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Terahertz Sensor and Digital Signal Image Processing for Moisture Detection in Terahertz Transparent Materials

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Abstract: This article proposes a system for moisture detection using highly sensitive terahertz sensors at room temperature and relatively high-resolution digital image processing of collected pixels. Moisture can lead to swelling, cracking, or chemical degradation in hygroscopic materials and is typically a time-dependent process. Such a system may help conduct noninvasive experiments with hydrophobic coatings or handle different challenges in appropriate material selection. It is helpful in applications involving recycled plastic, paper, ceramics, pharmaceuticals, and biological tissues. Even small amounts of absorbed moisture in a material can dramatically increase the terahertz attenuation. Besides different hydrophobic material analyses, it may also be helpful in plant health analysis. Pathogens, such as fungi, bacteria, viruses, and environmental stressors, usually cause plant infections and damage their leaves. They strongly influence plant health, yield, and overall aesthetic value. They are usually directly correlated with changes in the dielectric constant of leaf tissues and moisture, which is, again, known to have a strong absorption coefficient for terahertz radiation. This phenomenon leverages terahertz radiation's unique, noninvasive interaction with water molecules and plant tissues. We can repeat noninvasive moisture detection several times and analyze the amount of detected moisture in different areas. We developed and manufactured our low-cost, highly sensitive terahertz sensors and installed them in a terahertz camera. The article describes the properties of our terahertz sensor and some examples of practical usage of the terahertz camera in biology. We will show that the amount of leaf water content or internal leaf moisture for different leaf areas can be easily detected with such a camera and displayed as a relatively high-resolution gray-scale image using some digital signal processing. Combining optical and terahertz pictures of the leaf may mitigate the risk of infections and promote overall plant health.

Keywords: Moisture detection, THz rays, THz sensor, Nano-bolometer, THz camera, Leaf disease.

1. Introduction

This article will unlock some of the secrets of plant leaves using terahertz (THz) waves. We will present a system for moisture detection using highly sensitive THz sensors and relatively high-resolution digital signal image processing. THz radiation is non-ionizing and harmless to most materials and biological tissues. This feature allows safe and repeatable testing without damaging the samples.

Moisture can lead to mechanical or chemical degradation in hygroscopic materials and is typically a time-dependent process. Such a system may help conduct several noninvasive moisture experiments over time. We can experiment with hydrophobic coatings or do several long-term experiments to select an appropriate material for a specific use. It is helpful in applications involving materials from recycled plastic, paper, and ceramics. Moisture detection is also vital in pharmaceuticals and for observing thin biological tissues. Even small amounts of absorbed moisture in a material can dramatically increase the terahertz attenuation.

On the other hand, the difficulty is the limited penetration of THz waves in highly conductive materials and strong attenuation in water. Due to the longer wavelengths involved, imaging resolution is generally lower than we can achieve in optical imaging. This lower resolution limits the system's ability to resolve fine moisture patterns. High-quality THz systems are still expensive and require some expertise, although prices are dropping as technology matures.

THz waves are electromagnetic waves between microwaves and infrared light in the frequency range of 0.1–10 THz. As mentioned before, they are sensitive to water content and can penetrate plant tissues [1-3], making them ideal for assessing internal moisture and detecting several anomalies in plant leaves.

We did some experiments with THz waves to detect plant leaf moisture. We may detect early plant or plant leaf disease using several highly sensitive THz sensors assembled in an array. Such an array is used in our portable THz camera working at room temperature. The sensor array uses digital signal processing (DSP) to display a THz image of the leaf in almost real-time as a gray-scale image. Lighter gray represents dryer areas, and darker gray represents water-soaked or moisture areas.

This approach is novel since THz technology is not widely used in agricultural diagnostics. Most plant disease detection methods rely on optical, infrared imaging, or hyperspectral analysis. The latter operates in the visible to near-infrared spectrum, while THz waves can penetrate certain materials and offer insights into subsurface features, like detecting moisture-rich areas. Hyperspectral imaging is surface-sensitive and relies only on emitted or reflected light from the surfaces.

Leaf diseases are generally divided into four classes:

- Physiological disorders;
- Fungal;
- Bacterial;
- Viral diseases.

Internal leaf moisture plays a critical role in developing many leaf diseases. Plant disease and stress cause typical structural and biochemical changes in leaf tissues, which usually produce distinct spectral signatures in the THz detection range.

2. Materials and Methods

We developed and manufactured our highly sensitive, low-cost THz sensor [4-8]. It consists of a nano-bolometer coupled with an antenna, a low-noise amplifier and a multiplexer. We experimented with several antenna types of different sizes, mostly dipole and wideband antennas. Dipole antennas (Fig. 1 above) are optimized for 100, 300, and 600 GHz. Broadband antennas (Fig. 1 below) are generally optimized for over 100 GHz and up to 3 THz. We also constructed a prototype of a THz camera with an array of sensors for simultaneously detecting two different THz frequencies. Photos of the nano-bolometer and part of the wideband-type antenna are shown in Fig. 2. In the following chapters, we will describe some properties of our nano-bolometer and THz image acquisition system - camera, with a short description of digital signal processing.

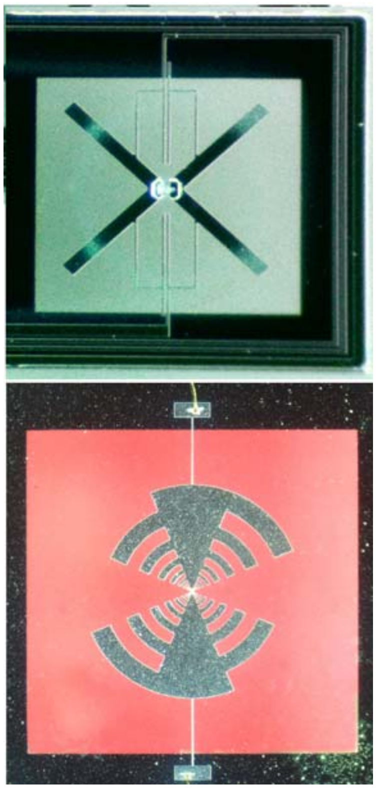

Fig. 1. Dipole (above) and broadband (below) antennas for nano-bolometer.

2.1. Nano-bolometer Properties

A nano-bolometer can be represented as a temperature-sensitive resistor, or in other words, a thermistor, that changes electrical resistance due to temperature changes. A sensor dipole or wideband antenna collects energy, heats the nano-bolometer, and adjusts its resistance accordingly. The alternative circuit is shown in Fig. 3.

$$\Delta R = R_{\circ} \cdot TC \cdot \Delta T, \quad (1)$$

where $R_{\circ}$ is the resistance at known ref. temperature, TC is the temperature coef. of resistivity, ΔT is a change of temperature.

$$\Delta T = \frac{P}{G}, \quad (2)$$

where P is the power dissipation, G□□ is the thermal conductivity.

Key factors of sensor sensitivity are TC and ΔT, *as described in* equation (1). We selected titanium (Ti) with TC = +0.13 % K^{-1}. The desired material criteria were about manufacturing possibility (manufacturing must be possible in a standard CMOS process), conductivity, and the desire to have a value of TC as high as possible. With equation (2), we can calculate nano-bolometer temperature rise due to the given amount of power and optimize energy transfer from the antenna by matching the sensor's characteristic impedance close to 1 kΩ. This impedance also defines the geometry of the nano-bolometer.

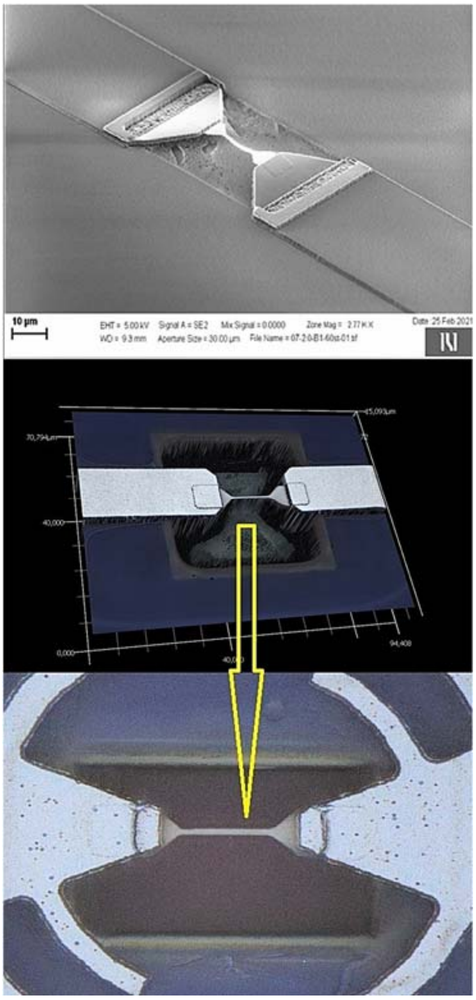

Fig. 2. Microscopic photos of nano-bolometer with part of wideband-type antenna.

$$R = \rho \cdot \frac{L}{W \cdot d}, \quad (3)$$

where ρ is the specific res. of titanium (app. 900 nΩm), L is the length = 12 µm, W is the width = 0,5 µm, d is the thickness = 30 nm.

We must optimize the nano-bolometer's thermal conductivity (Gth) to get a sensor temperature change that is as high as possible. Therefore, we removed the layers below the nano-bolometer structure by etching the wafer from the opposite side of the sensor fabrication. Etching makes a tiny hole through the silicon substrate. This etching also creates a resonant cavity below the sensor, improving the antenna properties. By etching a hole through the silicon substrate, we got the nano-bolometer structure surrounded by a temperature insulator – the air. Vacuum around the nano-bolometer further improves the desired parameters by a factor of two. However, we are still refining the vacuum solution.

Fig. 4 presents a thermal simulation of the nano-bolometer. The structure heats to about 50 degrees above the ambient temperature due to the bias current. Increasing the bias current also changes the resistivity of the nano-bolometer. Characterization of the nano-bolometer resistance can be accomplished by using DC measurements. Fig. 5 presents the graph of nano-bolometer resistance change versus bias current. The most important figures of merit are represented with equations (4-6), where NEP stands for Noise Equivalent Power.

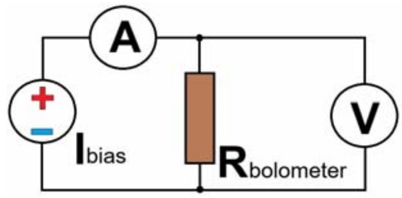

Fig. 3. The alternative circuit for DC nano-bolometer analysis.

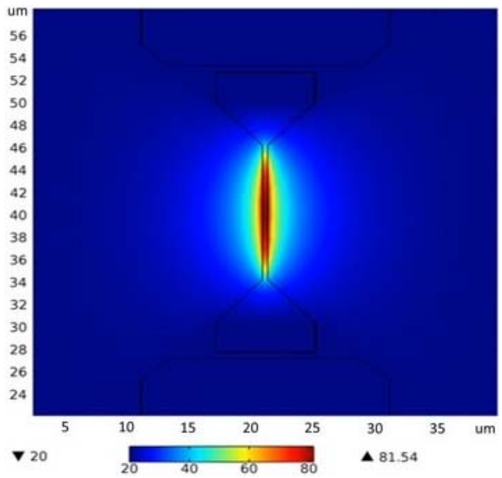

Fig. 4. Thermal simulation of the nano-bolometer. The structure heats to about 50 degrees above the ambient temperature.

Characteristic current:

$$I_\circ = \sqrt{\frac{G_{th}}{R_\circ \cdot TC}}\ [A], \quad (4)$$

Responsivity:

$$\mathcal{R} = \frac{dU\ sensor}{dP\ input}\left[\frac{V}{W}\right], \quad (5)$$

NEP:

$$\frac{noise\ amplitude\ spectral\ density}{\mathcal{R}}\left[\frac{W}{\sqrt{Hz}}\right] \quad (6)$$

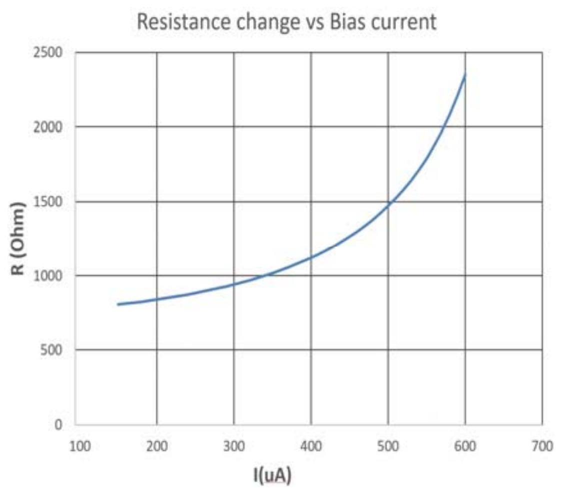

Fig. 5. The graph of nano-bolometer resistance change versus bias current.

The essential nano-bolometer average parameters we have are as follows:

- R_o ~ 800 Ω;
- I_o ~ 700 μA;
- □~500 V/W;
- NEP < 20 10^{-12} W / $\sqrt{Hz}$.

According to our knowledge and recently published results in this research area, this is still one of the best sensors of its kind, and it operates at room temperature.

2.2. THz Acquisition System Description

The terahertz sensor's nano-bolometer thermal time constant is lower than one microsecond, allowing a high-frequency frame rate of the THz image at room temperature. The resolution of the THz image is dependent upon pixel size and pixel response time. Our pixel size is 1 mm × 1 mm. It comprises the nano-bolometer, a four-channel low-noise amplifier (LNA), and a multiplexer.

We used our in-house developed THz system to take the THz pictures of the objects. It uses a 0.3 THz source, a terahertz acquisition system, and a separate digital signal processing element. With further refinement, the system could also become portable and be used for on-field operation.

Fig. 6 and Fig. 7 present two different types of terahertz image acquisition systems. One is a fast image acquisition system with a conveyor, and the second one is a high-resolution imaging setup. On the first one, we fixed a THz source above a belt conveyor to quickly investigate the amount of moisture in the plant leaves. The nano-bolometer sensor array is placed below the conveyor belt.

Fig. 8 represents a block diagram of the analog part of the signal acquisition system, and Fig. 9 illustrates a digital signal processing block diagram. In Fig. 10, we see an array of nano-bolometers assembled in a terahertz sensor.

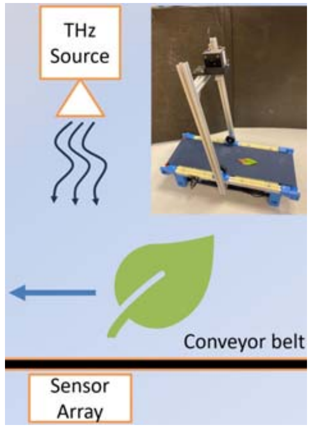

Fig. 6. Fast THz image acquisition system with a conveyor and sensor array below the belt.

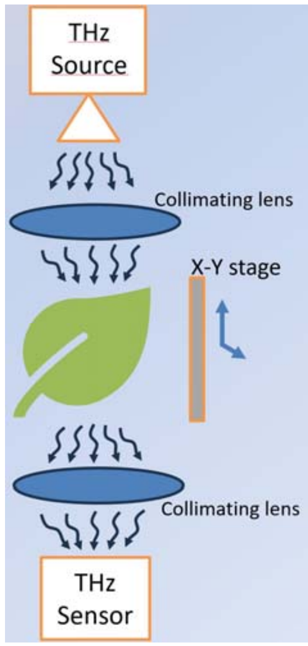

Fig. 7. High-resolution THz image acquisition system with collimating lenses and X-Y stage.

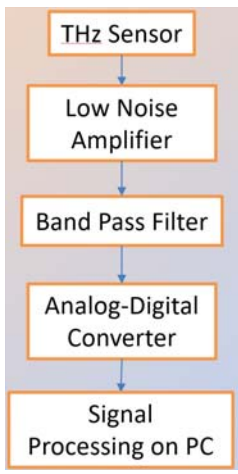

Fig. 8. Block diagram of the analog part of the terahertz signal acquisition system.

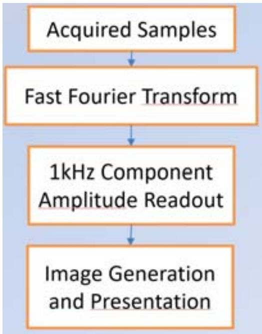

Fig. 9. Block diagram of the digital signal processing part of the terahertz signal acquisition system.

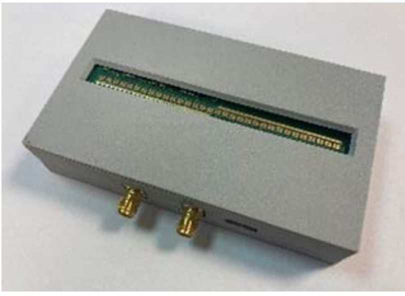

Fig. 10. Array of nano-bolometers assembled in a terahertz sensor.

2.3. Digital Signal Processing

The THz camera has image acquisition, processing, and display software. It enables us to visualize camera-captured images in almost real-time. We have also developed several unique features, such as image enhancement, filtering, and analysis tools to extract relevant information from the raw data of the THz camera. Additional digital signal processing algorithms enhance our image quality and reduce noise.

Images are obtained by raster scanning the area with a dimension of 100×100 positions corresponding to the image's pixels. Data are acquired using a fast, freely on-market available universal serial bus (USB) signal acquisition card. For each pixel, 3000 samples are acquired with a sampling frequency of 60 kHz. This means an acquisition time of 50 milliseconds for each pixel. Then, a fast Fourier transform is performed on each pixel dataset and an amplitude peak at 1 kHz frequency is observed to determine the brightness of each pixel. Signal processing must be synchronized with the X-Y manipulator's movement rate.

Due to the efficient software, this digital signal processing can run on an average laptop computer.

3. Results

Symptoms of leaf diseases include discoloration, spots or blotches, rusts, deformation, fungal growth, yellowing or browning edges, frost damage, mottled patterns, water-soaked lesions, curling, etc. It is important to note the relationship between leaf disease and moisture. Moisture is an essential component in many leaf diseases and how they develop. A longer duration of soaking the leaves increases the risk of infection [9, 10]. Water-soaked spots on leaves are frequently early signs of plant disease. Such marks may induce cell turgor loss and tissue maceration, further developing entry areas for pathogens [6]. On the other hand, water deficiency can also increase susceptibility to pathogens [11].

Figs. 12, 13 compares some terahertz images with photos of leaves of the "Prunus laurocerasus" or laurel plant. We picked fresh, as flat as possible leaves from the fence photographed in Fig. 11 and selected a healthy one and some with different disorders.

In Fig. 12, we can see a healthy leaf in wintertime. Fig. 13 shows the leaf in the process of drying. The dryer the area of the leaf is, the lighter gray is the color in the THz gray-scale image. On the other hand, darker regions are more prosperous with moisture. In Fig. 14, we can see a withered laurel plant leaf. Although there is still a green area in the left picture, the leaf is almost dehydrated, except for the leaf veins. Fig. 15 presents different type of fresh leaf from the cherry tree, and Fig. 16 presents an apple leaf with the corresponding terahertz image on the right.

Fig. 11. "Prunus laurocerasus" or laurel plant fence – the donor of the leaves.

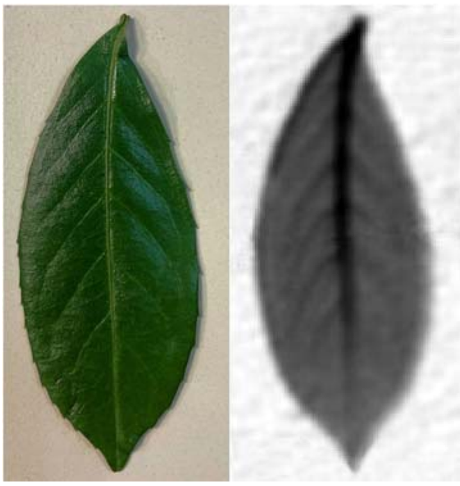

Fig. 12. Healthy leaf and terahertz image on the right.

Fig. 13. Leaf in the drying process with terahertz image on the right.

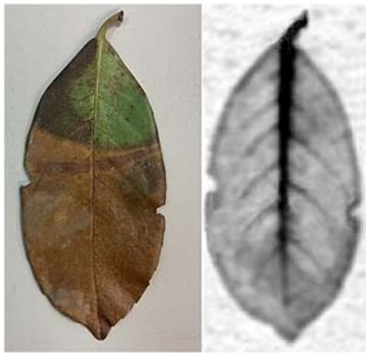

Fig. 14. Withered leaf – although there is still a green area in the left picture, the leaf is almost dehydrated, except for the leaf veins.

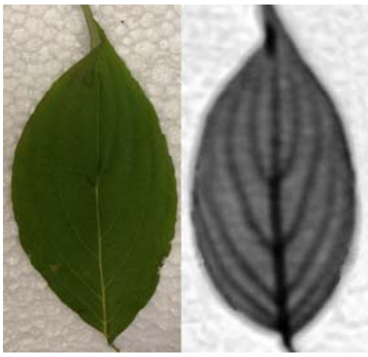

Fig. 15. Fresh leaf from the cherry tree with the corresponding terahertz image on the right.

Fig. 16. Fresh leaf from an apple tree with some disorders and the corresponding terahertz image on the right.

The advantage of THz spectroscopy for leaf internal moisture detection is its non-destructiveness, which can preserve the sample for further growth and analysis. Water's strong absorption of the THz waves can be detected accurately and quickly.

4. Conclusions

The future of evolving terahertz technology looks promising, especially in contactless, non-destructive moisture detection in plastics, paper, ceramics, pharmacy, and biology. We will soon see high-resolution, low-cost, field-deployable terahertz tools be more portable and combined with other spectral technologies like hyperspectral imaging and artificial intelligence. Further development in this direction will enable more comprehensive terahertz imaging and easier leaf moisture parameter analysis. We are developing an even higher-resolution terahertz camera to capture more detailed images of moisture in objects. Fig. 17 presents our new, high-resolution terahertz imaging prototype in development.

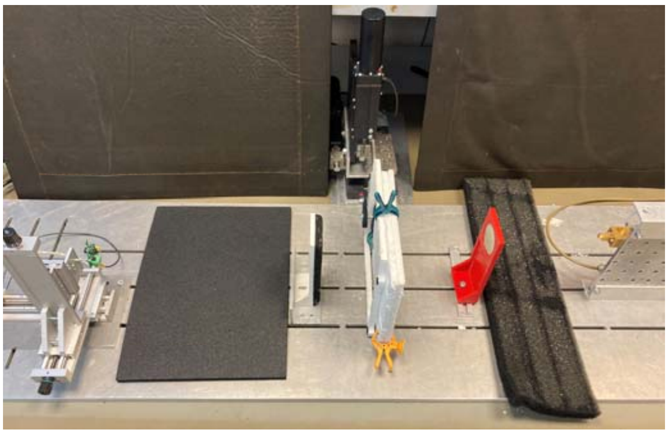

Fig. 17. A high-resolution terahertz imaging prototype is in development. From left to right, we have a THz source, a collimating lens, an X-Y stage with observed material, another collimating lens, and a THz sensor on the right.

Different leaf diseases are essential challenges in agriculture, landscaping, and gardening. Early detection, before visual leaf defects appear, may give us a proper diagnosis and allow us to implement management strategies necessary to maintain plant health. Maintaining optimal watering conditions through appropriate irrigation practices and environmental planning is crucial for enhancing plant resilience against diseases.

Using noninvasive THz technology and machine learning [12], detecting early signs of leaf disease on various plants and taking appropriate actions to promote overall plant health is possible. The integration of THz with DSP and imaging techniques in biology is, in our opinion, a significant advancement for the noninvasive detection of sub-surface moisture of plant leaves and for making the correct conclusions about plant conditions.

Our THz leaf monitoring experiments are not yet focused on research for detecting and treating specific leaf diseases. High-resolution THz images are expected to detect pathogens more effortlessly before visual disease symptoms appear, enabling even better plant treatment.

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