation upon generation of a faster-than-light source initiated by a cylindrically focused laser pulse obliquely incident on a wire target. By employing one

movable antenna and two fixed reference antennas, the angular distribution of the radiation pattern has been measured fairly accurately in the experiments. The radiation density in the far field region shows a maximum in the same direction as the reflected wave of the incident radiation. This particular spatial distribution demonstrates, in the case of a wire target obliquely irradiated by a laser pulse at moderate intensity, that the rf radiation was emitted via the Cherenkov mechanism due to the superluminal source in our experiments, rather than via the dipole antenna mechanism due to a strong return current along the wire as was proposed in Ref. [11].

II. EXPERIMENTAL SETUP

The experiments were carried out with a Q-switched Nd:YAG laser at the Institute of Fluid Physics, China Academy of Engineering Physics. The laser is capable of producing 150 mJ pulses with a pulse duration of 150 ps centered at $\lambda = 1.064 \mu\text{m}$. A schematic diagram of the experimental setup is shown in Fig. 1. The laser beam was incident from

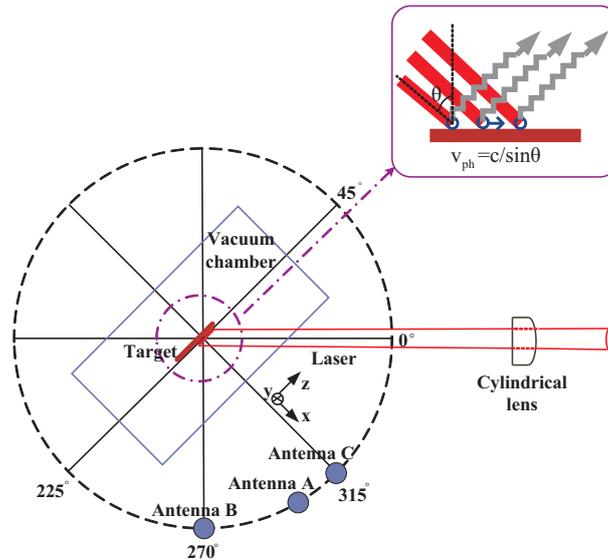


FIG. 1: Schematic of the experimental setup. The inset shows the principle of Cherenkov radiation by a superluminal macroscopic source.

the 0° direction and focused to a line by a cylindrical lens with a focal length $f = 200 \text{ mm}$. The target was positioned for p-polarized laser excitation. The incidence angle of the laser beam to the target normal was 45° . Accurate positioning of the laser onto the copper wire surface was achieved by imaging the focal spot onto a video charge coupled device (CCD) camera. The focal spot size was approximately $150 \mu\text{m}$ in the y -direction of a Cartesian coordinate system, much smaller than the radius of curvature of the copper wire (22 AWG).

Hence the surface can be assumed to be locally flat. At the same time the spot size in the z -direction was about 9 mm. Since the laser beam was strongly focused in the y -direction while loosely focused in the z -direction, the superluminal electron emission current created by the laser radiation is pointlike moving along the target surface to satisfy the Cherenkov condition [8, 9]. The copper wire target of 3 cm in length was placed in a organic glass vacuum chamber maintained at < 1.5 Torr. A similar experiment was performed in air, but no pronounced radiation signal was observed. This was probably due to the considerable loss of the laser energy through ionization of ambient gases.

To measure the rf emission from the laser-solid interaction, three dipole antennas were employed with a 1 cm stub perpendicular to the wire target axis. The antenna signals were detected directly by $50\ \Omega$ terminated cables driving a high-speed real time oscilloscope. Antenna A was movable and was placed at different points to measure signals in different directions from 225° to 315° in the $x - z$ plane along a constant radius of 20 cm. As the radiation source varied from shot to shot, relative power patterns instead of absolute power patterns are desired in our experiments. In order to increase the measurement accuracy, the other two antennas B and C were fixed at angles of 270° (front target specular direction) and 315° (front target normal direction) correspond to the laser incident direction, respectively. The radiation density recorded by these two antennas were taken as a reference. Since the distance from the the antennas to the laser focus was 20 cm, the far-field condition $R > 2D^2/\lambda$ was satisfied, where R is the radial distance from the source to the reception antenna, D being the maximum overall dimension of the antenna and λ the wavelength [10]. So the angular field distribution was essentially independent of the radial distance where the measurements are made. Then the relative angular radiation distribution could be obtained by taking the ratio of the radiation density measured by the movable antenna to that of the reference antennas for each measurement point.

III. RESULTS AND DISCUSSION

A typical temporal antenna signal oscillogram recorded by the movable antenna A is depicted in Fig. 2(a). It was performed at an angle of 245° . A fast oscillation starts when the laser pulse obliquely illuminates the metallic surface and lasts for about 100 ns. A Fourier transform of the antenna signal shows a well-defined oscillation frequency at 180 MHz and a series of oscillations at approximately 500 MHz and 900 MHz (see Fig. 2(b)). It can be seen from the spectrum that the peak value of the signals centered around 500 and 900 MHz is much smaller than that of 180 MHz. Significant oscillation is not found at the frequency range higher than 2 GHz in our experiments. This is attributed to performance properties of the linear wire antennas used in the experiments, which have very low gain when the signal frequency is up to the microwave range. In addition, the attenuation caused by the cables and other rf components used in our measurement circuit determines the frequencies of the signals recorded below 2 GHz. We choose this type of antenna not only because of its simplicity in construction, but also because of the greater sensitivity to stimulation by small electric current due to its small geometry in comparison with many

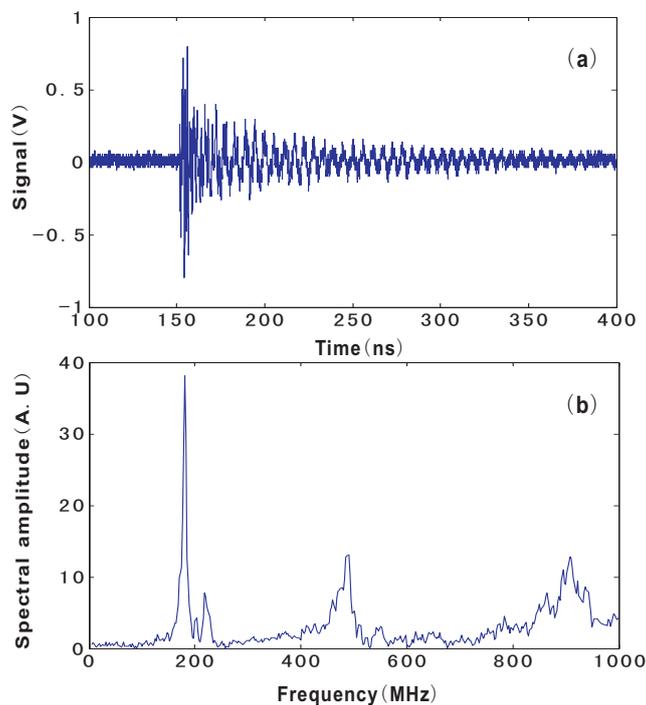


FIG. 2: A typical temporal oscillogram (a) and Fourier transform (b) of the rf signal recorded by antenna A. The measurement was performed at the angle of 245° .

other types of antenna.

Fig. 2(b) shows that the electromagnetic pulse is located in the discrete frequency region. Similar results have been reported in Ref. [12], which is attributed to natural oscillation modes in the vacuum chamber. Discrete emission frequencies have also been observed in an experimental chamber using a microwave horn for collection [13]. In order to study the frequency spectrum dependence of the characteristics and position of the antennas, signals recorded by the fixed antennas as well as the movable antenna have been analyzed and compared with one another. Fig. 3(a) and Fig. 3(b) present the Fourier transform of typical rf signals measured by antenna B and antenna C fixed at angles of 270° and 315° , respectively. Two distinct resonance frequency peaks are shown at 195 and 660 MHz in Fig. 3(a), and at 215 and 670 MHz in Fig. 3(b). For the same fixed antenna, quite similar spectral characteristics are found in the series of experiments. Fig. 4(a) and Fig. 4(b) show the frequency spectra of signals measured by antenna A at angles of 225° and 270° , respectively. Along with Fig. 2(b), it can be seen that there are substantial changes in the spectrum characteristics with a change in the antenna position, i.e., the second and third peaks above 200 MHz shift upon switching the positions of antenna A. While at the same angular position of 270° , the different antennas A and B show a similar signal spectrum. Thus the second and third peaks are dependent on the angular position but independent of the characteristics of the antennas. Considering that although the

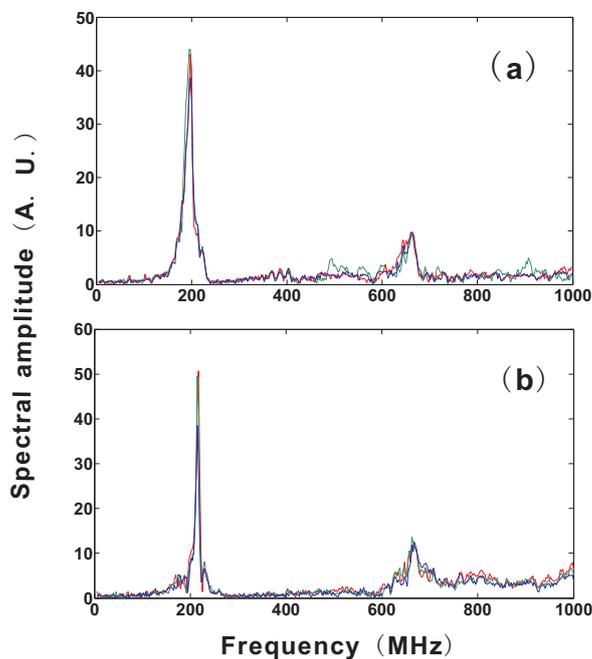


FIG. 3: Fourier transform of typical rf signals in a series of 3 shots measured by antenna B (a) and antenna C (b) fixed at the angle of 270° and 315° with respect to the laser incident direction, respectively.

organic glass vacuum chamber can transmit rf in our experiments, there is still part of the radiation which would reflect from the chamber wall and excite resonant modes. It appears likely that these resonant modes from different directions are related to the angular position dependence of the spectrum. It can also be seen that the first peak around 200 MHz is exhibited in all the spectra by the different antennas from different positions, which seems to be associated with a characteristic of the radiation source.

To identify the origin of the emission, the far field radiation pattern of the rf emission with respect to the laser incident direction has been analyzed. Figures 5(a)–5(b) show the results of the spatial distribution of the radiation density measured by antenna A over that of antenna B and antenna C, accordingly. The data has been normalized to unity. The radiation density is obtained by calculating the integration over the selected frequency range around 200 MHz of the first peak in the frequency spectrum. As can be seen, a highly directional rf radiation has been produced from the laser-solid interactions. The angular radiation profile with respect to the azimuth of both patterns are almost identical and exhibits a maximum in the direction of 270° , which is mirror-symmetric with respect to the direction of the incident optical pulse. This particular directional radiation pattern is the main feature of the macroscopic analog of Vavilov-Cherenkov radiation, which allows us to confirm that the rf radiation was generated by the superluminal electron-current source traveling along the target surface at a constant phase velocity $v > c$. Figures 5(c)–5(d)

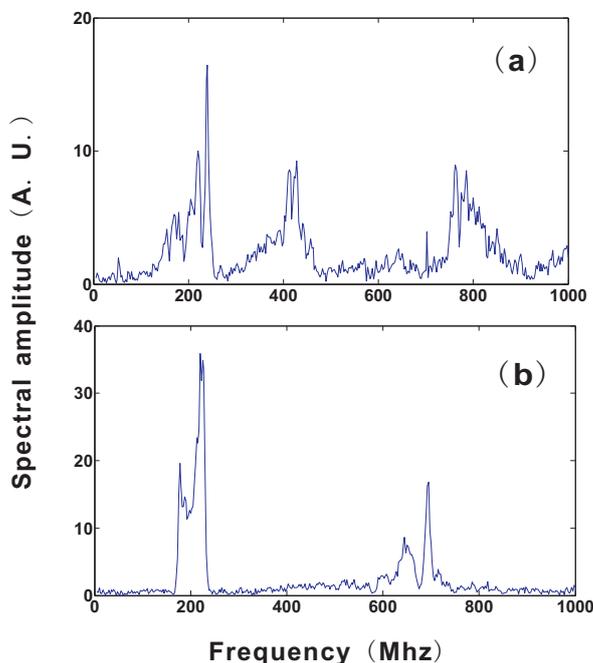


FIG. 4: Fourier transform of rf signals detected by antenna A at the angle of 225° (a) and 270° (b) with respect to the laser incident direction, respectively.

represent the radiation intensity measured by antenna B and antenna C, respectively. It can be seen that the radiation source is not very stable due to the shot-to-shot variation of the laser-target interaction parameters. For each shot, the two reception antennas show consistent response. Under this circumstance, the measurement of the angular distribution of the produced rf radiation using our method with the help of the reference antenna is reliable.

IV. CONCLUSION

In conclusion, directed rf radiation has been generated by oblique incidence of a picosecond laser pulse cylindrically focused to a line upon a metallic wire target. A simple and reliable method has been used to measure the angular distribution of the radiation. The frequency spectrum of the radiation has been analyzed and found to be located in the discrete frequency regions. The angular radiation pattern shows that the rf radiation is directional and has a maximum in the direction corresponding to the specular reflection of the incident pulse, which demonstrates that the radiation mechanism is due to the Cherenkov effect by a superluminal electron emission current source propagating along the target surface.

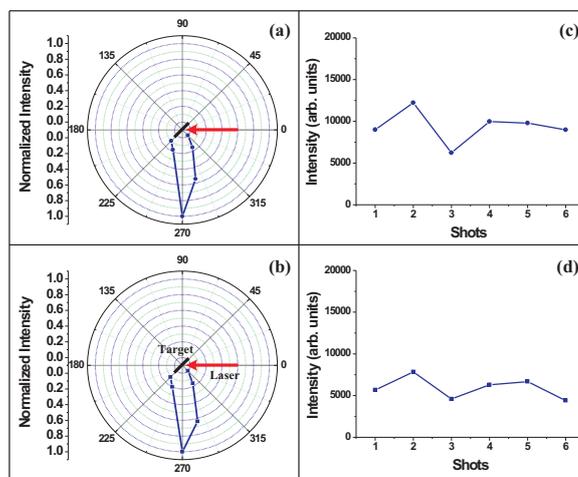


FIG. 5: Angular distribution of the rf radiation density around 200 MHz measured by antenna A over that of antenna B (a) and antenna C (b). (c) and (d) shows the radiation intensity measured by antenna B and antenna C, respectively.

Acknowledgements

The authors would like to thank Li-Guo Zhu and Yan Ye for stimulating discussions. This work was supported by the Pre-research Fund of China Academy of Engineering Physics under Grant No. 030305.

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