

Article

First Demonstration of Lock-In Camera-Enabled Optical Up-Conversion Imaging for Millimeter-Wave Detection Using Glow Discharge Plasma

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Abstract

This study presents a novel approach in millimeter wave (MMW) imaging by demonstrating the first experimental implementation of an imaging system that integrates optical up-conversion within a glow discharge detector (GDD) plasma alongside a phase-sensitive lock-in camera. In this novel approach, incident MMW radiation, modulated with an ON–OFF signal, strikes the GDD, which functions as an up-conversion sensor, transforming the MMW signal into ON–OFF-modulated near-infrared (NIR) optical emissions. This upconverted light is then captured by the lock-in camera, which synchronously demodulates the optical signal at each pixel. By simultaneously receiving the upconverted optical emissions and the original reference signal used to modulate the MMW radiation, the camera achieves synchronous demodulation of the incoming light at each pixel. This advanced configuration enables the direct extraction of amplitude and phase information with pixel-level synchronous demodulation, while actively and effectively increasing the SNR and eliminates the uncorrelated background plasma emissions. The proposed optical up-conversion system effectively addresses existing limitations, offering a unique combination of advantages. By inheriting the fundamental benefits of GDD, such as cost-efficiency per unit, simplified electronic design, and robust resistance to high radiation levels, the system demonstrates enhanced noise suppression and increased sensitivity. Validation experiments utilizing LED modulation verify an optical acquisition time of approximately 100 ms per scan position (pixel dwell time), representing a significant improvement of several orders of magnitude over conventional optical acquisition approaches. In the present proof-of-concept implementation, complete image formation additionally includes the mechanical scanning time required for image reconstruction. Ultimately, this work establishes an improved paradigm for MMW imaging, advancing the development of compact, rapid, and cost-effective imaging systems for advanced non-ionizing imaging applications.

Keywords: glow discharge detector; MMW imaging; lock-in camera



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1. Introduction

Millimeter wave and terahertz imaging technologies have become essential because they can easily pass through optically opaque materials while remaining completely safe and non-ionizing for biological tissue. These unique features make them ideal for a wide range of applications, including security screening, biomedical diagnostics, nondestructive testing, and remote sensing [1]. As these applications grow, there is a strong and urgent demand for imaging systems that are sensitive, efficient, and capable of real-time video processing.

Currently, the widespread adoption of millimeter-wave (MMW) imaging is limited by the technological constraints of traditional detectors. Commercial technologies impose considerable trade-offs among sensitivity, speed, durability, and cost. CMOS plasmonic arrays facilitate the production of dense two-dimensional configurations; however, they demonstrate low sensitivity, high noise equivalent power (NEP), rapid saturation, and a limited dynamic range, thereby necessitating high-power external radiation sources. Schottky diode arrays (GaAs) deliver peak sensitivity and response times on the order of picoseconds; yet they face substantial barriers due to extremely high manufacturing costs, the lack of structured dense two-dimensional arrays, and their high vulnerability to electrostatic discharge (ESD) and intense power pulses. Alternative methods, such as bolometers, offer high sensitivity but are characterized by slow response times and the need for cryogenic cooling [2].

To address these limitations, Glow Discharge Detectors (GDDs), based on low-cost neon lamps, have emerged as a promising alternative. These detectors offer a unique combination of advantages, including cost-effectiveness, room-temperature operation, broadband frequency response, and exceptional robustness against intense radiation and high-power pulses. Detection occurs through the interaction of incident MMW radiation with the weakly ionized plasma within the detector [3–5]. The absorbed energy perturbs the electron energy distribution, modifying both the discharge current and the optical emission intensity. Consequently, GDDs support two detection modalities: electrical detection via discharge current measurement, and optical detection via the emitted plasma luminescence, a process referred to as optical up-conversion.

Historically, the extraction of this optical emission has posed considerable challenges. Conventional electrical detection methods depend on data acquisition systems and computationally intensive signal processing techniques, such as spectral analysis via Fast Fourier Transform (FFT), which introduce system complexity and increase susceptibility to stochastic noise. Previous optical detection techniques utilized conventional photodiodes or standard Charge-Coupled Device (CCD) and Complementary Metal-Oxide-Semiconductor (CMOS) cameras. To attain sufficient image contrast and suppress background plasma emission, these systems necessitate multiple frame acquisitions, sequential frame subtraction, and external optical filtering. This process is inherently slow, vulnerable to background variations, and inadequate for real-time imaging [6–10].

The development of lock-in camera technology presents a fundamentally different methodology for addressing these challenges. Unlike traditional imaging systems, a lock-in camera conducts pixel-by-pixel synchronous demodulation, independently processing the incoming signals at each pixel concurrently. By utilizing a reference signal synchronized with the modulation frequency, the system selectively isolates weak modulated optical signals amidst strong ambient illumination and substantial plasma noise. This technique effectively suppresses uncorrelated noise, markedly improves the signal-to-noise ratio, and facilitates true real-time imaging without the need for post-processing or frame subtraction. Recent advances in terahertz imaging and phase-sensitive detection have further demonstrated the effectiveness of coherent optical detection techniques for improving

sensitivity, noise suppression, and imaging performance, thereby reinforcing the potential of lock-in-based detection for advanced MMW/THz imaging applications [11,12].

This paper presents the first experimental demonstration of a millimeter-wave imaging experimental setup that integrates optical up-conversion within a Glow Discharge Detector (GDD) plasma and a phase-sensitive lock-in camera (the HeliCam C4 of Heliotis AG.). In this configuration, incident MMW radiation is modulated via an ON–OFF scheme, which the GDD converts into corresponding ON–OFF-modulated near-infrared (NIR) optical emissions. The lock-in camera simultaneously acquires the upconverted optical signal and the original reference, performing pixel-level synchronous demodulation. This enables the direct extraction of both amplitude and phase information while effectively suppressing background noise and uncorrelated plasma emissions.

The key contributions of this work include:

- The first integration of optical up-conversion with pixel-level lock-in demodulation: Establishing a novel and effective paradigm for millimeter-wave imaging;
- Direct phase-sensitive detection: Extracting MMW-induced optical signals at the pixel level with high precision;
- Elimination of the GDD imaging bottlenecks: Removing the requirement for sequential frame subtraction and computationally intensive external signal processing;
- Real-time imaging capability: Achieving an image acquisition time of approximately 100 ms per scan position (pixel dwell time), representing a significant enhancement over conventional methods;
- A robust and effective solution: Overcoming the high manufacturing expenses, limited sensitivity, and vulnerability to damage associated with conventional CMOS and Schottky array technologies.

In summary, this study establishes the foundation for the development of compact, high-speed, durable, and cost-effective imaging systems with a high signal-to-noise ratio for advanced non-ionizing applications.

2. System Architecture and Operating Principle

2.1. Core Framework

The proposed imaging system, illustrated in Figure 1, comprises three sequential principal subsystems: the millimeter-wave projection system, the GDD-based optical up-conversion unit, and the phase-sensitive lock-in camera detection unit. Within this architecture, the GDD serves as the transduction element, converting incident MMW radiation into detectable optical emission. The system is designed to encode high-frequency radiation onto an optical carrier, enabling the extraction of the modulated signal component via synchronous detection. Figure 1 is intended to illustrate the conceptual operating principle and signal flow of the proposed optical up-conversion imaging framework, while the detailed experimental implementation used for proof-of-concept validation is presented separately in Figure 2.

2.2. Optical Up-Conversion Mechanism

The GDD operates in the abnormal glow discharge regime, in which a stable plasma is sustained between the electrodes. Under steady-state conditions, the baseline optical emission intensity is determined by the discharge current and electron density. Incident MMW radiation, modulated via an ON–OFF scheme, interacts with this plasma and perturbs the electron energy distribution and collision dynamics. This interaction induces a corresponding modulation of the optical emission intensity, particularly within the near-infrared spectral region, constituting the optical up-conversion mechanism whereby the MMW signal is translated into a modulated optical carrier. The underlying physical

mechanism is attributed to the perturbation of the electron energy distribution within the weakly ionized glow discharge plasma by the incident MMW field. This perturbation modifies electron-impact excitation and ionization processes, resulting in changes in the population of excited neon atoms responsible for near-infrared emission. Consequently, the emitted optical intensity follows the applied MMW modulation, thereby enabling optical up-conversion of the incident MMW signal into a modulated optical output [9,13]. Crucially, the emitted optical intensity is directly proportional to the intensity of the incident MMW radiation striking the GDD.

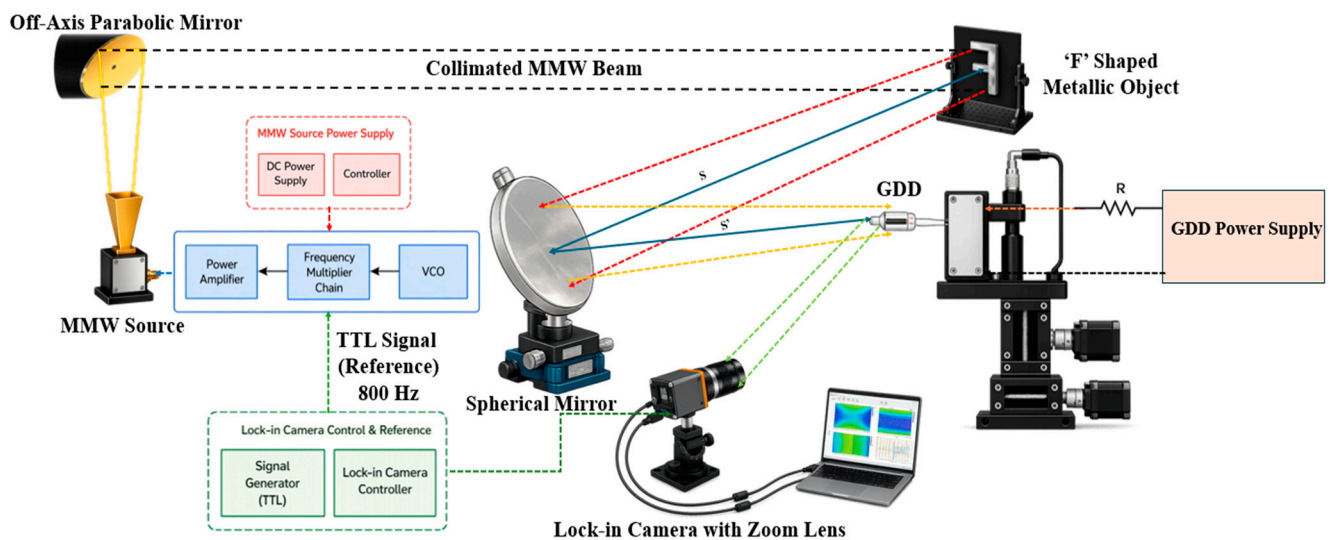


Figure 1. Conceptual architecture of the proposed lock-in camera-enabled optical up-conversion imaging system.

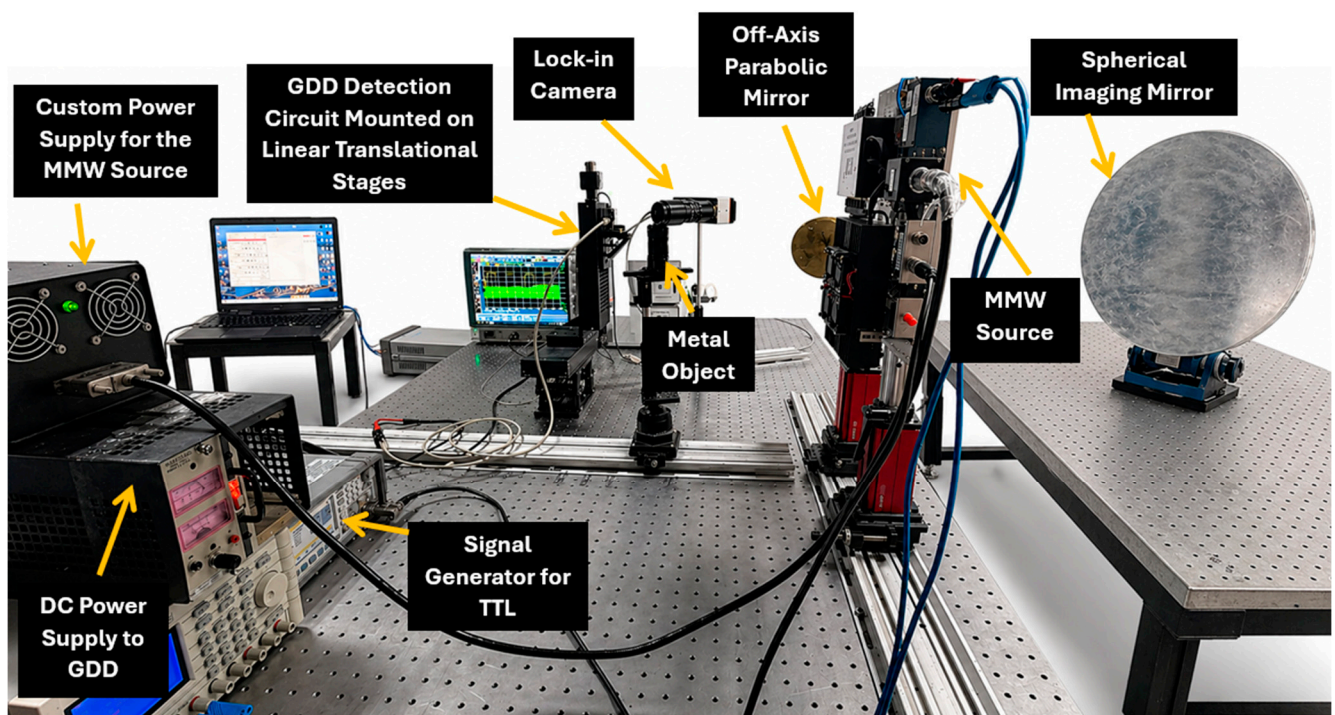


Figure 2. Experimental setup used for the proof-of-concept validation of the MMW imaging system based on optical up-conversion and lock-in detection.

Unlike conventional electronic detectors, the GDD does not measure the electromagnetic field directly in electrical form. Instead, variations in the incident MMW radiation are encoded as corresponding variations in optical emission intensity, enabling the use of optical imaging techniques for detection. Both the intensity and spatial distribution of this emission are governed by local plasma characteristics, which may vary across the discharge region. Consequently, the upconverted signal manifests as a weak AC modulation superimposed on the dominant DC background arising from steady-state plasma emission.

2.3. Spatial Demodulation Principle

The optical signal generated by the glow discharge detector is captured across the entire field of view using a HeliCam C4 lock-in camera (Heliotis AG, Root, Switzerland). This specialized camera is based on a unique pixel-wise lock-in detection architecture, where every single pixel functions as an independent synchronous demodulator. The sensor is fully capable of extracting both the in-phase component, known as X, and the quadrature component, known as Y, of the incoming modulated optical signal simultaneously. The X and Y components are obtained by correlating the detected optical signal with the external reference signal and a 90° phase-shifted version of the same reference, respectively. This synchronous demodulation process enables each pixel to independently recover the phase-correlated signal while effectively suppressing uncorrelated background emissions.

From these extracted components, the system computes the amplitude, known as (R), and the phase, known as (ϕ), as shown in Equation (1).

$$R = \sqrt{X^2 + Y^2}, \quad \phi = \tan^{-1} \left(\frac{Y}{X} \right) \quad (1)$$

This enables the generation of real-time spatial maps of both signal magnitude and phase distribution across the entire detector plane. The camera operates in synchronization with the modulation signal applied to the MMW source. The same reference signal used to modulate the MMW source is simultaneously supplied to the lock-in camera as the external synchronization reference, ensuring accurate pixel-level phase-sensitive demodulation and reliable extraction of both amplitude and phase information. In the present configuration, the MMW signal is modulated at approximately 800 Hz, to which every pixel is hardwired to synchronize.

This pixel-level architecture provides a significant computational advantage. Since lock-in detection is performed independently within each pixel at the hardware level, the need for external computing resources is substantially reduced, rendering software-based noise filtering and post-acquisition frame subtraction unnecessary. Consequently, two complementary images are obtained simultaneously: an amplitude map representing signal strength, and a phase map indicating the relative phase of the detected signal. Furthermore, this hardware-level implementation enables the detection of low-intensity optical signals originating from the GDD plasma, such that even minute variations in emission intensity can be resolved with high accuracy, while eliminating external demodulation bottlenecks and significantly enhancing overall sensitivity. This lock-in detection mechanism shortens the MMW image generation by 5–6 orders of magnitude compared to the conventional camera detection mechanism as was described in [10].

2.4. Operating Principle, Noise Rejection, and Core Advantages

The operating principle of the proposed framework is founded on the integration of optical up-conversion with synchronous phase-sensitive detection. The MMW radiation source is modulated using either an ON–OFF keying (OOK) scheme or a sinusoidal modulation pattern, inducing a corresponding modulation in the optical emission intensity of the

GDD plasma. This interaction encodes MMW information onto an optical carrier, enabling detection via high-resolution optical sensors. The resulting upconverted signal comprises two components: a dominant DC component arising from steady-state plasma emission, and a weak AC component corresponding to the MMW-induced modulation. The primary challenge lies in extracting this weak AC component from the dominant DC background.

To address this, the system employs phase-sensitive lock-in detection [14–18], wherein the lock-in camera utilizes a reference signal synchronized with the MMW modulation frequency. Performing synchronous demodulation at each pixel simultaneously, the camera isolates only the phase-correlated signal components. The detected signal after lock-in processing is expressed as:

$$S_{\text{out}} \propto A \cdot \cos(\Delta\phi) \quad (2)$$

where A denotes the amplitude of the modulated optical signal and $\Delta\phi$ is the phase difference between the signal and the reference. This operation functions as an ultra-narrowband filter centered at the modulation frequency [15], actively rejecting all uncorrelated noise components, including DC plasma glow, ambient light fluctuations, and thermal and electronic noise. Critically, this enables high-sensitivity operation even in the presence of intense background emission, a fundamental limitation of conventional CCD and CMOS-based approaches.

The resulting SNR improvement is directly proportional to the square root of the effective integration time T_{int} [15]:

$$\text{SNR} \propto \sqrt{T_{\text{int}}} \quad (3)$$

By increasing the integration time or the number of average periods, the framework suppresses stochastic noise while preserving the coherent signal component, enhancing the detectability of weak MMW-induced signals that would otherwise remain obscured in conventional systems. Collectively, this approach delivers direct extraction of the modulated signal without frame subtraction, high SNR through synchronous detection, real-time imaging capability, robust operation under severe noise conditions, and pixel-level parallel demodulation, establishing this framework as a high-performance alternative to conventional MMW imaging techniques.

3. Experimental Configuration

3.1. Overview of the Experimental Configuration

The experimental setup is based on a single integrated MMW projection system responsible for generating and delivering controlled radiation with ON–OFF modulation capability. Radiation is produced by a high-frequency source manufactured by Virginia Diodes Inc. (VDI, Charlottesville, VA, USA), operating within a central frequency range of 100–105 GHz. A voltage-controlled oscillator (VCO) followed by frequency multiplication stages yields an output power of several hundred milliwatts, ensuring sufficient field strength for plasma interaction. The radiation is coupled into free space via a horn antenna and subsequently collimated by an off-axis parabolic mirror into a quasi-parallel wavefront, minimizing diffraction-induced beam spreading over the propagation path. The collimated beam is then directed onto the metallic target object.

3.2. Target and Imaging Path

To evaluate imaging performance, a metallic target in the shape of an inverted letter “F”, with dimensions of approximately 50×60 mm, was positioned in the path of the collimated beam. A radiation absorber placed behind the target suppressed unwanted reflections and multipath scattering, enhancing signal contrast.

The reflected MMW radiation is collected and focused by a spherical mirror with an aperture of approximately 500 mm, forming an image at the detector plane where the GDD is located. The system employs a symmetric imaging configuration in which the object-to-mirror and mirror-to-detector distances are both approximately 2 m, consistent with the focal length of the spherical mirror. This arrangement yields a magnification of unity, maintaining a precise one-to-one spatial correspondence between the object plane and the image plane.

In the present proof-of-concept study, a metallic target was intentionally selected because of its high millimeter-wave reflectivity, enabling reliable validation of the proposed optical up-conversion imaging framework under controlled experimental conditions. Although reflection-mode imaging was adopted in this work, the proposed detection principle is not inherently limited to highly reflective targets. Imaging of low-reflectivity or strongly scattering objects is expected to be feasible with reduced signal-to-noise ratio and will be investigated in future studies. The complete experimental arrangement employed for proof-of-concept validation of the proposed imaging methodology is shown in Figure 2, illustrating the practical implementation of the conceptual framework presented in Figure 1.

3.3. Detector Instrumentation and Scanning

The sensing element is an N523 model glow discharge detector (GDD), featuring a cylindrical geometry with a diameter of 6 mm and a length of 12 mm. To achieve spatial sampling, the GDD was used to scan the image plane. The GDD was mounted on a two-axis translation stage driven by precision stepper motors manufactured by Thorlabs. The detector scanned the image plane in a discrete grid pattern of 11 by 11 points with a step size of 5 mm. At each scan position, the changes in optical emission intensity driven by the millimeter wave interaction were recorded. This process allows the system to detect the intensity of the millimeter wave signal at the image plane at each sample point of the scan, enabling the accurate reconstruction of the spatial distribution of the field. In the present proof-of-concept implementation, the detector is mechanically scanned over the imaging plane; therefore, the reported acquisition time of approximately 100 ms corresponds to the optical acquisition time at each scan position (pixel dwell time), whereas the total image acquisition time also includes the mechanical translation time between successive scan positions.

3.4. Optical Detection, Camera Configuration, and Image Reconstruction

The optical emission generated by the glow discharge detector was captured using a HeliCam C4 lock-in camera, which employs a pixel-wise synchronous detection architecture in which each individual pixel functions as an independent lock-in amplifier, enabling parallel demodulation across the entire field of view. A Navitar MVL7000 zoom lens (Navitar Inc., Rochester, NY, USA) was mounted on the camera to collect and focus the emitted optical signal onto the sensor. The adjustable aperture was utilized to regulate the optical input, reduce background illumination, and prevent sensor saturation during high-intensity plasma emission.

The lock-in detection and signal acquisition parameters were configured through the software interface, as shown in Figure 3, where the optical signal input was operated in alternating current coupling mode to suppress direct current plasma glow and enhance sensitivity to modulation-correlated signals. The acquisition parameters included a sensitivity level of 80%, an internal reference modulation frequency of 800 Hz, a time constant of 100 periods, and an integration time of 125 ms, resulting in an acquisition speed of approximately 7.96 frames per second which is 5–6 orders of magnitude better

than our previous technology [10]. During operation, the lock-in camera receives the same modulation reference used to drive the MMW source, thereby maintaining phase synchronization throughout the measurement and minimizing phase errors associated with asynchronous acquisition.

1. LIGHT CONTROL (Heliotis LED module)

Light Controller Source

- ☒ Off
- ☐ Signal Generator (internal)
- ☐ SFIOS (analog input)

2. OPTICAL SIGNAL INPUT

Coupling

- ☒ AC
- ☐ DC

Sensitivity Level [%]

0 50 100 80.0

3. DEMODULATION

Time constant (# periods) 100

Integration Time [ms] 125

Framerate [s^{-1}] 7.9602

Frequency [Hz] 800

☐ Ext. Ref. ☒ Int. Ref.

4. OUTPUT

Frames 4

Frames to host PC

☒ In-phase and Quadrature (X,Y)

☐ Resultant and Phase (R, Theta)

☒ Time resolved

☐ Frame index

RTIO2 Signal None

Set DIO control, output None

RTIO3 Signal None

Set output(s) to HIGH

☐ DIO1 ☐ DIO10

☐ DIO2 ☐ DIO11

☐ DIO3 ☐ DIO12

☐ DIO4 ☐ DIO13

☐ DIO5 ☐ DIO14

☐ DIO6 ☐ DIO15

☐ DIO7 ☐ DIO16

☐ DIO8 ☐ DIO17

5. INPUT

External Reference Source FI2

Frequency deviation [%] 10

Input Frequency [Hz] 0

Trigger source

☒ Internal ☐ External RTIO6

6. REFERENCE INPUT SCALER

Phase delay [μs] 0

Reference scaler Off

Parameter Summary (Current Settings)

Reference Source	: FI2	Modulation Frequency	: 800 Hz	Framerate	: 7.9602 s^{-1}	Phase Delay	: 0 μs
Input Frequency	: 0 Hz	Time Constant	: 100 periods	# Frames	: 4	Reference Scaler	: Off
Sensitivity Level	: 80.0 %	Integration Time	: 125 ms	Output Mode	: Time resolved		

Figure 3. Lock-in detection parameter settings used for phase-sensitive acquisition of the optical signal from the glow discharge detector.

The framework was configured to output the in-phase component X and quadrature component Y , enabling the direct computation of amplitude and phase information through synchronous demodulation. At each scan position of the detector, the time-resolved demodulated signal components were recorded and assembled into a two-dimensional matrix for image reconstruction. This configuration enabled direct extraction of the modulated signal without requiring frame subtraction or computationally intensive post-processing, while simultaneously providing enhanced noise suppression and improved signal-to-noise ratio across the optical up-conversion-based millimeter-wave imaging system.

3.5. Data Acquisition and Image Reconstruction

During measurements, the MMW source was amplitude-modulated, and the lock-in camera synchronized accordingly. The camera performs pixel-level synchronous demodulation, extracting only phase-correlated signal components. At each spatial position of the GDD, the recorded demodulated signal is proportional to the MMW-induced modulation in the optical emission. Unlike conventional CCD-based approaches, this method eliminates the requirement for separate background and signal frame acquisition or subsequent subtraction.

The data collected across all scan positions were assembled into a two-dimensional matrix representing the spatial distribution of the detected signal intensity, which was subsequently used to reconstruct an image of the target object, effectively mapping the MMW field distribution into the optical domain. Consequently, the total image acquisition and reconstruction time includes both the optical acquisition time at each scan (approximately 100 ms per pixel dwell time) and the mechanical translation time required to scan the entire measurement grid. The lock-in camera performs synchronous optical demodulation at

each scan position, whereas the final image is reconstructed only after assembling the data acquired from all scan positions.

3.6. Key Functional Advantages of the Setup

The proposed experimental configuration ensures:

- Accurate spatial mapping: The symmetric imaging arrangement enables faithful reproduction of the object's spatial features in the measurement plane;
- Efficient up-conversion detection: The GDD converts MMW radiation into optical emission, allowing high-resolution optical sensing;
- Enhanced sensitivity: Detection is limited only to modulation-correlated signals, improving signal-to-noise ratio;
- Elimination of post-processing: Direct extraction of the modulated signal removes the need for multiple integrated successive frame subtractions and additional image processing. Thus, enabling real time MMW imaging.

4. Results and Discussion

4.1. Validation of Lock-In Detection Using LED Excitation

As an initial step, controlled optical experiments were conducted using light-emitting diodes to validate the functionality of the lock-in camera and the phase-sensitive detection scheme. The LED-based configuration enabled the generation of both constant (DC) and modulated (AC) optical signals, providing a simplified environment to test the system response. Under constant illumination conditions, the reconstructed images exhibited uniform intensity distributions, representing the steady-state background signal. In contrast, when a modulated LED source was introduced, the lock-in camera successfully isolated the temporally varying component of the signal. The resulting amplitude images (Section 4.3, Figure 4) clearly highlighted the modulated regions, while the phase images provided additional information regarding the synchronization between the excitation and detection signals.

For the validation experiment, the LED was driven using the same external reference signal supplied to the lock-in camera, ensuring synchronous operation of the excitation and detection systems. The LED was operated at a modulation frequency of 10 kHz with an amplitude of 100 mV and a DC offset of 4 V. Under constant illumination, the reconstructed image exhibited a nearly uniform background response, whereas periodic modulation produced a distinct localized high-intensity circular region corresponding to the blinking LED. These observations experimentally verify the correct synchronization of the measurement chain and demonstrate the capability of the lock-in camera to selectively detect modulated optical signals while suppressing the constant background component.

These observations confirm that the lock-in camera effectively separates modulated signals from constant background illumination. Unlike conventional imaging approaches, where the DC component dominates the acquired signal, the phase-sensitive detection mechanism selectively extracts only the synchronized component. This experiment validates the fundamental capability of the system to perform noise rejection and signal isolation, which is essential for detecting weak MMW-induced optical emission in the presence of strong plasma background.

4.2. Experimental Validation Using GDD Under MMW Irradiation

The experimental results (Section 4.3, Figure 5) reveal distinct spatial and temporal characteristics within the glow discharge detector, where reconstructed images display localized high intensity regions known as emission hotspots that correspond to areas of enhanced plasma activity where electron density and excitation processes are more

pronounced. This spatial non-uniformity indicates that the plasma does not behave as a homogeneous sensing medium but rather acts as a collection of localized interacting regions, an observation that supports the hypothesis that different regions within the plasma respond independently to incident millimeter wave radiation and potentially enables spatially resolved sensing even with a single detector. Furthermore, unlike the stable and repeatable signals observed in baseline light-emitting diode experiments, these glow discharge detector measurements exhibit clear temporal fluctuations in signal intensity. These variations arise directly from inherent plasma instabilities, including fluctuations in electron density, ionization rates, and overall discharge dynamics, which the lock-in detection system captures as irregular amplitude changes in the reconstructed signals.

While such behavior introduces a degree of variability, it directly reflects the dynamic sensitivity of the plasma to external electromagnetic excitation and clearly demonstrates the capability of the framework to measure dynamic plasma responses induced by millimeter wave interaction. The detected signal also exhibits a strong dependence on the modulation frequency of the millimeter wave source, where signal amplitudes are found to be weak or entirely negligible at higher modulation frequencies such as 10 kHz. However, as the modulation frequency is systematically reduced, a significant increase in signal strength is observed, yielding enhanced signal responses at modulation frequencies of 5 kHz, 2.5 kHz, 1.25 kHz, and approximately 600 Hz.

This frequency-dependent behavior indicates that the system response is limited by the combined bandwidth of the plasma dynamics and the lock-in detection system, as the plasma cannot respond rapidly enough at higher frequencies to follow the modulation, resulting in a significantly reduced modulation depth. Conversely, at lower frequencies, the plasma response becomes far more pronounced and leads to stronger detectable signals, highlighting the critical importance of optimizing the modulation frequency to precisely match the specific response characteristics of both the plasma and the detection system.

To experimentally validate these observations, a series of measurements was performed using the GDD under modulated MMW irradiation. Initial experiments were conducted using a modulation frequency of 10 kHz; however, systematic optimization demonstrated that a modulation frequency of approximately 600 Hz produced the most stable and well-defined optical response. Oscilloscope measurements further verified proper synchronization between the TTL modulation signal applied to the MMW transmitter and the corresponding AC response generated by the GDD as shown in Figure 6. A measurable detector response was observed for signal amplitudes of approximately 40 mV, while the most distinct optical response was obtained at approximately 80 mV. These experimentally determined operating conditions were therefore adopted for the subsequent imaging experiments.

These experimental observations demonstrate that the GDD exhibits a stable and repeatable optical response under synchronized MMW excitation when operated under optimized modulation conditions. The experimentally observed dependence on modulation frequency further confirms that appropriate selection of the excitation frequency is essential for maximizing the detectable optical signal and forms the basis for the subsequent MMW imaging experiments.

4.3. Analysis of the Spatial and Temporal Signal Characteristics

The experimental validation results presented in Sections 4.1 and 4.2 provide further insight into the spatial and temporal characteristics of the proposed lock-in camera-enabled optical up-conversion imaging system. The lock-in detection process enables selective extraction of only the optical signal that is synchronized with the external modulation reference, thereby effectively suppressing constant background illumination and uncorrelated

optical emissions. This capability is evident from the LED validation experiments, where a clear distinction is observed between the constant illumination and periodically modulated optical signals.

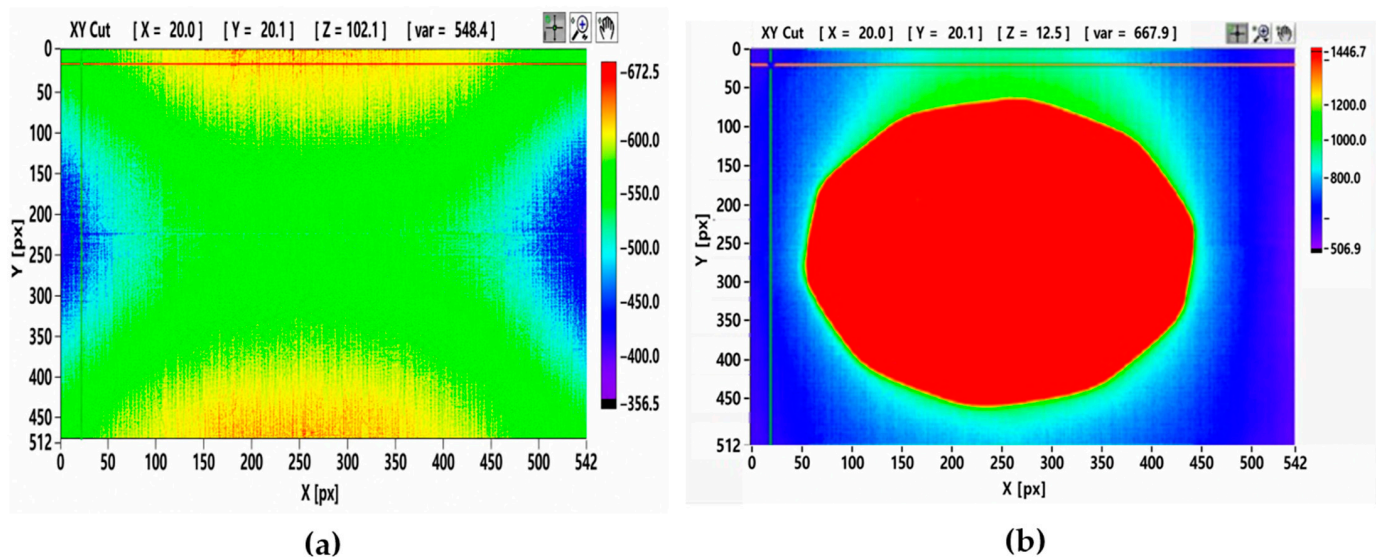


Figure 4. Experimental validation of lock-in detection using LED excitation. (a) Baseline optical response under constant LED illumination, showing the steady-state background signal. (b) Optical response under modulated LED excitation, demonstrating the selective extraction of the synchronized optical signal by the lock-in camera. For improved visualization, the color scale of each image has been independently normalized to emphasize the corresponding spatial optical response and should not be interpreted as a direct quantitative comparison of signal intensity between (a) and (b).

As observed in Figure 4a, constant optical illumination produces a nearly uniform background response across the detector, representing the steady-state optical emission. In contrast, the modulated LED shown in Figure 4b generates a localized high-intensity region corresponding to the periodically varying optical signal. The clear separation between these two operating conditions experimentally verifies the ability of the lock-in camera to reject the DC background component while selectively detecting only the phase-correlated optical signal. These observations confirm the correct synchronization of the complete measurement chain and establish the suitability of the proposed detection architecture for weak optical signal extraction.

Following the successful validation of the lock-in detection principle, the same methodology was applied to the glow discharge detector operating under millimeter-wave irradiation. Unlike the LED source, the optical emission generated by the GDD originates from dynamic plasma processes and therefore exhibits localized intensity variations associated with the interaction between the incident millimeter-wave radiation and the discharge plasma.

The baseline GDD response shown in Figure 5a exhibits a relatively uniform optical emission corresponding to stable plasma operation. Under millimeter-wave excitation, however, a localized high-intensity emission region becomes evident, as shown in Figure 5b, indicating enhanced plasma excitation induced by the incident radiation. These localized emission hotspots demonstrate that the plasma does not behave as a perfectly homogeneous sensing medium but instead exhibits spatially varying emission characteristics governed by localized electron density and excitation processes. Furthermore, compared with the highly stable response observed during the LED validation experiments, the GDD measurements exhibit temporal fluctuations arising from the intrinsic dynamics of the glow discharge plasma, including variations in electron density, ionization rate, and discharge stability.

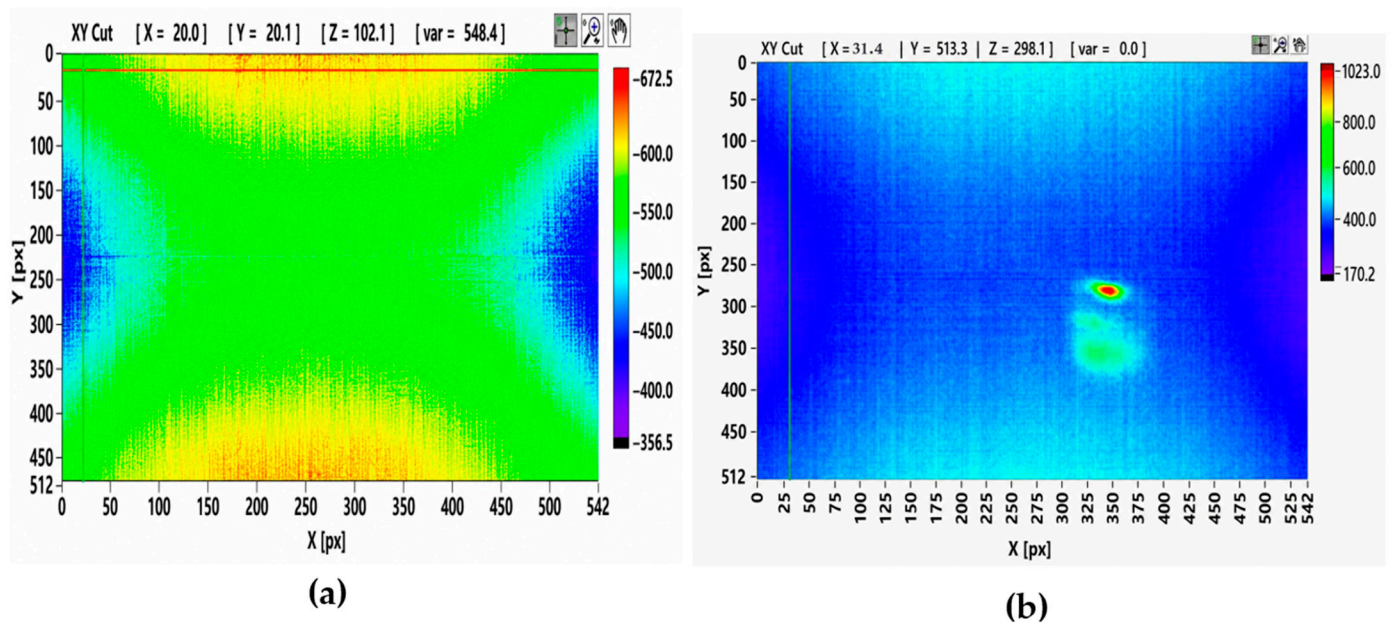


Figure 5. Experimental validation of the GDD under MMW irradiation. (a) Baseline optical emission of the GDD in the absence of MMW irradiation, showing the steady-state plasma response. (b) GDD optical response under MMW irradiation, exhibiting a localized high-intensity emission region corresponding to the modulated plasma response induced by the incident MMW radiation. For improved visualization, the color scale of each image has been independently normalized to emphasize the corresponding spatial optical response and should not be interpreted as a direct quantitative comparison of signal intensity between (a) and (b).

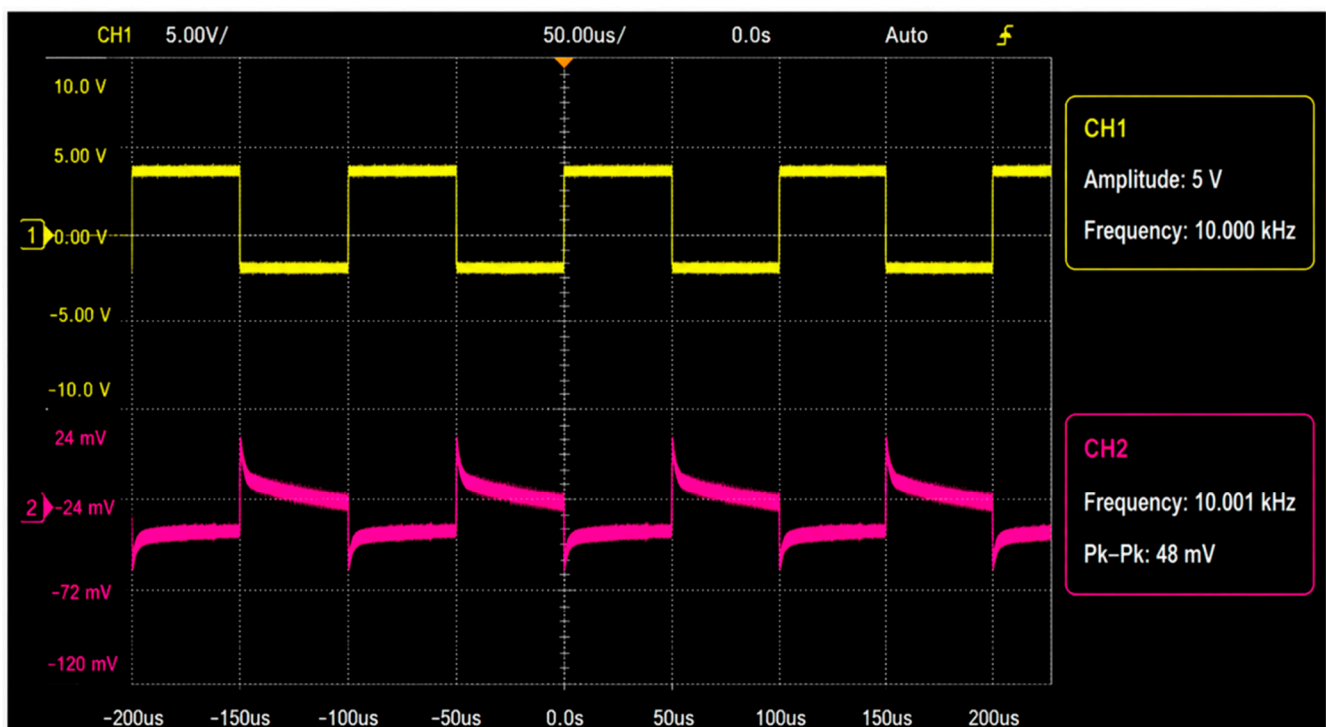


Figure 6. Oscilloscope traces showing the synchronization between the reference modulation signal (Channel 1) and the electrical response of the GDD (Channel 2) during millimeter-wave irradiation. Channel 1 corresponds to the externally applied square-wave modulation signal (5 V, 10 kHz), while Channel 2 corresponds to the AC response generated by the GDD (10.001 kHz, 48 mV peak-to-peak). The synchronized waveforms verify the correct operation of the proposed lock-in detection scheme.

4.4. Experimental Imaging Results of the F-Shaped Metallic Target

The imaging performance of the proposed MMW imaging system was experimentally validated using a metallic F-shaped target. The corresponding raw optical output acquired by the lock-in camera, and a digitized reconstructed image are presented in Figure 7. The inverted orientation of the reconstructed image is expected from the conventional optical configuration, as the spherical mirror forms a real image at the detector plane, resulting in inversion in both the horizontal and vertical directions in accordance with geometric optics. The digitized reconstruction represents an 11×11 spatial measurement grid corresponding to the mechanical scanning positions, where each pixel denotes the optical response of the glow discharge detector at an individual scan location. Regions corresponding to the metallic F-shaped target exhibit higher optical emission intensity, demonstrating the successful mapping of the incident MMW field distribution into the optical domain through the proposed optical up-conversion mechanism.

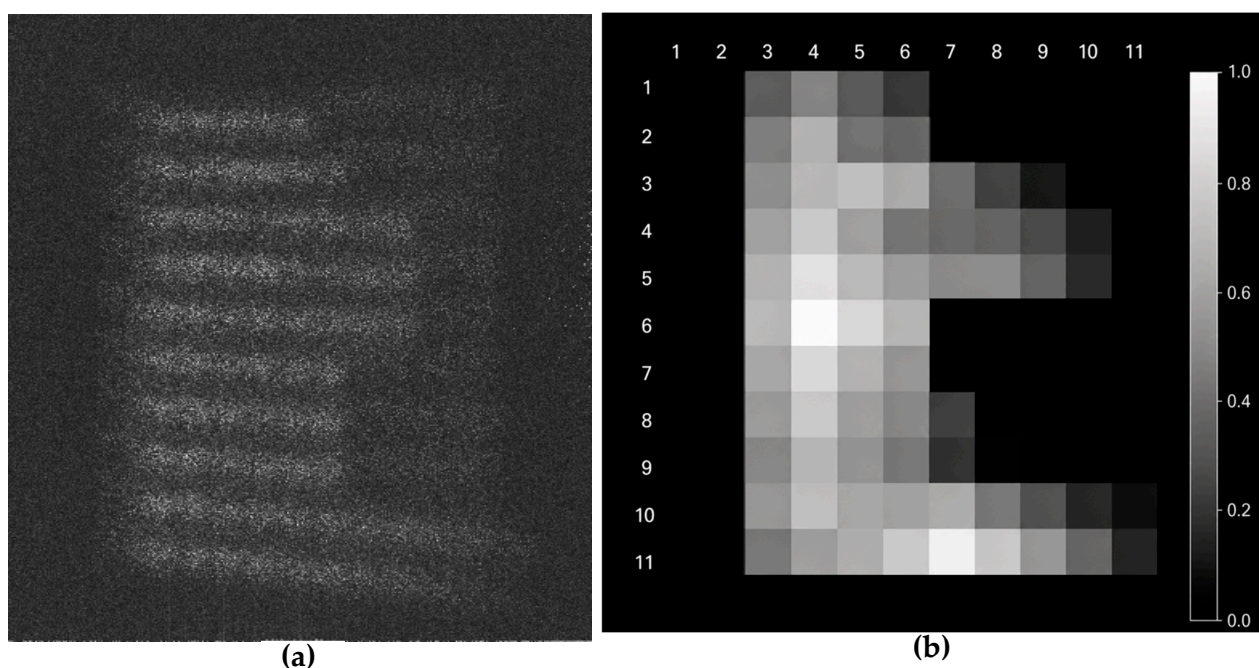


Figure 7. Experimental imaging results of a metallic F-shaped target using the proposed millimeter-wave optical up-conversion with lock-in detection imaging system. (a) Raw optical output acquired directly from the lock-in camera, showing the MMW-induced optical emission from the glow discharge detector (GDD) without image enhancement or post-processing. (b) Digitized 11×11 reconstructed image obtained from the measured data, where each pixel corresponds to the optical response of the GDD at an individual scan position. Regions of higher intensity correspond to stronger MMW-induced optical emission, clearly revealing the geometry of the F-shaped target.

The observed image contrast originates from the modulated NIR emission of the GDD, which is selectively extracted using phase-sensitive lock-in detection. Although the reconstructed image exhibits noticeable background noise and non-uniform intensity distribution, the geometry of the F-shaped target remains clearly distinguishable, confirming the effectiveness of the proposed imaging approach.

The observed speckle-like noise appearance is primarily attributed to localized fluctuations in the glow discharge plasma emission, measurement noise, and the discrete spatial sampling associated with the mechanical scanning process. These intensity noise variations arise from the dynamic behavior of the plasma together with the limited spatial sampling resolution of the proof-of-concept system. Despite these effects, the reconstructed image preserves the essential structural features of the target, demonstrating the capability of

the proposed optical up-conversion framework to perform MMW image reconstruction using a single GDD element. Further improvements in image quality are expected through optimized signal conditioning, advanced image reconstruction algorithms, and the future implementation of two-dimensional GDD arrays, thereby eliminating the need for mechanical scanning.

4.5. Quantitative Signal and Noise Floor Analysis

To quantitatively evaluate the performance of the proposed millimeter-wave imaging system, an adaptive signal-to-noise ratio (SNR)-based image analysis framework was employed. The methodology was designed to estimate the signal strength, background noise characteristics, and effective noise floor under low-intensity optical detection conditions.

For each acquisition, two images were considered:

- (i) a signal image containing the modulated optical response from the glow discharge detector; and
- (ii) a corresponding background image acquired under identical experimental conditions without millimeter-wave illumination.

The acquired signal image can be represented as:

$$I_{\text{signal}(x,y)} = S_{(x,y)} + N_{(x,y)} \quad (4)$$

where $S_{(x,y)}$ denotes the useful signal component and $N_{(x,y)}$ represents additive noise. The background image was assumed to contain only noise contributions.

To localize the signal, Gaussian smoothing was applied within the selected region of interest (ROI) to reduce the influence of high-frequency noise [19,20]. The signal center was then identified from the maximum response of the smoothed image, and a local analysis window was extracted around the detected signal position for statistical evaluation.

The window uses the pixels in the surrounding region to define the local background statistics around the signal:

$$\mu_{bg} = \left(\frac{1}{N} \right) \sum_{i=1}^N b_i \quad (5)$$

$$\sigma_{bg} = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (b_i - \mu_{bg})^2} \quad (6)$$

where:

- b_i represents the local background pixel intensity;
- N denotes the number of pixels in the background region.

The signal-to-noise ratio was then evaluated using both peak-based and mean-based formulations [21,22].

$$SNR_{\text{Peak}} = \frac{I_{\text{max}} - \mu_{bg}}{\sigma_{bg}} \quad (7)$$

$$SNR_{\text{Mean}} = \frac{\mu_{\text{signal}} - \mu_{bg}}{\sigma_{bg}} \quad (8)$$

where:

- I_{max} is the peak signal intensity;
- μ_{signal} is the mean signal intensity within the selected signal window.

Prior to subtraction, the background image was normalized to match the global statistical properties of the signal image:

$$I_{\text{without}}^{\text{norm}} = \frac{I_{\text{without}} - \mu_{\text{without}}}{\sigma_{\text{with}}} \cdot \sigma_{\text{with}} + \mu_{\text{with}} \quad (9)$$

where:

- $I_{without}$ represents the background image;
- $\mu_{without}$ and $\sigma_{without}$ denote the mean and standard deviation of the background image;
- μ_{with} and σ_{with} correspond to the statistical parameters of the signal image.

An adaptive scaling factor was then computed to account for local signal variations:

$$\alpha = w_{peak} \cdot \alpha_{peak} + w_{mean} \cdot \alpha_{mean} \quad (10)$$

where the individual components were derived from the relative SNR and intensity differences between the signal and background images.

The normalized background image was further adjusted using this adaptive scaling factor:

$$I_{without}^{matched} = \alpha \cdot (I_{without}^{norm} - \mu_{with}) + \mu_{with} \quad (11)$$

To improve robustness against random fluctuations and structured noise, multiple processed images were aggregated using maximum intensity projection:

$$I_{final} = \max \{I_{diff}(x, y)\} \quad (12)$$

This approach emphasizes regions with consistent signal presence across multiple measurements while suppressing both random and structured noise components.

The resulting SNR values obtained for different analysis window sizes are summarized in Table 1.

Table 1. Quantitative SNR analysis for different local window sizes.

Window Size	Mean Intensity	Peak Intensity	Background Mean	Background Std	SNR (Mean)	SNR (Peak)
3 × 3	56.32	81.60	34.35	15.94	1.38	2.96
5 × 5	56.82	108.30	33.80	15.39	1.50	4.84
7 × 7	52.21	108.30	33.52	14.92	1.25	5.01
9 × 9	49.03	108.30	33.01	14.53	1.10	5.18
11 × 11	47.99	108.30	32.67	14.15	1.08	5.34

From Table 1, it can be observed that the peak-based SNR increases with increasing window size, while the mean-based SNR decreases. This behavior is expected, as larger windows incorporate additional background pixels, reducing the average signal intensity while preserving the dominant peak response.

The system noise floor was estimated using the background statistics obtained from the surrounding regions of the detected signal. The noise floor is defined as:

$$\sigma_{noise} = \sigma_{bg} \quad (13)$$

From the measurements, the noise floor was found to be approximately within the range of 14–16 intensity units, depending on the selected window size.

Using the estimated noise floor, a statistical detection threshold was defined as [23]:

$$T = \mu_{bg} + K \cdot \sigma_{bg} \quad (14)$$

Here, K is typically selected between 3 and 5 for reliable signal discrimination.

The analysis demonstrates that:

- Peak-based SNR provides a robust detection criterion for localized signals;
- Proper window selection is critical for balancing signal preservation and noise suppression;

- Adaptive background normalization significantly improves signal extraction under noisy conditions.

These results provide quantitative support for the effectiveness of the proposed lock-in-based optical up-conversion imaging system for weak millimeter-wave signal detection under low signal-to-noise conditions [24]. Although the measured peak-based SNR values are below 10, the lock-in camera performs synchronous phase-sensitive detection using the known modulation reference, thereby selectively extracting only the optical signal component correlated with the incident MMW modulation while effectively suppressing uncorrelated background plasma emissions. Consequently, reliable target detection and image reconstruction can be achieved even under relatively low raw optical SNR conditions. The successful reconstruction of the target images presented in the subsequent sections experimentally confirms the practical effectiveness of the proposed imaging approach.

4.6. Performance Comparison with CCD/CMOS-Based Approach

A comparative analysis was performed between the proposed lock-in camera-based approach and conventional CCD/CMOS-based up-conversion imaging methods. In earlier implementations, the extraction of the MMW signal relied on capturing consecutive frames with and without radiation and performing a subtraction operation to isolate the modulated component. This approach required a large number of frames to achieve acceptable signal quality, resulting in long acquisition times and limited robustness to noise.

In contrast, the lock-in camera performs direct synchronous demodulation at each pixel, eliminating the need for frame subtraction and significantly improving detection efficiency.

The performance comparison summarized in Table 2 is based on the experimentally validated lock-in camera implementation presented in Sections 4.1–4.5 and the previously reported CCD/CMOS-based optical up-conversion imaging approach described in [10].

Table 2. Comparison of imaging approaches.

Feature	CCD/CMOS-Based Method	Lock-In Camera-Based Method
Signal extraction	Frame subtraction	Direct synchronous demodulation
Noise rejection	Limited	High (phase-sensitive filtering)
Acquisition time	~90 s	~100 ms
Processing complexity	High	Low
Stability	Sensitive to fluctuations	Robust
Real-time capability	Not feasible	Achievable

4.7. Improvement in Acquisition Speed and SNR

One of the most significant outcomes of this study is the drastic improvement in imaging speed. The proposed system achieves an acquisition time on the order of approximately 100 ms per scan position (pixel dwell time), compared to approximately 90 s in previous CCD-based approaches. This corresponds to an improvement of nearly three orders of magnitude ($\sim 1000\times$), representing a major advancement in the feasibility of real-time MMW imaging. This improvement is supported by the experimental acquisition results presented in the preceding sections and reflects the practical benefit of direct pixel-wise synchronous demodulation provided by the lock-in camera.

In addition to speed, the signal-to-noise ratio (SNR) is significantly enhanced due to the inherent properties of lock-in detection. By selectively detecting only the modulation-correlated component of the signal, the system effectively suppresses:

- DC plasma emission;
- Ambient light interference;
- Random noise sources.

This results in cleaner signal extraction and improved image quality without the need for extensive post-processing.

4.8. Discussion on System Behavior

The combined results from LED validation and GDD-based experiments demonstrate that the proposed system successfully integrates optical up-conversion with phase-sensitive detection to achieve high-performance MMW imaging. The LED experiments confirm the fundamental operation of the lock-in detection mechanism, while the GDD results illustrate the practical behavior of the system under real plasma conditions. The observed spatial non-uniformity and temporal fluctuations highlight both the challenges and opportunities associated with plasma-based detection.

Importantly, the system demonstrates the ability to capture weak modulated signals in the presence of strong background emissions, which has been a major limitation in previous approaches. The frequency-dependent response further provides insight into the dynamic characteristics of the plasma and the detection system, guiding future optimization.

5. Conclusions

This study demonstrates a novel MMW imaging approach based on the integration of optical up-conversion in glow discharge plasma with phase-sensitive lock-in camera detection. In contrast to earlier CCD/CMOS-based implementations, which relied on frame subtraction and extensive post-processing, the proposed method enables direct extraction of the modulated signal through synchronous detection. Experimental results confirm a substantial improvement in signal-to-noise ratio, acquisition speed, and robustness, with imaging times reduced from seconds to approximately 100 milliseconds optical acquisition time per scan position.

To the best of the authors' knowledge, this is the first experimental demonstration of MMW imaging using a lock-in camera combined with optical up-conversion detection. The proposed approach establishes a new framework for real-time, high-sensitivity, and scalable MMW imaging systems. The present study employs a single GDD as a proof-of-concept implementation, with spatial imaging achieved through mechanical scanning. Nevertheless, the proposed optical up-conversion and lock-in detection methodology is inherently scalable to future two-dimensional GDD focal plane arrays, in which each GDD element would produce a localized modulated optical emission. In such a configuration, the lock-in camera would simultaneously perform pixel-level demodulation of all detector elements, eliminating the need for mechanical scanning and enabling true near video-rate imaging.

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