NEP characterization and analysis method for THz imaging

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ABSTRACT

Over the last decade, significant progress has been made in the development of Terahertz (THz) imagers to satisfy the growing interest for see-through devices for different market applications. The noise-equivalent power (NEP) is a widely accepted figure of merit used to compare the sensitivity performance of detectors. However, with no widely recognized standard for NEP, it is often difficult to have a fair comparison between different sensors. Having a clear understanding of the characterization method used to calculate this important metric will lead to better estimation of the performances that could be expected from an imaging device.

There is some confusion regarding whether NEP should be expressed in terms of power (W) or power by spectral density ($W/Hz^{1/2}$). The difference between the two expressions is the normalization of the first by the square root of the detector's equivalent noise bandwidth (ENBW). By properly defining the ENBW for a specific sensor, the translation between the two is then consistent.

This paper presents the NEP characterization of INO's Microxcam-384i camera over a wide frequency range. A description of the measurement setup is provided, as well as the details of the analysis method, including the estimation of the ENBW. Finally, values for the NEP using both expressions are provided for wavelengths between 70µm (4.5 THz) and 1.5mm (198 GHz), demonstrating the broadband sensitivity of the camera.

Keywords: Terahertz, THz, NEP, imaging, characterization, camera, INO

1. INTRODUCTION

Imaging technologies in the terahertz (THz) frequency band have become more widely available in recent years. Significant advances have been made in active imaging systems with the goal of providing innovating solutions for industrial applications such as non-destructive testing, and process control as well as homeland security applications such as body scanning. New imaging devices are being developed for the market with improved performances to satisfy the most demanding needs. The problem is that the current lack of an 'official' recognized standard to accurately evaluate the performance of these devices makes it difficult to establish a reliable comparison between the different options.

The noise-equivalent power (NEP) is by far the most accepted metric in the industry, however the characterization method must be well explained to make it meaningful. This paper will present the measurement and analysis methods used by INO to evaluate the performances of its Microxcam-384i camera. Commercialized as a broadband imager, NEP results for the Microxcam-384i will be presented for a wide section of the THz spectrum (198 GHz to 4.5THz). This figure of merit is directly linked to the noise characteristics, the responsivity and the equivalent noise bandwidth (ENBW) of the camera.

2. METHODOLOGY

2.1 Responsivity measurement

An optical setup has been specifically developed for accurate evaluation of the responsivity of different imaging detectors fabricated at INO. A schematic of the setup is shown in Figure1. The responsivity is defined as the output electrical signal of a detector for a given radiant power incident on the detector.

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By comparing the THz signal (expressed in counts) collected by the camera against the power (expressed in Watts) measured by an absolute power meter (TK Instruments) we can calculate the responsivity of the system. This direct relation between the camera and the power meter will be accurate only if both detection devices (the THz camera and power meter) are able to collect the same energy. This is done by focusing the beam directly over the active area on the detector and making sure the beam size is smaller than this surface.

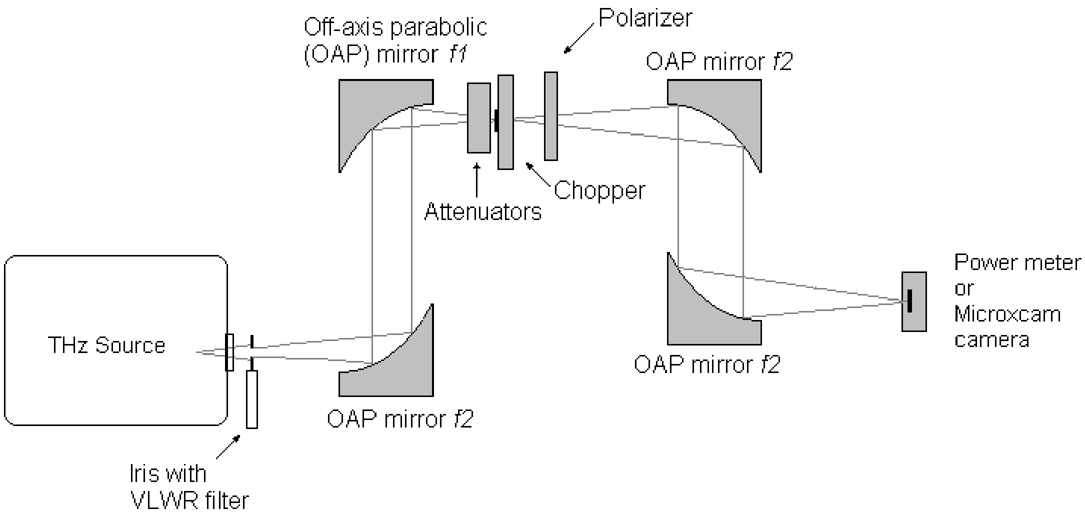

Figure 1. Schematic of the optical setup used for responsivity measurement.

In order to increase the level of accuracy of this measurement, INO has worked with a national metrology institute (PTB) to calibrate the power meter used for this characterization at the following frequencies: 2.52 THz, 1.89THz, 762GHz and 693GHz. The original correction factors provided by the manufacturer of the detector were used for the other frequencies. As for the calibration at PTB, a SIFIR-50 Laser System from Coherent was used to cover frequencies between 4.25THz and 693GHz. In addition, a 397GHz/198GHz/99GHz Transmitter / Amplifier Multiplier Chain from Virginia Diodes (VDI) was used to extend the measurement bandwidth.

As an additional precaution, a low pass filter (Tydex) with a cutoff frequency of 27.5µm has been added at entrance of the optical setup to eliminate any undesired signal (thermal and IR) that could be emitted by the source.

2.2 Noise measurement

The noise level of the complete system must be evaluated correctly in order to calculate the performances of the device. It is necessary to determine the dominant noise (white, 1/f, $1/f^2$, etc) of the detector within the time scale of the measurement. This is performed by calculating the Allan variance of the detector [1]. Instead of calculating the average of the standard deviation of all pixels over a 1 second period, the Allan variance can be calculated using a much longer time period (20 seconds). This method provides more information on the noise mechanism present in the complete system.

The first data point of the Allan variance curve gives information regarding the minimum signal that can be measured with a SNR=1 when the camera is running at a frame rate of 50 Hz. It is important to note that this metric is related to the camera itself and will not change with wavelength.

2.3 NEP and Equivalent Noise Bandwidth

For systems with a white noise spectrum, the Allan variance can be described as $\sigma^2 = \frac{NEP^2}{2\tau}$ [2], where τ represents the integration time of the camera. The conversion factor that allows the translation between frequency-domain quantities (NEP) and time-domain quantities (variance) is called equivalent noise bandwidth (ENBW). From the previous equation, which is true for unweighted averaging devices such as INO's camera, the ENBW is equal to 1/2 τ.

3. RESULTS

3.1 Responsivity

Using INO's Microxcam-384i camera, the THz signal from different frequencies was recorded to calculate the responsivity of the camera over a large range (198GHz to 4.25THz). The values presented in Table 1 represent the average signal variation generated by the THz source compared to the background signal. This averaging has been done over a period of 10s (500 frames) to minimize any power fluctuation from the source. The same averaging period was used for the power measurement using the power meter.

Table 1. Responsivity measurement for INO's Microxcam camera. Calibrated power measurements are marked with an asterisk.

Frequency (Wavelength)	Microxcam-384i signal [counts]	TK power meter reading [μW]	Responsivity [counts/W]
4.25 THz (70 μm)	4.00×10^7	22.4	1.79×10^{12}
2.52 THz (118 μm)	1.60×10^8	152 *	1.05×10^{12}
1.89 THz (158 μm)	1.72×10^8	159 *	1.08×10^{12}
762 GHz (394 μm)	2.43×10^8	154 *	1.58×10^{12}
693 GHz (432 μm)	2.14×10^8	140 *	1.53×10^{12}
397 GHz (755 μm)	9.11×10^7	150	6.07×10^{11}
198 GHz (1510 μm)	3.17×10^8	536	5.92×10^{11}

The detector used in the Microxcam-384i camera is sealed using a HRFZ-Si window [3]. This window could be coated with parylene to increase its transmission over a specific waveband for better performance, however that was not the case for the actual measurement. The same uncoated detector was used for all measurements mentioned above.

Being a 2D imager, the Microxcam-384i camera was also used to ensure that the beam dimension for every frequency was smaller than its active area (10.08mm x 13.44mm), meaning that all the THz energy could be collected. Several beam images taken from the camera at different frequencies are presented in Figure 2.

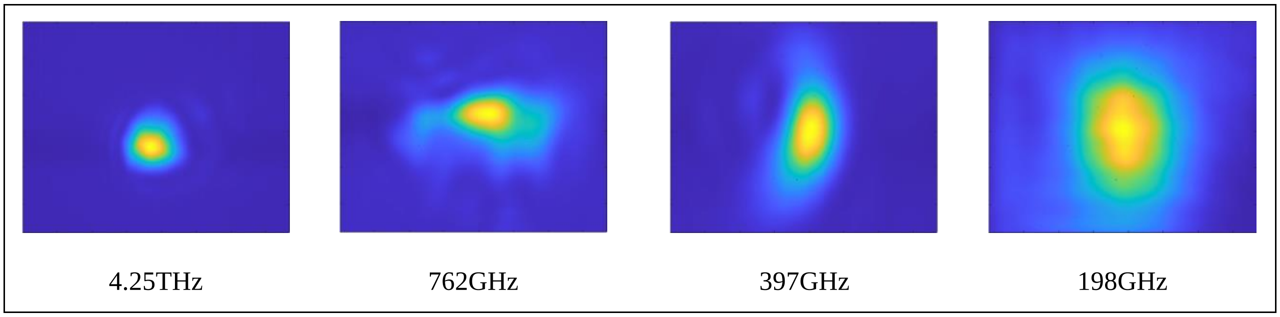

Figure 2. Beam images taken with the Microxcam-384i camera at 4.25THz, 2.52THz, 762GHz, 397GHz and 198GHz

3.2 Noise

The Allan variance was measured using the same Microxcam-384i camera by acquiring 1000 consecutive frames without any THz signal. Being able to record at a framerate of 50Hz, the acquisition was performed over a period of 20s. The Allan variance of all pixels of the camera was than averaged and is presented in Figure 3. From the Allan variance data, we can then calculate the Allan deviation which represents the square root of every variance measured (shown in Figure 4).

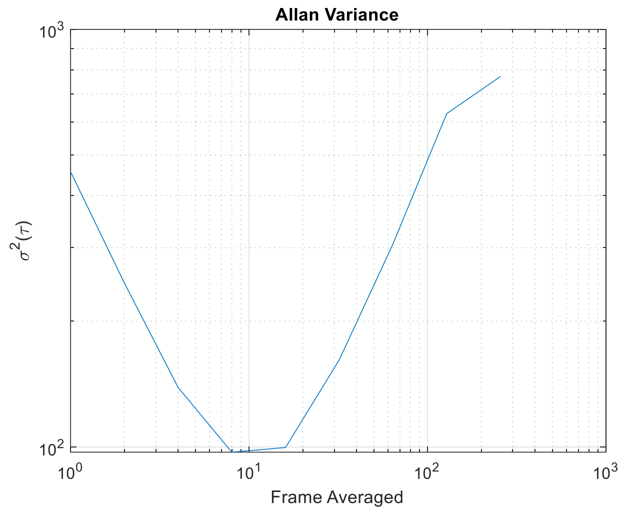

Figure 3. Allan variance measured over 1000 frames using the Microxcam-384i camera.

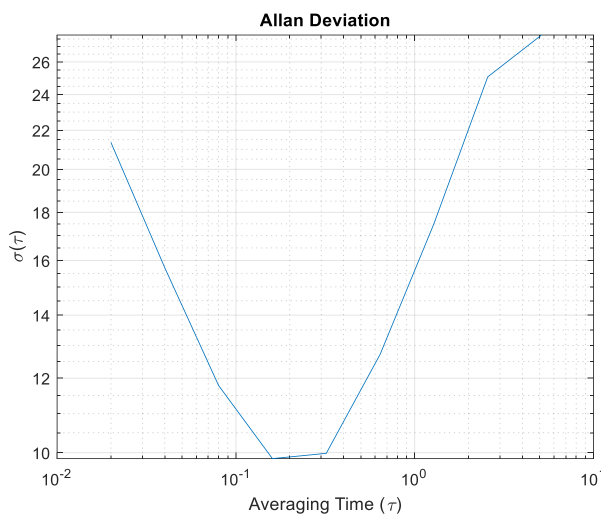

Figure 4. Allan deviation measured over 1000 frames using the Microxcam-384i camera.

The first data point of the Allan deviation curve provides information regarding the minimum signal (given in counts) that can be measured with a SNR=1 when the camera is running at its maximum frame rate (50Hz). It is important to note that this metric is related to the noise of the camera itself and will not change with wavelength. In the case of the Microxcam-384i camera, this noise level is 21.12 counts.

Using the responsivity presented previously, it is now possible to calculate the required incident power on a camera pixel to obtain a signal-to-noise ratio of one (Table 2). This value, previously reported by INO as NEP [4-6], is now defined more precisely as the optical Minimum Detectable Power (optical MDP) per pixel.

Table 2. Optical Minimum Detectable Power for the Microxcam-384i-THz camera for frequencies between 198 GHz and 4.25 THz.

Frequency (Wavelength)	Optical MDP [pW]	Standard deviation [pW]
4.25 THz (70 µm)	11.2	4.7
2.52 THz (118 µm)	19.9	3.7
1.89 THz (158 µm)	19.1	3.3
762 GHz (394 µm)	13.3	1.9
693 GHz (432 µm)	13.9	1.1
397 GHz (755 µm)	25.0	7.3
198 GHz (1510 µm)	34.0	8.9

3.3 NEP

As mentioned above, the ENBW for a system mainly dominated by a white noise, is defined as 1/2 τ. The integration time of the Microxcam-384i can be adjusted to favorize either its sensitivity or its dynamic range. For the measurements presented previously, the integration time was set to 40µs to have a good balance between those two characteristics. This led to an ENBW of 12.5 kHz.

Knowing the optical MDP and the ENBW, the NEP can now be calculated for the different frequencies characterized. Table 3 presents the NEP calculated for the Microxcam-384i camera over a wide range of frequencies.

Table 3. NEP measurement for INO's Microxcam-384i-THz camera.

Frequency (Wavelength)	NEP [pW/Hz$^{1/2}$]	Standard deviation [pW/Hz$^{1/2}$]
4.25 THz (70 µm)	0.11	0.04
2.52 THz (118 µm)	0.18	0.03
1.89 THz (158 µm)	0.18	0.03
762 GHz (394 µm)	0.12	0.02
693 GHz (432 µm)	0.12	0.01
397 GHz (755 µm)	0.31	0.07
198 GHz (1510 µm)	0.32	0.08

4. CONCLUSION

Without a universally recognized standard for NEP, characterization and comparison of THz imaging devices presents a challenge. We have presented in detail a systematic method to determine the Noise Equivalent Power of an imaging device that includes measurements of the responsivity, Minimum Detectable Power and Equivalent Noise Bandwidth. This characterization method has been applied to INO's Microxcam camera over a wide section of the THz spectrum to demonstrate the broadband behavior of detector. The measurements presented have shown that the optical minimum detectable power of the camera was lower than 35 pW which leads to a NEP below 0.32 pW/Hz$^{1/2}$ for frequencies between 4.25 THz and 198 GHz.

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