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A novel terahertz detector technology based on vacuum electronics

Naoya Kawai*[a], Tobias Olaf Buchmann[b], Hisanari Takahashi[a], Kota Katsuyama[a], Simon Jappe Lange[b], Matej Sebek[b], Peter Uhd Jepsen[b], Hiroshi Satozono[a], and Takayuki Ohmura[a]
[a]Hamamatsu Photonics K.K., 314-5 Shimokanzo Iwata City Shizuoka Pref., Japan 438-0193;
[b]DTU Elektro, Technical University of Denmark, 2800 Kongens Lyngby, Denmark

ABSTRACT

A THz detector with both high sensitivity and fast time response has been required for industrial applications such as nondestructive testing (NDT), security, and spectroscopy. Through a collaboration with the Technical University of Denmark (DTU), we have recently developed a THz-sensitive point detector and imager based on metasurface and photomultiplier tube (PMT) and image intensifier (I.I.) technologies, respectively. A fast time response is one of the unique characteristics of these devices: the PMT-based point detector provides a nanosecond response time while the I.I.-based imager is capable of frame rates up to 1000 fps. These devices have a double split-ring resonator (DSRR) at the photocathode for THz-electron conversion (metasurface). In this paper, we discuss the two devices and report on the development and results for increasing their sensitivity for ultrafast, broadband THz pulses by sharpening the field-enhancing antenna tips. This leads to a smaller tip diameter, which increases the electric field confinement and thus intensity at the tip, making the field emission more likely to occur at lower field strengths as a result. Both devices thus offer a sensitive and simple method to detect THz frequencies easily, with the I.I. offering a handheld, 9V battery-powered device.

Keywords: metasurface, metamaterial, THz, terahertz, field emission, imaging, photomultiplier tube, image intensifier

1. INTRODUCTION

Various terahertz (THz) detection techniques have been developed for decades, applying photonics and electronics technologies in various cases. However, the typical THz photon energies (meV order) are too low to drive the photoelectric effect (eV order), and the typical radio frequency detection methods are not applicable either, due to the high frequencies of THz radiation. In addition, while thermal detectors such as pyrodetectors have high sensitivity for THz detection, the response times of the devices are relatively slow. These technical difficulties make terahertz's industrial implementation slower, even as THz technology is gaining attention for many industrial applications.

Our group developed a novel approach based on the ultrafast electron cold field emission from periodically arranged resonant antenna structures [1]. We have developed both point detector and imaging devices [2][3][4]. The point detector is based on the photomultiplier tube (PMT) technique, and the imaging device is based on the image intensifier (I.I.) technique [5]. Both detectors have a photon-to-electron conversion approach based on a metasurface. The metasurface consists of the two-dimensional gold antenna arrays such as DSRR or dipole antennas, produced using standard CMOS technology on a THz-transparent substrate. When the THz wave is incident on the metasurface, its electric field is confined to the antenna tips and enhanced due to the antenna resonances, which in turn modifies the potential barrier between the vacuum level and the gold surface. At sufficient modulation, a tunneling current from the gold tips to the vacuum is established. This phenomenon is well known as cold field electron emission (Fig. 1). The potential barrier is altered linearly with the incident THz electric field, but the resulting tunneling current density follows the highly nonlinear Fowler-Nordheim (FN) relation

$$J(E) = a\frac{(\beta E)^2}{\Phi}\exp\left(-\frac{b\Phi^{3/2}}{\beta E}\right), \tag{1}$$

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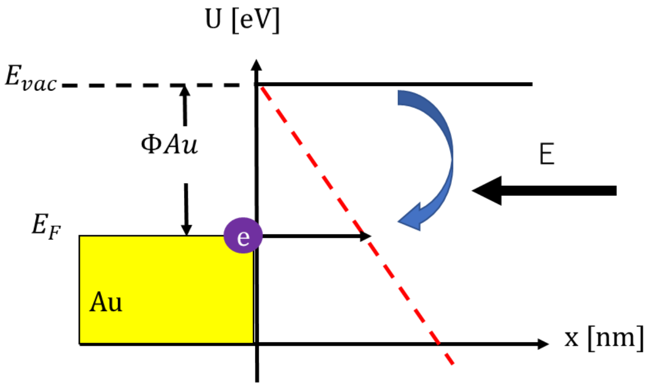

Figure 1. Conceptual diagram of the potential barrier modulation by an external electric field

where a and b are FN constants, Φ is the material specific work function, β is the achieved field enhancement at the antenna tips, and E is the applied (THz-) electric field. We have developed our THz PMT (Fig. 2) and I.I. (Fig. 3) by combining this metasurface with the corresponding established technologies. In the THz-PMT, the electrons emitted from the metasurface are multiplied by CuBe dynodes, resulting in a strongly amplified current at the anode, which is detected as the signal output. On the other hand, in the THz-I.I., the electrons emitted from the metasurface are multiplied by a microchannel plate (MCP), allowing to keep each electron's position information, which is subsequently projected onto a phosphor screen, converting the electrons to visible light. In both devices, the electron multiplication occurs under vacuum conditions, providing an increased signal-to-noise ratio and a faster time response as a result.

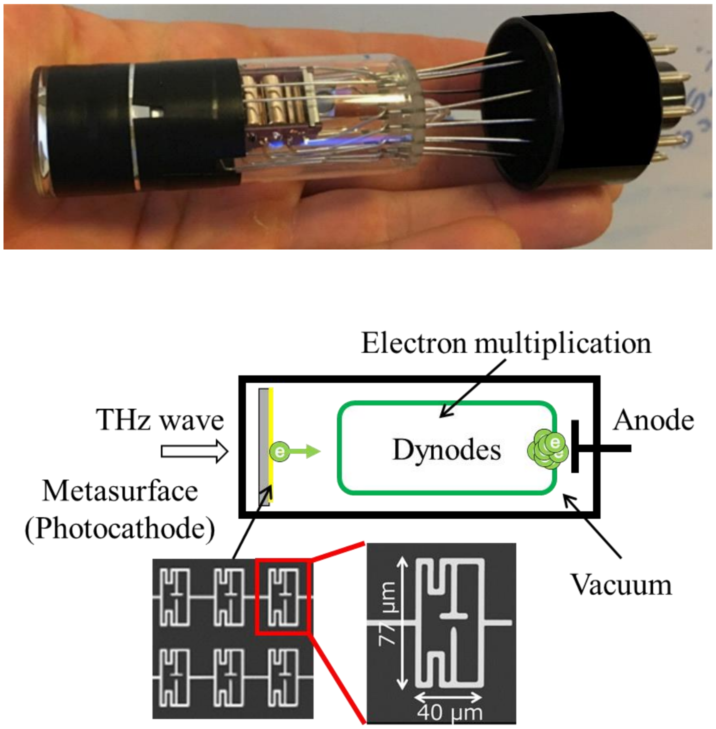

Figure 2. Photo and principle of THz-PMT

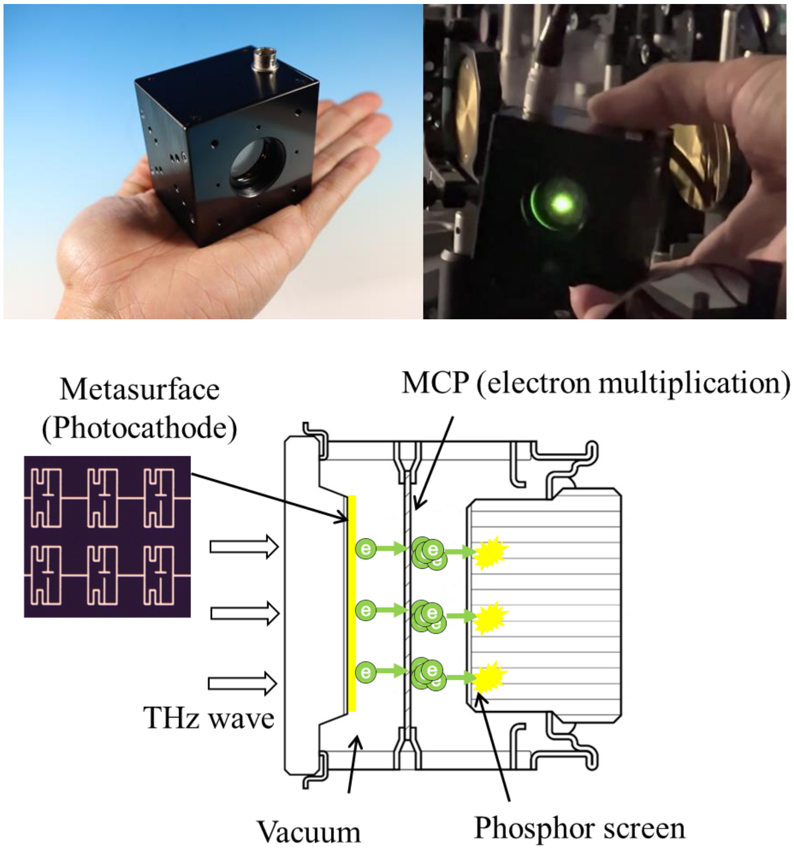

Figure 3. Photo and principle of THz-I.I.

In this paper, we modified the metasurface to increase the sensitivity of the devices. In particular, we evaluated the sensitivity of a modified device with sharper antenna tips to enhance the incident electric field.

2. METHODS & RESULTS

We worked on improving the antennas to increase the sensitivity of these devices. Under the expectation that sharpening the tip of the emitter portion would concentrate the electric field more strongly and increase sensitivity, we prepared several samples that have different emitter tips. The emitter shapes are shown in Fig. 4, with the two tip diameters being 1 μm and 0.1 μm. All other parameters and processing conditions are the same when implementing the metasurfaces into a THz-PMT. We experimentally obtained the relationship between the strength of the incident terahertz electric field and the signal output from the THz-PMT. The THz pulse was generated by using a Ti:Saph regenerative amplifier system with conventional tilted-pulse front technique [6]. The results are shown in Fig. 5.

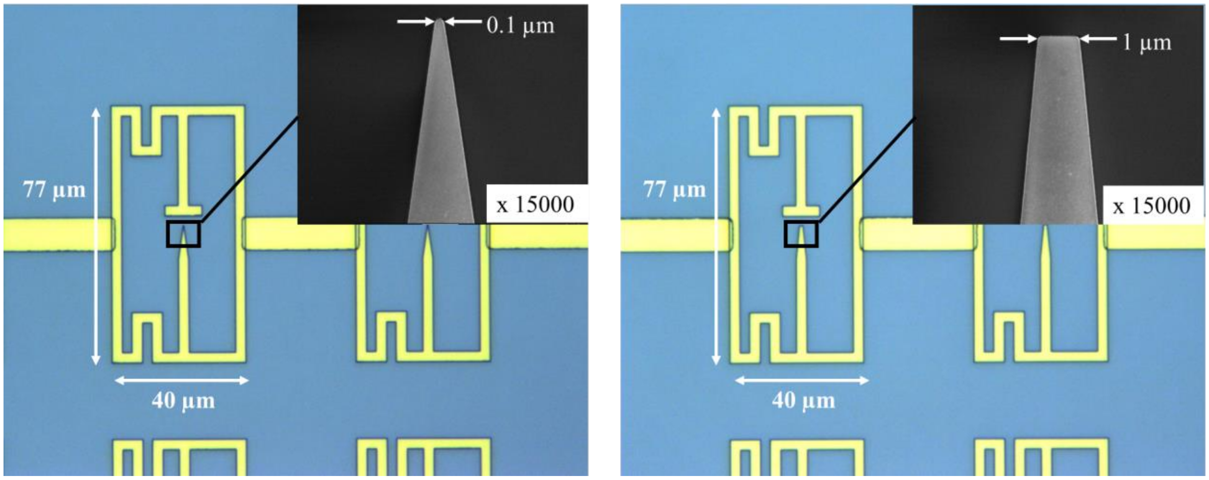

Figure 4. Fabricated metasurface. The substrate and material of the antenna were high resistivity Si and Au, respectively. Inset: tip of the antenna.

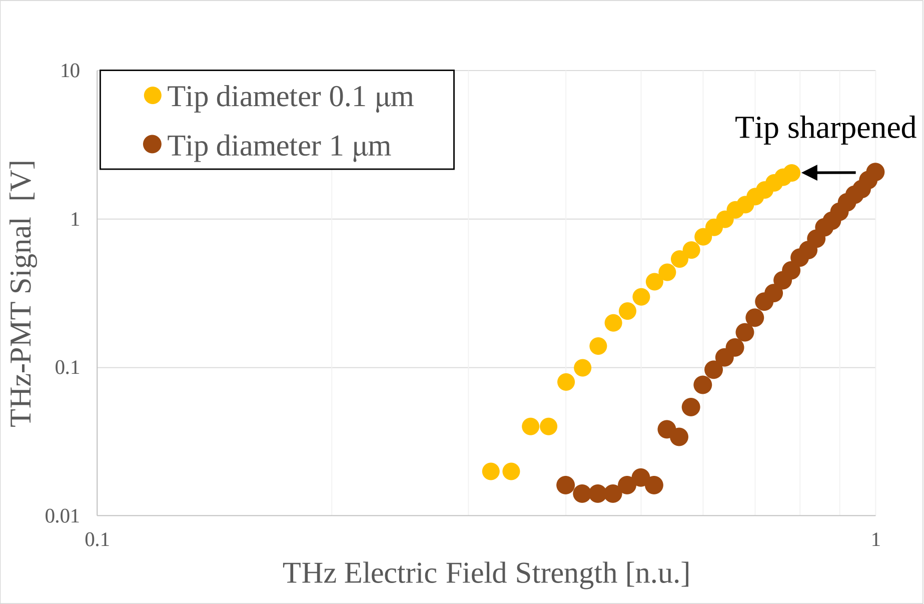

Figure 5. THz-PMT response curves for various modifications

Applying these changes to the metasurfaces implemented into the THz-I.I. offers enhanced sensitivity in the same way. Figure 6 shows the THz-I.I. beam image of a focused and of a collimated terahertz beams using THz pulses obtained from optical rectification in a ZnTe crystal, pumped by a regenerative Ti-sapphire fs laser. The terahertz electric field strength of the collimated beam is on the order of a few kV/cm, measured by EO sampling.

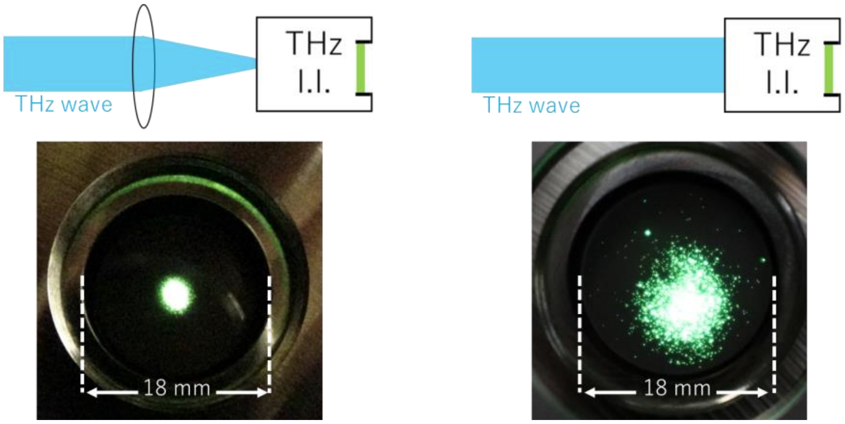

Figure 6. THz-I.I.: beam image of a focused (left) and a collimated (right) light of a terahertz wave

As a proof-of-concept for NDT, we conducted an experiment to image a 1.5 mm diameter wrench enclosed in a standard paper envelope. The results are shown in Fig. 7. We succeeded in detecting the wrench in the envelope in real time.

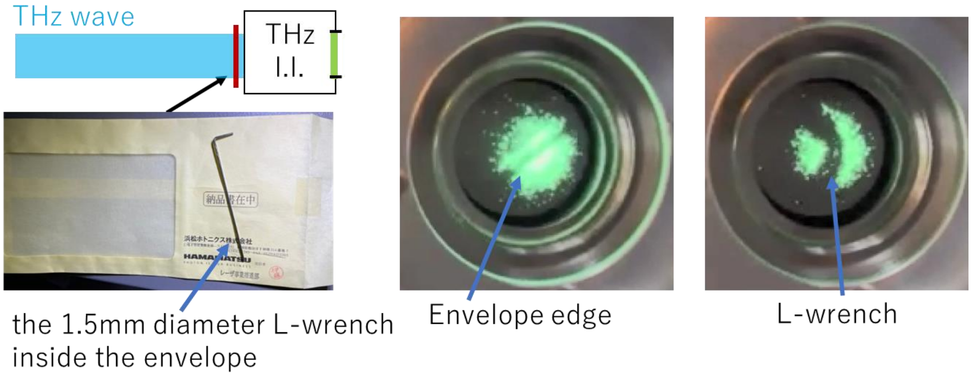

Figure 7. Nondestructive detection of wrenches in envelopes

The I.I. also offers a straightforward approach to the user, as the only external requirement is a 9V battery. We have fitted the I.I. with an adjustable gain knob to adjust the brightness of the emission on the phosphor screen. Because the metasurfaces are only responsive to their resonance frequency, and in addition only the absolute field strength, they are not affected by any background radiation as commonly is the case for other detectors at these frequencies. This means that the THz-I.I. is inherently background-free. Combining the THz-I.I. screen with a standard CCD camera thus gives a useful combination for several imaging applications in the THz range.

3. CONCLUSION

We confirmed the improvement of sensitivity by sharpening the tip diameter. Additionally, we also confirmed that the relationship between the incident THz field strength and the detector output is strongly nonlinear. This means that the THz-PMT is able to detect even a slight change in incident THz field strength as a significant change of its output signal. Thus, the sensitivity of the devices can be improved by a sharper design of the metasurface antenna tips. We implemented these metasurfaces into two devices, a PMT and an imaging device, essentially extending the frequency range of existing technologies. Lastly, we proved the real-time imaging capabilities of the THz-I.I., showing that this type of device can be applied in NDT, for example.

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