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Improvement of a Terahertz Detector Performance Using the Terajet Effect in a Mesoscale Dielectric Cube: Proof of Concept

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Herein, a simple terahertz (THz) receiver that uses subwavelength focusing of the THz beam on the detector area is proposed. As a proof of concept, a THz detection system with an original optical coupling scheme is implemented, where the signal to be detected is coupled to a THz detector through a mesoscale dielectric particle lens. Coherent detection is successfully demonstrated with an enhancement of the detector sensitivity of about 4.3 dB, compared with that of a direct detection system with the slight decreasing (≈1.67 times) of noise equivalent power value. The results show that the proposed method can reduce the size and increase the sensitivity of various THz systems, including imaging, sensing, and ranging, which would enable significant progress in different fields such as physics, medicine, biology, astronomy, security, etc.

Terahertz (THz) waves have attracted great attention in communication, medicine, product quality control, nondestructive testing, and homeland security applications, to name but a few,[1–4] in which the detector, a key element,[5] uses one of the oldest radiation-sensing techniques.[6] Considerable efforts have been made to develop sensitive and compact THz receivers in the past decades. The THz band is usually characterized using optical matching methods of the radiation flux to the receiving element through a quasioptical lens or a horn antenna.[7–13]

These methods provided important advancements, but they also had drawbacks as the sizes of such classical quasioptical elements usually are much larger than the wavelength, and they could not be directly integrated with THz detectors, hindering the development of new THz components. Moreover, optical methods suffer from significant diffraction limitations when radiation is introduced into the receiving elements. As a result, limitations in sensitivity to the received radiation signal also appear. For example, the noise equivalent power (NEP) of the receiving element depends on its volume (V) and operation temperature (T) as[14,15]

$$\mathrm{NEP} \propto T^3\sqrt{V} \tag{1}$$

From this simple equation, it follows that reducing the volume of the receiver could lead to a lower NEP. In addition, this volume should be consistent with the volume of the focusing area of the incident light. However, the diffraction effects do not allow the concentration of the radiation flow below the diffraction limit[16] without the absence of additional optical or waveguide elements. Accordingly, the presence of such additional elements usually leads to an increase in losses and an increase in the NEP value.

The problem of superdirectivity or subwavelength focusing (localization) is a topic that started with the "Einsteinian needle radiation" mentioned in a 1922 article by Oseen.[17] As photonics will play a key role in future THz systems, recently, new approaches to enhance the resolution, relying on the effects of THz field localization near the shadow surface of mesoscale dielectric particles, were investigated. For example, cubic particles are a natural Mie scatterer; therefore, a solid immersion lens could generate the so-called photonic terajets beyond

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Abbe's diffraction limit and will confine the scattering within a small divergence solid angle.[18–22]

The phenomena of terajets provide a simple approach to boost the performance of almost any focusing system by simply placing a mesoscale dielectric particle in front of the focal area.[23,24]

In this work, to increase the coupling efficiency of a THz radiation source with a field-effect transistor-based detector, we use a terajet formed by a Teflon (polytetrafluoroethylene, PTFE) cube with wavelength dimensions. A gain enhancement of around 4.3 dB was experimentally observed along with a slight decrease of the NEP value.

A field-effect transistor was used for the detection of the THz radiation due to some advantages: high responsivity, room-temperature operation, fast response, low cost, and a low NEP.[25,26] The transistor is a strained silicon modulation field-effect transistor (Si MODFET) based on the Si/SiGe system. More information on the device can be found in Delgado-Notario et al.[26] A dielectric resonant oscillator (DRO) at 12.5 GHz followed by frequency multiplication steps was used to generate radiation at a 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 photoinduced drain-to-source voltage ΔU at THz illumination 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 (Figure 1). More detailed information on the experimental setup may be found in a previous study.[25] A $1 \times 1 \times 1\,mm^3$ Teflon cube was fixed on a 100 μm thick Teflon film and placed on an XYZ stage in front of the detector (Figure 1). An aluminum plate with a hole of a diameter of around 10 mm was used to hold the cube and the Teflon film (see inset in Figure 1). The beam spot with a radius of about 1.5 mm at 0.3 THz was centered within the cube. The area of the detector, including the contact pads, was less than $0.047\,mm^2$ (or $0.255\,mm \times 0.183\,mm$).[26]

Figure 2 shows the measured photoresponse (ΔU) as a function of the gate bias voltage (V_g) where no drain-to-source bias was applied ($V_{ds} = 0$ V). The inset shows the transfer characteristics of the device obtained at $V_{ds} = 100$ mV from which a threshold voltage of $V_{th} \approx -0.8$ V was extracted. The photoresponse was initially measured without the cube. Then, the cube was placed in the focal plane of the THz beam and the photoresponse measurement repeated. A maximum of the photoresponse for both cases (with and without the cube) was observed around the threshold voltage, which is related to the nonresonant behavior of the plasma waves.[25] A clear enhancement of the photoresponse was observed when the cube (that induces the terajet effect) was used.

The effect of the terajet formation near the shadow surface of the dielectric cube is shown in **Figure 3**. A numerical model of the cube was built in the commercial FEM software package CST Microwave Studio. A mesh size of 0.0142857 mm (or $\approx\lambda/70$) was selected for the smallest cell and 0.0569375 mm (or $\approx\lambda/18$) for the largest one. A plane wave of 1 mm wavelength equalling 0.3 THz frequency propagates from $+z$ to $-z$ direction with a polarisation along the X-axis, which is vertical to the optical bench in the experiment. Optical property parameters of the Teflon were taken based on previous results[21] (refractive index

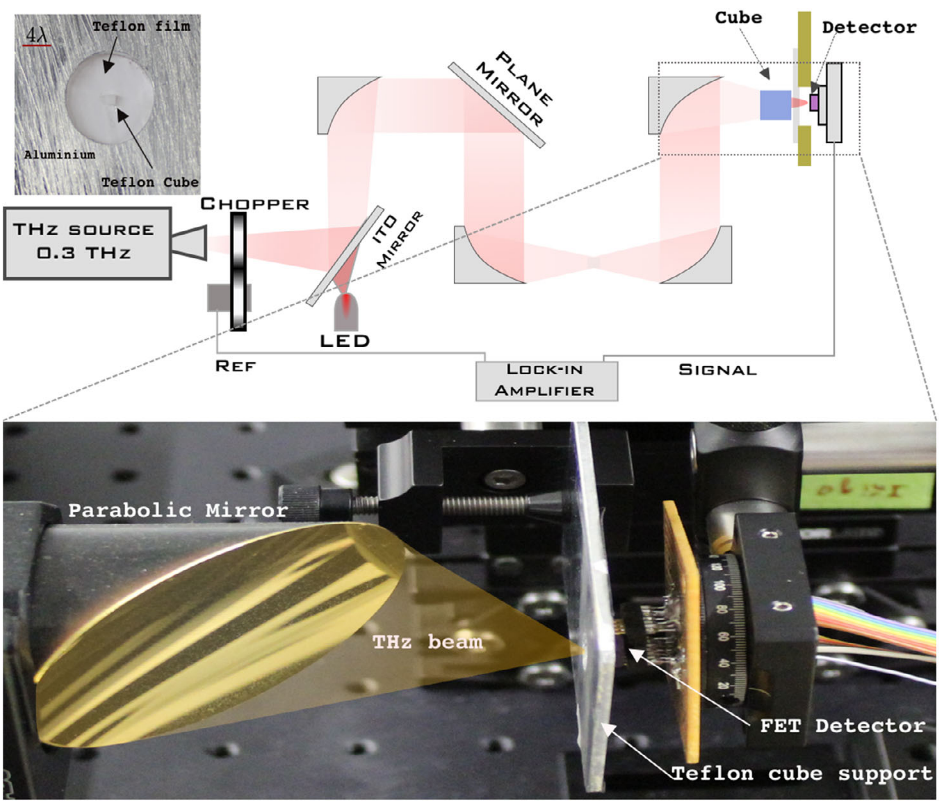

Figure 1. A schematic diagram (top) and experimental setup (at the bottom) for THz detector characterization.

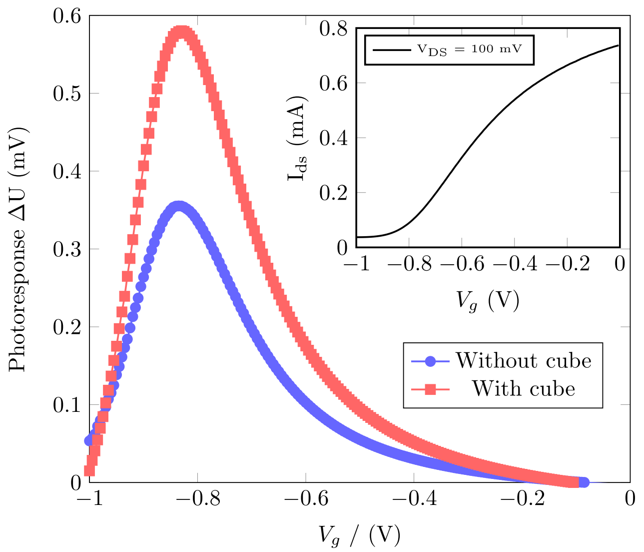

Figure 2. Photoresponse as a function of the gate voltage with (red square) and without (blue circle) the cube. The inset shows the transfer characteristics of the Si MODFET device at $V_{ds} = 100$ mV.

$n = 1.4491$ and extinction coefficient $k = 0.00014$). It is clearly seen that near the rear surface of the cube there is a localization (focusing) of the radiation incident on it with dimensions of the field localization area defined as full width at half maximum (FWHM)[28] of about 0.4λ along the Y-axis and of about 0.6λ along the X-axis, with the length of a terajet similarly defined as FWHM along the Z-axis, of about one wavelength. This gives a volume of E^2 field localization as $V_E \approx 0.126\lambda^3$, E being the module of the electric field. A maximum value of the electric field enhancement of $E^2 \approx 9\,\mathrm{V^2\,m^{-2}}$ is obtained. In measurements, the distance between the shadow surface of the cube and the detector was about the length of the terajet. The inset of Figure 3 shows a microscope image of the transistor with the terajet beam spot illustration. The effect allows the confinement of the THz beam in a small volume that enhances the measured photoresponse (Figure 2).

Responsivity ($\Re$) was extracted from the measured data via

$$\Re_i = \frac{\pi}{\sqrt{2}} \frac{\Delta U}{P} \frac{S_t}{S_a} \tag{2}$$

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 that was replaced by the diffraction limit area $S_\lambda = \lambda^2/4$ in Equation (2). Experimental results of responsivity ($\Re$) versus gate voltage (V_g) with and without the use of the Teflon cube and the obtained NEP values for both cases are shown in **Figure 4**. A maximum responsivity close to 22 V W^{-1} was obtained with a gate bias voltage (V_g) close to the threshold voltage ($V_{th} \approx -0.8$ V) when no cube was used (Figure 4, left). The responsivity was increased to 36 V W^{-1} with the introduction of the cube. This gives a gain of around 4.3 dB.

The NEP was also deduced from the responsivity[25] using the following formula

$$\mathrm{NEP} = \frac{N}{\Re} \tag{3}$$

where N is the noise spectral density of the transistor in V Hz$^{-1/2}$. As 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

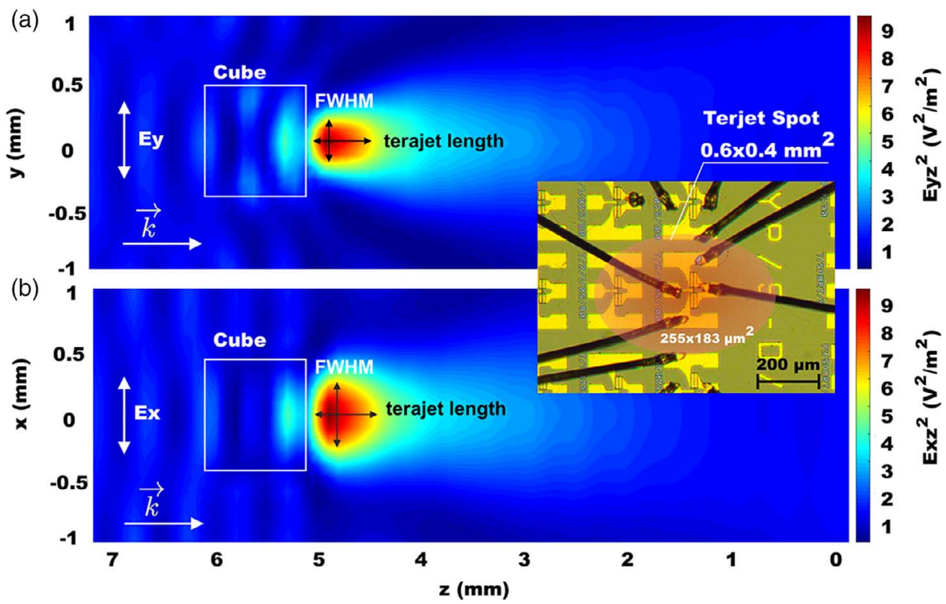

Figure 3. Simulation results of terajet formation in a) X and b) Y plane: the electric field intensity E^2. The inset shows a microscope image of the transistor[27] with the terajet beam spot for illustration.

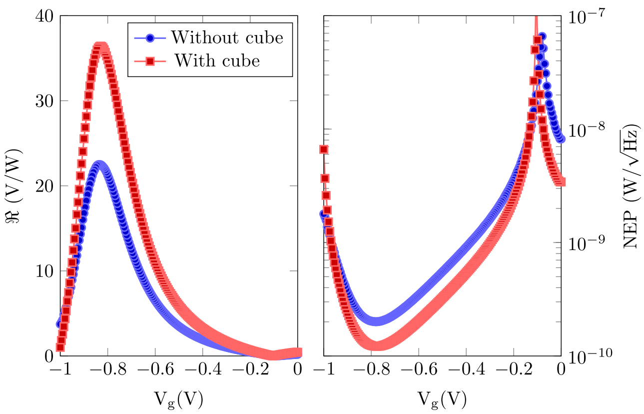

Figure 4. Experimental responsivity (ℜ) versus gate voltage (V_g) with (red) and without (blue) the use of the Teflon cube (left). The obtained NEP for both cases (right).

and k_B the Boltzmann constant. The channel resistance R_{SD} was extracted from the transfer characteristics of the transistor at $V_{ds} = 100$ mV (inset of Figure 2). The minimum value of NEP was found to be 200 pW $Hz^{-1/2}$ without the cube and 120 pW $Hz^{-1/2}$ with the cube (Figure 4, right picture) at a gate voltage close to the threshold voltage and equal to −0.8 V. Given the estimated localization volume of the incident radiation as $V_E \approx 0.126\lambda^3$, from Equation (1), it follows that the NEP value should be reduced by a factor of 2.7 when the cube is used. The measured factor is 1.67, which is reasonably consistent with the above estimate, taking into account that the terajet beam area is two times higher than that of the device (see inset in Figure 3).

In conclusion, we have demonstrated a receiver at 0.3 THz, with an original coupling scheme between the incident radiation and the detector through the air using a subwavelength terajet concept with a volume of electric field intensity localization of $V_E \approx 0.126\lambda^3$.

It is shown that use of the terajet effect in a wavelength-scaled dielectric cuboid particle lens opens a new degree of freedom in designing efficient field localizations for sensitivity enhancement of THz detectors at ≈4.3 dB with a slight decrease (about 1.67 times) of the NEP.

The terajet width was about two times larger than the area of the detector, including the contact pads (see inset in Figure 3); therefore, one should expect an increase in the observed effect with a further decrease in the width of the beam focused on the detector, for example, by the anomaly apodization effect.[21]

The proposed concept of increasing the sensitivity of detectors can be applied to other types of receivers, for example, to concentrate the incident light within a subwavelength active volume on a photodiode, as the subwavelength volume integration of the E^2 field intensity also leads to photocurrent enhancement.[29]

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Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

I.V.M. and O.V.M. conceived of the idea and initiated the works; I.V.M., O.V.M., J.E.V.P., and Y.M.M. supervized and wrote the article; Y.M.M. and J.A.D.N. conducted the experiments; and J.C.G., M.F.B., and J.E.V.P. conducted the simulations. All authors discussed the results.

Keywords

detector sensitivity, dielectric cube, gain enhancement, terahertz detectors, terajet effect

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