# Millimeter Wave Imaging Using Up-Conversion Detection Method with Glow Discharge Detector and Photoreceiver Combination

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Abstract: This paper presents an advanced photonic detection system for high-resolution millimeter-wave (MMW) imaging, utilizing an up-conversion detection method with a Glow Discharge Detector (GDD) and a photoreceiver to capture detailed images of metallic objects. The system employs a 105 GHz MMW beam, generated by a custom transmitter, which illuminates the object. Reflected MMW radiation is collected by a large spherical mirror and directed to the GDD, where the MMW signal is up converted to an optical signal. The GDD's response to MMW incidence produces a measurable increase in light intensity, detected by a low-noise photoreceiver equipped with a Si-PIN photodiode, enhancing the sensitivity and accuracy of the detection process. The GDD-photoreceiver assembly is mounted on motorized linear stages, enabling precise vertical and horizontal scanning in patterns, which facilitate the creation of grayscale MMW images. Data acquisition is conducted through a dedicated platform that translates the detected signals into clear, high-quality images. This system showcases significant advancements in photonic detection for MMW imaging, offering enhanced resolution and sensitivity, which are advantageous for a range of applications.

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## 1 INTRODUCTION

Millimeter wave (MMW) imaging has gained significant attention across various fields, including security screening, medical diagnostics, and industrial inspection, due to its ability to penetrate non-metallic materials and produce detailed images (Siegel, 2002). However, traditional MMW imaging systems often face limitations in resolution, sensitivity, and operational complexity, which restrict their effectiveness and application scope.

The advancement of affordable, durable, and easy-to-use room-temperature sensors for MMW applications is critical for the successful deployment of MMW imaging systems. Conventional MMW detectors, such as Schottky diodes, Golay cells, and bolometers, often come with high costs and increased sensitivity to electrostatic discharge (ESD), making them vulnerable to damage from high-power MMW exposure (Rogalski and Sizov, 2011). In this context, glow discharge detectors (GDDs) (Kopeika, 1975) utilizing weakly ionized plasma (Hou and Shi, 2012) have emerged as a promising alternative, demonstrating superior sensitivity to MMW/THz radiation alongside a faster response time. This capability not only simplifies the detection system but also significantly reduces costs, which is particularly beneficial for applications involving imaging and detector arrays (Rozban et al., 2008).

In our work, we focus on two fundamental principles for MMW detection using GDDs: the electrical current method, which measures changes in bias current due to incident radiation, and the optical up-conversion method (Haj Yahya et al., 2021).

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However, our primary emphasis is on the up-conversion technique, which detects alterations in the emitted light from the GDD when exposed to MMW radiation (Aharon et al., 2016). By integrating a photoreceiver with the GDD, we can accurately measure these light intensity changes, taking advantage of the rapid response time inherent in this method (Aharon et al., 2019). The up-conversion approach not only minimizes internal noise compared to conventional electrical detection but also provides a cost-effective solution for enhancing the performance of MMW imaging systems. This synergy between the GDD and photoreceiver is pivotal in advancing our ability to capture high-quality MMW images, thereby facilitating further developments in THz applications.

This study introduces an innovative MMW imaging system that addresses these limitations by integrating a Glow Discharge Detector (GDD) with a high-sensitivity photoreceiver, utilizing an up-conversion detection method. By converting the MMW signal into an optical signal, this system enables the use of advanced optical components, which offer enhanced sensitivity and bandwidth compared to conventional electrical detectors.

At the core of the system is a 105 GHz MMW source, which illuminates metal objects positioned in the object plane. The collimated MMW beam, shaped by an off-axis parabolic mirror and transmitted through a horn antenna, is modulated by a 10 kHz TTL pulse, providing precise control over the MMW radiation. The GDD converts the MMW signal into an optical signal, creating a measurable increase in light intensity in response to MMW incidence. This optical signal is then detected by a low noise photoreceiver, significantly enhancing the sensitivity and accuracy of signal capture.

The single GDD-photoreceiver assembly is mounted on motorized linear stages (NRT100M from Thorlabs) that enable precise raster scanning in both vertical and horizontal directions. By moving in a controlled, stepwise pattern, the system captures data points across the object plane to construct an 8x8 grayscale MMW images. The flexibility in scanning patterns allows for various levels of detail, with finer grids providing higher image resolution and greater detail for applications requiring in-depth MMW analysis. Each captured data point is processed through a dedicated data acquisition platform, enabling the construction of detailed images that are valuable for applications requiring rigorous MMW analysis and imaging clarity.

This research demonstrates the effectiveness of combining the up-conversion detection method with the GDD-photoreceiver configuration in advancing MMW imaging systems. Through enhanced detection sensitivity and precise scanning capabilities, this system overcomes key limitations of conventional MMW imaging, opening new possibilities for high-resolution imaging applications across multiple domains.

## 2 EXPERIMENTAL SETUP

The experimental setup depicted in Figure 1 consists of a millimeter wave source manufactured by Virginia Diodes Inc. (VDI TX272), a quasi-optic design based on an off-axis parabolic mirror (OPM), a reflecting/imaging mirror, and a lock-in amplifier (MFLI) from Zurich Instruments. The detection circuit is comprised of a single Glow Discharge Detector of type N523 from International Light Inc. and a photoreceiver, which together serve as the primary pixel/detector element.

The GDD is positioned in a head-on configuration, providing a total detection cross-section with an approximate diameter of 6 mm. The effective detection area, where sensitivity is strongest between the electrodes, has a diameter of about 3 mm, which is at least twice the electrode separation.

The MMW source is capable of radiating signals in the frequency range of 100 GHz, which are modulated using a 10 kHz square wave with a peak-to-peak amplitude of 5 V. The off-axis parabolic mirror collects and collimates the MMW radiation towards the metallic object placed in the object plane. Reflected MMW radiation from the object is then focused onto a spherical mirror, which projects the radiation to the image plane where the detection circuit is located.

Calibration and alignment of the GDD and photoreceiver assembly are achieved using a laser to ensure that the GDD is positioned at the reflective focal length of the spherical mirror. The detection circuit recognizes changes in the bias current of the GDD due to the incidence of MMW radiation, while the photoreceiver detects the resulting optical signal. The signal output from the photoreceiver is connected to the +V signal input of a lock-in amplifier (MFLI) from Zurich Instruments, which operates at frequencies of 500 kHz to 5 MHz and has a sampling rate of 60 MSa/s.

The modulating signal is also routed to the auxiliary input of the lock-in amplifier to facilitate synchronous detection. The detected analog signal is then processed by the lock-in amplifier for further signal analysis and the generation of grayscale images. The data acquisition is implemented using an FFT-based algorithm incorporated into LabVIEW, ensuring compatibility with the optical detection system and enhancing the overall performance of the imaging setup.

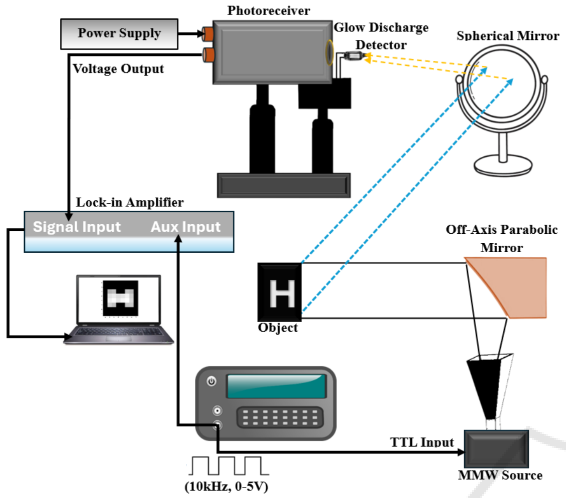


Figure 1: Schematic Diagram of the Experimental Setup for MMW Imaging Using GDD and Photoreceiver.

## 2.1 Optimizing Detection for Improved MMW Detection

To enhance the performance and accuracy of the GDD and photoreceiver combination in our MMW imaging system, specific modifications were made to the experimental setup, addressing issues related to ambient light interference and optimizing the detection of MMW-induced optical signals. During initial experiments, the photoreceiver experienced saturation due to two main sources: ambient room lighting and the high-intensity light emitted from the GDD. To mitigate this interference, an optical long-pass filter was introduced between the GDD and the photoreceiver. This filter effectively blocks all visible light wavelengths, thereby preventing ambient light from reaching the photoreceiver and reducing saturation issues.

## 2.2 Influence of MMW Radiation in the NIR Spectrum

Experimental findings suggest that the GDD emits light across a broad spectrum when interacting with MMW radiation, with a notable increase in intensity around the near-infrared (NIR) region, specifically between 800 nm and 1000 nm (Kurup et al., 2021). Preliminary research also showed that the MMW or terahertz (THz) influence on the GDD emission spectrum is strongest within this NIR range. In contrast, almost no influence of the MMW/THz radiation was observed in the visible spectrum, particularly around 500 nm to 600 nm. This observation justified the use of a long-pass NIR filter to enhance the system's performance by isolating the relevant signal range.

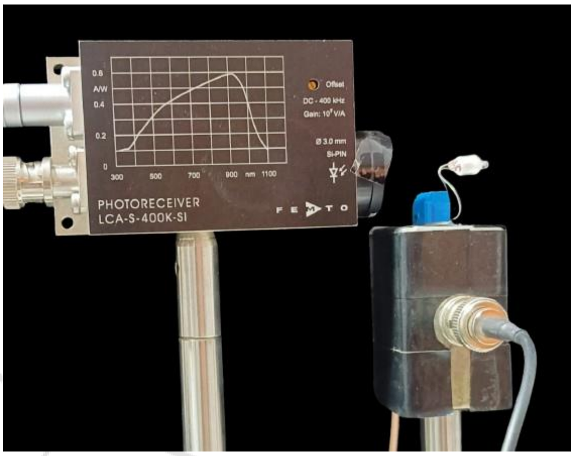


Figure 2: Photograph of the GDD-Photoreceiver Module Integrated with a Near-Infrared (NIR) Filter.

By blocking visible wavelengths, the filter reduces background illumination noise that originates from both room lighting and the GDD's own bias illumination. This results in a cleaner signal output and enhances the signal-to-noise ratio (SNR) of the photoreceiver, thus minimizing interference from unwanted visible light sources. The filter also contributes to a subtle increase in signal strength. Due to back reflections from the filter body, a fraction of the filtered light is directed back toward the GDD's detection cross-section, effectively increasing the detected signal level. This reflective effect, combined with the noise reduction properties, results in higher sensitivity and improved overall detector performance for MMW or THz radiation. These adjustments significantly improve the efficiency and reliability of the GDD-photoreceiver assembly as a pixel detector in our imaging system.

# 3 ENHANCING SIGNAL QUALITY FOR OPTIMAL DETECTION

In the initial stages of experimentation, we evaluated the photoreceiver's performance at the image plane position without an optical filter. Under standard lighting conditions, including ambient room light and the intense output from the Glow Discharge Detector (GDD), the photoreceiver exhibited elevated noise levels, resulting in suboptimal signal clarity. To address this, preliminary tests were conducted in complete darkness, where the photoreceiver's baseline performance was assessed.

To explore the impact of optical filtering, we conducted tests in two configurations: with the filter in a dark environment and with the filter in ambient room light. The filter mitigated light interference effectively, allowing for a significant reduction in noise levels in both cases. Figure 3 and 4 presents the signal acquisition data, highlighting the improved signal detection level achieved with the optical filter under varied lighting conditions.

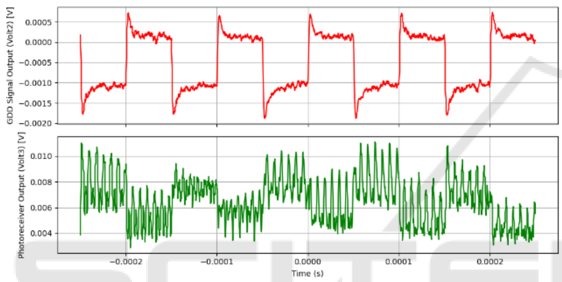


Figure 3: Signal acquisition data for the GDD-photoreceiver system with the optical filter under ambient room light conditions.

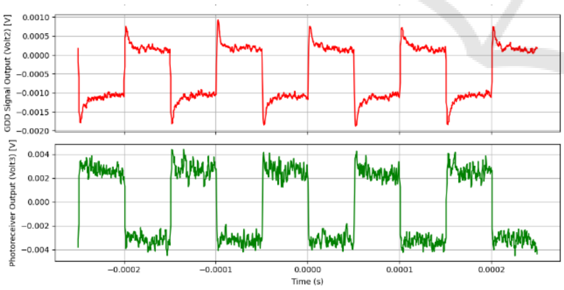


Figure 4: Signal acquisition data showing the performance of the GDD-photoreceiver system with the optical filter in a dark environment.

For further signal enhancement, an SR445A amplifier from Stanford Research Systems, Inc. was introduced into the setup. This addition provided a noticeable boost in the signal level as shown in Figure 5, proving beneficial for initial tests.

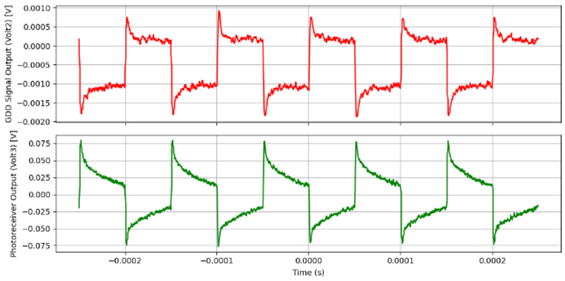


Figure 5: Waveform illustrating the enhanced signal output from the GDD-photoreceiver system after the introduction of the SR445A amplifier.

However, as we integrated a lock-in amplifier (LIA) module from Zurich Instruments, the necessity for the external amplifier diminished. The LIA's high sensitivity allowed it to reliably detect even minimal signal outputs from the photoreceiver, effectively enhancing the system's ability to capture faint MMW signals.

## 4 IMAGING RESULTS

In this section, we present the MMW imaging results obtained from the experimental setup using a GDD-photoreceiver combination. The object imaged was a 50 mm x 50 mm square metal plate with a thickness of 2 mm and a 20 mm x 20 mm hollow square cutout at its center, as shown in Figure 6, designed to evaluate the system's ability to capture distinct shapes and internal structures. The imaging mirror utilized had a 500 mm diameter, positioned with the object and image distances both set to 2 meters, ensuring that the MMW reflection would accurately project onto the detection plane.

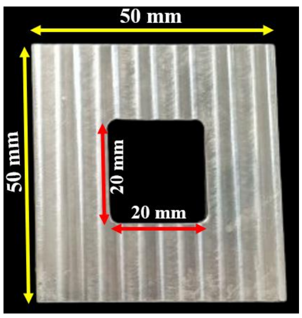


Figure 6: The square metal plate object used for imaging.

To optimize the performance, the setup underwent meticulous optical alignment and calibration. Initial trials involved refining the orientation and positioning of the GDD-photoreceiver module within the 8x8 scanning matrix, a configuration established in the image plane to maximize resolution and accuracy. Mounted on motorized linear stages, the GDD-photoreceiver assembly could perform precise vertical and horizontal raster scanning, enabling detailed coverage of the target area. Using this controlled scanning mechanism, the system produced an 8x8 grayscale image, accurately capturing the metal square's boundaries and internal hollow. The iterative adjustments to positioning and scanning patterns were essential in refining image clarity, yielding well-defined and high-quality MMW images. The final grayscale MMW images of the square shape are presented in Figure 7. The image processing steps significantly improved the clarity and definition of the features within the MMW data, allowing for a more precise representation of the object's structure. This enhancement demonstrates the effectiveness of the applied methods in refining the imaging capabilities of the GDD-photoreceiver system.

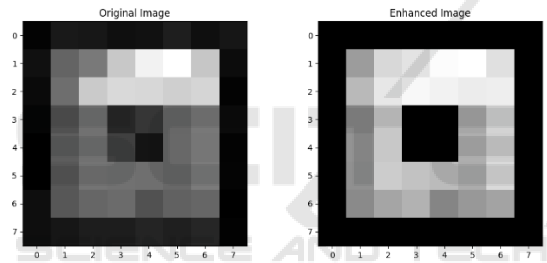


Figure 7: Final Grayscale MMW Image of the Square Shape. The left image displays the original acquired MMW data, while the right image illustrates the enhanced result following image processing, showcasing improved clarity.

## 5 CONCLUSIONS

This study presents the design and implementation of a novel millimeter wave imaging system that leverages a Glow Discharge Detector coupled with a high sensitivity photoreceiver. By employing an up-conversion detection method, the system effectively converts MMW signals into optical signals, enhancing the detection capabilities in terms of sensitivity and resolution. The integration of a long-pass NIR optical filter between the GDD and photoreceiver further improved the system's signal-to-noise ratio by filtering out visible light interference, thus optimizing performance in ambient light conditions. Additionally, the utilization of motorized linear stages for controlled raster scanning allowed the generation of detailed 8x8 grayscale images, confirming the setup's capability to capture complex structures with high fidelity.

Overall, this MMW imaging system represents a significant advancement in high-resolution imaging for industrial, security, and scientific applications, where precise detection of MMW radiation is essential. Future work will focus on extending the scanning resolution, exploring different object geometries, and refining the data acquisition process to broaden the system's application range and improve its performance further. submission.

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