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Invited Paper

Terahertz detectors based on vacuum electronics

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ABSTRACT

We report on various metasurfaces for the purpose of THz driven electron field emission and subsequent detection using vacuum electronics. The underlying principle is based on strong localised field enhancement at metal and semimetal emission points, which bends the vacuum potential temporarily to allow for field emission of electrons from the parent material. The structures are investigated for varying electric field strength using electron time-of-flight measurements as well as electron multiplication and visualisation on a phosphor screen. Measured properties include the emitted electron energy, their count, and the emission threshold. From the recorded data, the local field enhancement for each structure is extracted and compared to simulated values. Subsequently, optimised metasurfaces are implemented into handheld devices that serve as easy-to-use THz detectors. These devices include photomultiplier tubes which operate at frequencies from THz to infrared, as well as live imaging devices with kilohertz framerates. The investigated metallic structures include standard dipole antennas, double split-ring resonators, bow-tie designs, hybrid split-ring and dipole designs, and logarithmic spirals. Semimetallic structures are based on structured and unstructured graphene, which show different emission characteristics. All samples are investigated using strong-field THz radiation generated using lithium-niobate tilted pulse front setup, as well as commercial THz-TDS instruments. In conclusion, we present a holistic overview of the current state-of-the-art THz-PMTs and image intensifiers.

Keywords: THz PMT, THz imaging, THz driven field electron emission

1. INTRODUCTION

Terahertz (THz) radiation, owing to its unique attributes and wide-ranging applications, from spectroscopy in the food industry [1] to imaging and security [2], has drawn considerable attention. With the recent emergence of high power, high repetition rate THz-generation technology [3], simple THz detection has taken on a heightened level of importance to harness the full potential of this radiation. Though traditional THz detection methods, such as bolometers, pyro-electric detectors, and electro-optic sampling (EOS) systems have been widely used, they each have inherent limitations. Consequently, this has prompted the exploration of alternative avenues, notably vacuum electronics, including photomultiplier tubes (PMTs), which have several advantages that make them highly suitable for the detection of light. PMTs are renowned for their exceptionally high sensitivity and offer fast response times in the order of nanoseconds, crucial for high-speed or time-resolved measurements. Importantly, their large dynamic range allows them to function effectively across a wide array of light intensities and by a suitable choice of the photo-cathode are currently capable of detecting a broad spectrum of wavelengths from UV to near-infrared light frequencies. Extending these capabilities to encompass the terahertz regime promises to pioneer new advancements in fields such as spectroscopy and imaging.

THz driven electron emission

Essential to vacuum-electronic systems is the liberation of electrons induced by the incident lightwaves intended for detection. To achieve electron emission, we harness the effect of intense localised field enhancement in metals and semimetals. The localised electric field temporarily modulates the vacuum potential, facilitating field emission of electrons from the parent material, see fig. 1.

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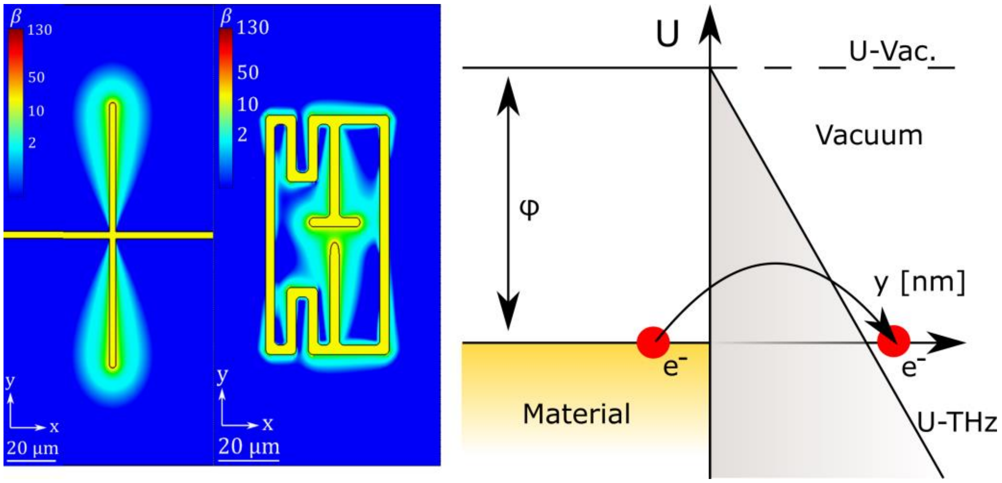

Figure 1. Left: Simulation of the localised field-enhancement at emitter tips (taken from [4]). The colour bar shows the localised field enhancement factor β. Right: Schematic of the electron-tunnelling resulting from the application of an external electric field. The dashed line shows the potential barrier for field-free case, while the U-THz applied field leads to the bending of said barrier. Once the barrier reaches low enough width, on the orders of nm, electrons can tunnel out of the material without the need to acquire the necessary energy φ to overcome the potential barrier.

To establish a better understanding of the metasurface emission, we fabricated and studied various metallic structures, including standard dipole antennas, double split-ring resonators, bow-tie designs, hybrid split-ring and dipole designs, and logarithmic spirals. We experimentally simulate the PMT environment in a small vacuum chamber with a multichannel plate for electron multiplication and a phosphor-screen, which is connected to an ammeter in order to record the (variable) THz-field induced electric current upon discharge. In a larger vacuum chamber, equipped with a time-of-flight tube, we study the emission characteristics in regards to electron energy as a function of the THz field-strength. Here, we also investigate the THz driven emission from structured and unstructured semimetals such as graphene. Through these investigations, we can evaluate the threshold field-strength to drive electron emission (equating to the THz-PMT sensitivity), estimate the out-of-plane component of the electric field at the metasurface through the emitted electron energy, the experimentally derived enhancement factor based on the recorded current vs field-strength data, and the limitations due to damage. The recorded data is further compared to simulated values from finite-element numerical solvers, such as CST or COMSOL, via either a time- or frequency domain solver (e.g. the field enhancement shown in fig. 1). Two emission models are used; field emission based on the Fowler-Nordheim model and thermionic emission based on Richardson-Dushman model, as both emission origins contribute to the total tunnel current.

2. IMPLEMENTATION INTO THZ DETECTORS

THz-PMT

When replacing the standard photo-cathode in established PMTs with a suitable metasurface, the PMT-technology is thus available for the entire mid-IR (>2 µm) to THz frequency (<1 mm) range. A key difference to PMTs in the visible range is that the electron liberation process applied here is highly nonlinear and relies on the lightwave’s electric field rather than the intensity. The THz-PMTs can detect minute concentration changes of e.g. gases that affect the THz probing beam, offering more sensitive detection compared to linear, intensity-based detectors. In addition, the THz-PMT can detect certain properties of the incident lightwaves, such as their polarisation and polarity, and its absolute field-strength when using a field-calibrated PMT. An image of a THz-PMT is shown in fig. 2. Due to the different electron emission process compared to classical PMTs where the photocathode material’s work function defines the signal threshold (through the photoelectric effect), our PMTs are defined to have a sensitivity threshold that produces sufficient field emission to deliver a constant electric signal. Currently, our PMTs can be activated with electric field strengths as low as 1 kV/cm.

THz-Image Intensifier (THz-I.I.)

By placing the metasurface into a slightly different vacuum electronics configuration, the liberated electrons can be multiplied and accelerated onto a phosphor screen. This leads to the direct visualisation of THz lightwaves for imaging applications, as shown in fig.2. Specifically, the dynode-structure in the PMT is replaced by a multichannel plate for electron multiplication, and the electrons are subsequently accelerated towards a phosphor screen where they emit green light upon impact. Compared to existing imaging options, the THz-I.I. offers kHz framerates with high sensitivity, limited by the framerate of the recording digital camera.

Figure 2. Left: Picture of the THz-PMT. Right: Picture of the THz.I.I., showing the imaging resolution for a 0.5 THz beam.

Conclusion

Our efforts in metasurface investigation and combination with existing technology shed light on the promising prospects of vacuum-based THz detectors. The examined metasurfaces, particularly those integrated into state-of-the-art THz-PMTs and image intensifiers, show potential for improved sensitivity and imaging speed. Consequently, they offer promising future directions for THz detection technology when combined with tuneable frequency swept THz sources [5]. Our ongoing studies focus on deepening our understanding of THz-driven electron emission and enhancing the sensitivity of these systems. Currently, our sensitivity allows for operation and detection with lightwave field-strengths below 1 kV/cm.

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