Improvement of plasma waves terahertz detector using terajet effect in mesoscale dielectric cube: proof of concept

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Terahertz (THz) wave band has much attention for communication, medical, product quality control, nondestructive testing and homeland security applications, to name a few [1–4] in which detectors are one of the oldest radiation sensing techniques [5] and are a key elements [6] and so the development of sensitive detectors has attracted much interest. THz band is usually characterized by optical matching methods for the radiation flux with the receiving element by a quasi-optical lens or a horn antenna [7–12]

These methods were important advancements, but they also had drawbacks since the sizes of such classical quasioptical elements usually are much larger than the wavelength and these devices could not been directly integrated with THz detectors, which stimulating the development of a new THz component base. Moreover, the main feature of such methods is significant diffraction limitations when radiation is introduced into the receiving elements, as a result of which limitations in sensitivity to received radiation signals appear. For example, the noise equivalent power (NEP) of the receiving element depends on its volume and temperature as [13,14]

$$NEP \propto T^3\sqrt{V} \qquad (1)$$

where V is the volume of the receiving element and T is the working temperature. From this simple equation Eq. 1 it is followed, that the minimum NEP can be reached using a decrease in volume. Accordingly, this volume should be consistent with the volume of the focusing area of the incident light. However, the diffraction effects does not allow the concentration of the radiation flow below the diffraction limit [15] without the absence of additional optical or waveguide elements. However, the presence of such additional elements usually leads to an increase in losses and an increase in the NEP value.

Due to photonics play a key role in future THz systems, recently, a new approaches for the resolution enhancement relying on the effects of THz field localization near the shadow surface of a mesoscale dielectric particles were investigated. For example, a cubic particles are a natural Mie scatterer and solid immersion lens, which can generate so called photonic terajets beyond Abbe's diffraction limit and confine the scattering within a small divergence solid angle [16–20].

The phenomena of terajet yield simple approach to boost the performance of almost any focusing system by simply placing the mesoscale dielectric particle in front of the focal area [21,22].

In this work, to increase the coupling efficiency to a radiation source with THz plasma waves based detector we use a terajet formed by teflon cube with dimensions

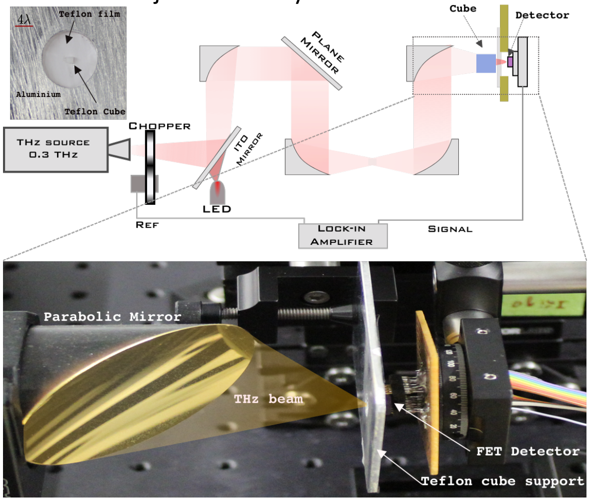

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Figure 1 Schematic diagram (a) and experimental setup (b) for terahertz detector characterization.

of wavelength. A gain enhancement of around 5 dB was experimentally observed with slight decrease of the noise equivalent power value.

A plasma waves based field effect transistor was used for the detection of the terahertz radiation. It's a strained silicon Modulation field effect transistor based on Si/SiGe system. More information of the device could be found in ref. [24]. A Dielectric Resonant Oscillator (DRO) at 12 GHz with series of frequency multipliers were used to emit at frequency of 0.3 THz. The output power, 6 mW, was measured close to the output of the source using a calibrated pyroelectric detector. The THz beam was collimated and focused by off-axis gold coated parabolic mirrors as shown in figure 1. The photo-induced drain-to-source voltage ΔU was measured using a lock-in technique where the THz beam was chopped at 298 Hz. A visible laser in combination with an indium tin oxide (ITO) mirror was used for the alignment of the THz beam 1. More detailed information according experimental setup may be fined in [23].

A 1x1x1 mm3 Teflon cube was fixed on a 100 µm film with glue transparent in THz of the Teflon and placed on an XYZ stage in the front of the detector (Fig.1). An aluminium plate with a hole of around 100 mm was used to hold the cube and the Teflon film (see insert in Fig.1). The beam spot diameter was about 2 mm at the frequency of 300 GHz was centered with a cube and the area of the detector, including the contact pads, was less than 0.05 mm^2 [24].

The effect of terajet formation near the shadow surface of dielectric cube is shown in figure 2. Numerical model of the cubic particle was built in the commercial FEM software package—CST Microwave Studio. A mesh size was selected as *****8. A plane wave of 1-mm wavelength equalling to 300 GHz frequency propagates from +z to –z direction with a polarisation along y axis which is vertical to the optical bench in the experiment. Optical properties — refractive index, n, and extinction coefficient, k, for Teflon (n = 1.43, k = 0.00014) are based on the previous results [19].

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It is clearly seen that near the rear surface of the cubic particle there is a localization (focusing) of the radiation incident on it with a maximum value of electric field enhancement about of $E^2 \sim 9$ V^2/m^2. The Full Width at Half Maximum (FWHM) [25] about 0.4 λ along X-axis and FWHM about 0.5 λ along Y-axis with the length of a terajet (defined as a Full Length at Half Maximum) about one of wavelength are observed.

So at measurement of detector characteristics the distance between shadow surface of a cube and detector was about the length of terajet.

The photoresponse was performed without the cube. Then, the cube was placed in the focal plane of the THz beam and the measurement repeated. The Responsivity (<) was extracted from the measured data via:

$$\Re_i = \frac{\pi}{\sqrt{2}} \frac{\Delta U}{P} \frac{S_t}{S_a} \qquad (2)$$

where P is the THz power incident on the transistor (~1 mW at the device position), measured by a calibrated pyroelectric detector. The factor $\pi/\sqrt{2}$ comes from the Fourier transform of the square-wave modulated THz signal detected as its rms value by the lock-in amplifier. S_t denotes the THz beam area given by $S_t = \pi r^2$ where r = 1.5 mm is the radius of the beam spot at 0.3 THz. S_a is the active area of the detector which it was replaced by the diffraction limit area $S_\lambda = \lambda^2/4$ in equation 2. A maximum responsivity close to 22 V/W was obtained with a gate voltage (V_g) close to the threshold voltage (V_{th} ~-0.8V) when no cube was used (Fig. 3). The responsivity was increased up to 36 V/W with introduction of the cube. This gives a gain of around 5dB . The NEP was also deduced from responsivity[23] by using the following formula:

$$NEP = \frac{N}{\Re} \qquad (3)$$

where N is the noise spectral density of the transistor in V/$\sqrt{\text{Hz}}$. Since no V_{DS} bias was applied to the channel, we assumed that thermal noise (N_{th}) is the only source of noise in measurements. Hence, $N = N_{th} = \sqrt{4k_B T R_{SD}}$ where T is temperature. The channel resistance R_{SD} was extracted from the transfer characteristics of the transistor at V_{DS}=100√mV. A minimum value of NEP was f√ound to be 200 pW/ Hz without the cube and 120 pW/ Hz with the cube (Fig. 3) at a gate voltage close to the threshold voltage and equal to -0.8V.

Conclusion From Radar range maximum detection formula determinate how Rmax increase if we increase the gain to 4 dB

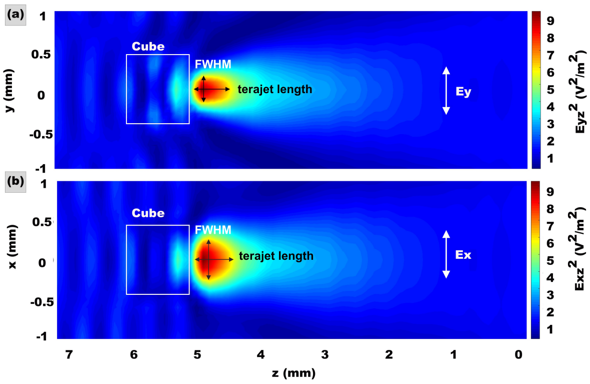

Figure 2 Simulation results of terajet formation for electric (a) and magnetic (b) components of field intensity

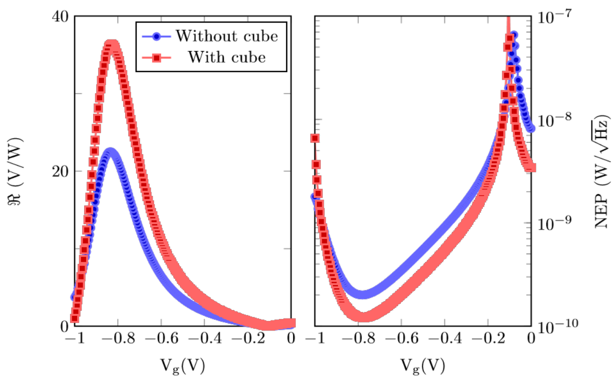

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Figure 3 (left) Responsivity versus gate voltage with and without the use of the teflon cube. (right) The obtained NEP for both cases.

It is shown that use of terajet effect in wavelength scaled dielectric cuboid particle-lens opens a new degree of freedom in designing efficient field localizations for sensitivity enhancement of THz detectors with minor decreasing (about 1.67 times) of NEP value.

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