Real-Time Shadow Projection Millimeter-Wave Imaging Using Visible Continuum from a Slab of the Cs-Xe DC Discharge

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***Abstract*—A slab of the positive column of the Cs-Xe DC discharge has been employed as a 2-D sensor for real-time shadow projection millimeter-wave (MMW) imaging. MMW images are converted into visible images using the visible continuum from the plasma slab. Real-time shadow projection MMW images of test objects have been successfully obtained using 35.4 GHz millimeter waves for object illumination.**

Active imaging and sensing with millimeter waves attracts attention due to important industrial, security, biomedical, and scientific applications [1]. A 2-D array of millimeter-wave receivers is typically used for real-time record the MMW image. This allows achieving high frame rates, but 2-D imaging arrays are complex systems and their cost is too high for many applications. Besides, the use of 2-D arrays of millimeter-wave receivers does not provide sufficiently high spatial resolution. The shortcomings of the 2-D imaging array technique make the development of the method for time-resolved measurements of the spatial distribution of millimeter waves, which would be inexpensive and convenient for real-time active 2-D MMW imaging, a challenging task. Recently a new technique using the visible continuum (VC) from a slab of the positive column (PC) of a Cs-Xe DC discharge was developed for time-resolved imaging of the spatial distribution of the MMW intensity [2]. The concept of this technique is based on the effect of the increase in the intensity of the e-Xe bremsstrahlung continuum in the visible region, when the electrons in the positive column of a Cs-Xe DC discharge are heated by millimeter waves [3]. By means of this technique, MMW images are converted into visible images, thus allowing conventional CCD cameras to acquire images at a rapid rate. This imaging technique has high energy flux sensitivity (about ten $\mu J/cm^2$), microsecond temporal resolution, and spatial resolution 2 – 3 mm. In this paper, we applied the technique for active MMW imaging using the shadow projection method. The experimental setup (top view) is shown schematically in Fig. 1. A sealed discharge tube (DT) was used to generate the slab of the positive column of the Cs-Xe DC discharge [2]. A hollow rectangular parallelepiped glued from fused quartz plates was located in the middle of the tube. Two square plane quartz windows (1) with apertures 10 cm x 10 cm and a thickness 0.65 cm were set at a distance 2 cm between their internal surfaces. Two plane anodes (2) and two heated cathodes (3) were placed in glass cylinders. The discharge tube was filled with 45 Torr xenon. To obtain the required density of cesium vapor, the discharge tube was heated in an oven (4). Millimeter wave imaging experiments were performed for a discharge current of 1.5 A and a tube temperature of 95^o C. Under these conditions, the PC of the Cs-Xe discharge had the shape of a spatially uniform slab which filled the entire tube aperture 10 cm x 8 cm. The spatial distribution of VC intensity was recorded by a black and white CCD camera (5). The CCD camera exposure time was 1 ms. An optical filter (6) rejecting atomic emission lines was mounted on the camera lens. The data from the CCD camera were processed by a computer (7). Millimeter waves were generated by a 35.4 GHz magnetron (8) with its maximum output power of 20 W. The MMW pulse length was about 10 ms. The MMW pulses repetition rate was 12.5 Hz. A rectangular TE_{10} waveguide (9) was used to feed the millimeter waves to the pyramidal horn antenna (10). The MMW beam was collimated using a plane-convex Teflon lens (11). The test object (12) was placed nearby the window of the discharge tube.

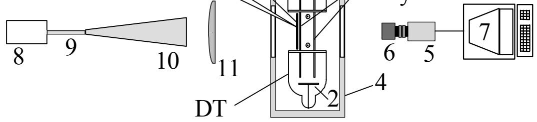

Fig. 1

Amplitude and phase objects were used as the test objects to evaluate the imaging system. At first static objects were imaged. Letters from **IRMMW-THZ08** acronym cut out in aluminum foil were used as amplitude test objects. The height of the letters was 50 mm. The width of the rectangular strips transparent for MMWs was 12 mm. The foils were pasted on cardboard sheets. The images of the VC intensity variation due to the effect of the MMWs transmitted through slits are shown in Fig. 2. Since the variation of VC intensity $\Delta I(x,y)$

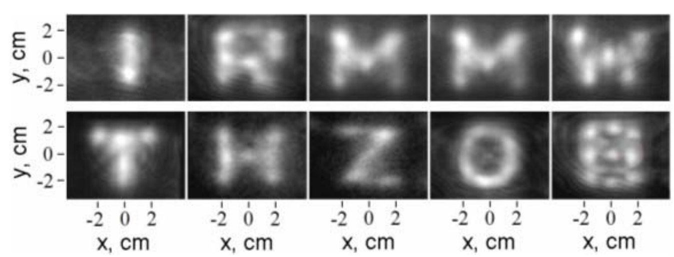

Fig. 2

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was directly proportional to the intensity of the MMWs $W(x,y)$ into the plasma slab (for $W < 1$ W/cm^2), the images represented 2-D distribution of the MMW intensity behind the object [2]. The effect of electron heat conduction blurred the images slightly. Obtained images of the letters were distorted by the diffraction because the plasma slab was located in the Fresnel region, where the quasi-plane waves transmitted through the cuts progressively become cylindrical waves [4]. Nevertheless all letters can be easily recognized. Fig. 3 (a) shows the image of letter **E** cut out of aluminum foil and glued to cardboard. The height of the letters was 50 mm, its width was 45 mm. The width of the foil strips was 10 mm. The image of this opaque object was clear enough.

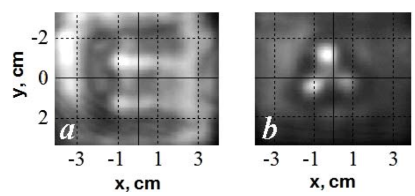

Fig. 3

The phase objects were made of dielectric materials having low MMW absorption. In Fig. 3 (b) the MMW transmission image of three Septogal pellets (cough-lozenge made by JADRAN, Croatia) is shown. The pellets were disks of 16 mm in diameter and their thicknesses were about 3.5 mm. The pellets were arranged as trefoil and placed inside an envelope. The three pellets were clearly visible in the MMW image (see Fig. 3 (b)), although their diameter exceeded the wavelength by less than two times. This experiment demonstrated that one could use the imaging technique for the nondestructive detection of chemicals including illicit drugs hidden in envelopes. In Fig. 4 MMW transmission

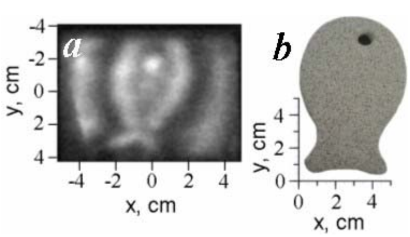

Fig. 4

image (a) and a photograph (b) of a pumice-stone in the shape of a fish are shown. The thickness of the pumice fish was 18 mm. The MMW transmission image of the phase object demonstrated the edge contrast enhancement (see Fig. 4(a)). There is a deep minimum of the intensity at the boundary of the object image. The minimum occurred between bright maxima of the intensity. The edge contrast enhancement phenomenon arose from MMW edge-diffraction by transparent object which produced the additional phase shift for the wave passing through it [5].

We have demonstrated that the technique can provide real-time imaging as well. In particular, we imaged oscillation of a pendulum. The pendulum was a Teflon ring suspended by thread about 15 cm long. The outer ring diameter was 25 mm, the inner ring diameter was 13 mm, and its thickness was 8 mm. The ring operated as three-zone phase mask which focused the MMW beam in the near-field in the focal spot about wavelength in diameter (see Fig. 5). The pendulum oscillation period was equal to about 0.8 s. In Fig. 5 continuity of MMW transmission images of pendulum motion obtained during a half of the oscillation period are shown.

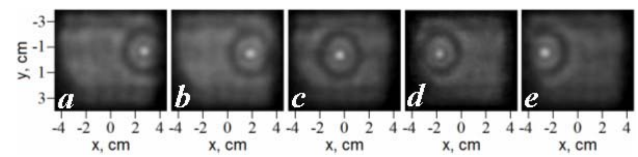

Fig. 5

We imaged how a glass tube filled with water was being emptied. The outer tube diameter was 8 mm, the inner tube diameter was about 6 mm. The tube filled with water was opaque for MMWs (see Fig. 6 (a)). When we opened a

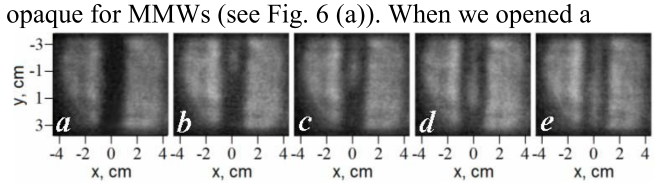

Fig. 6

discharge cock located at the foot of the tube (outside the aperture) the water began to flow out of the tube. Figs. 6 (b) – 6 (d) show how a glass tube was being emptied and becoming transparent for MMWs. The water poured out the tube for about 1 s. In Fig 6 (e) the MMW transmission image of the empty tube is shown. Because of the considerable difference in the refractive indexes of glass and air, the boundaries of the tube are well-defined in Fig 6 (e).

REFERENCES

[1] K. Watabe, et al., "Millimeter-wave active imaging using neural network for signal processing", *IEEE Trans. on Microwave Theory Tech.*, vol. 51, pp. 1512-1515, 2003.

[2] I. E. Abubakirov, M.S. Gitlin, et al., "Imaging the spatial distribution of microwave intensity using the recombination continuum emitted by the positive column of the Cs-Xe DC discharge", *Radiophys. Quantum Electron.*, vol. 46, pp. 722-728, 2003.

[3] M. S. Gitlin, A. G. Spivakov, "Mechanism of the electric field effect on the intensity of visible continuum emission from the positive column of gas discharge in a cesium vapor–xenon mixture", *Tech. Phys. Lett.,* vol. 33, pp. 205–208, 2007.

[4] S. Laybrous et al., "The "very-near-field" region of equiphase radiating apertures", *IEEE Antenn. Propag. Mag.*, vol. 37, pp. 50 – 66, 2005.

[5] S. P. Anokhov, "Plane wave diffraction by a perfectly transparent half-plane", *J. Opt. Soc. Am. A.,* vol. 24, pp. 2493 – 2498, 2007.

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