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THZ TECHNOLOGY FOR VISION SYSTEMS

J. Trontelj[1], A. Sešek[1], A. Švigelj[2]

[1]Faculty of Electrical Engineering, Laboratory for Microelectronics, Tržaška 25, 1000 Ljubljana, Slovenija
[2]LetrikaLAB d.o.o, Polje 15, 5290 Šempeter pri Gorici, Slovenija

Abstract. *The THz radiation brings new technology challenges and new opportunities to overcome some of the current application obstacles. In the paper a portable THz system is presented operating at room temperature. The presented solution is robust and inexpensive, convenient for many applications. The THz sensor fabricated at the Faculty of Electrical Engineering in the Laboratory for Microelectronics is currently one of the best sensors in its frequency operating range. It reaches sensitivity up to 1000V/W and NEP down to 5pW/√Hz in vacuum. With the proposed system solution variety of application can be covered. Some imaging results captured with the proposed system at different stand-off distances are shown in the paper.*

Key words: *THz sensors, THz systems, Stand-off THz detection, bolometer*

1. THz Technology

Nowadays many kinds of material inspection systems that are used, for example in the semiconductor industry, paper industry, medical and security applications, or many other see-through systems are based on X-ray techniques. As X-rays are ionizing and thus extremely harmful for biological tissue, their usage is area and time limited. Therefore, new technologies and non-destructive methods emerging especially for biological tissues are used.

THz technology promises suitable substitution, as it is nonionizing and comprises some other new properties which are available only in the THz frequency region of the electromagnetic spectrum. THz waves propagate through different non-metal materials such as plastics, clothes, paper, ceramics, some thermal insulation materials, and also dry wood. Furthermore, very good reflection can be obtained by flat surfaces, and especially from metals. The main obstacle is humidity, which brings very high attenuation in the THz spectral range. Air humidity absorbs THz radiation and makes THz waves improper for use at long stand-off distances. It was also shown that when THz waves propagate through or reflect from different materials, especially drugs and explosives, a specific fingerprint of each material can be recognized. All of these facts open a lot of new

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Corresponding author: Janez Trontelj
Faculty of Electrical Engineering, Laboratory for Microelectronics, Tržaška 25, 1000 Ljubljana, Slovenija
(e-mail: janez.trontelj1@guest.arnes.si)

possibilities of THz waves usage in e.g. material quality control, the pharmaceutical industry, medical imaging, and security – which is one of the most emerging fields.

Generally, there are two approaches of generation and detection of THz waves. First is the electro-optical approach, which is based on an ultra-short laser pulse, where the pulse width is in the femtosecond range. Such a pulse illuminates a special crystal or semiconductor material and an electromagnetic wave in the THz region is emitted. The same material can also be used for detection. The TDS principle is mostly used for spectroscopy, but imaging can also be done. Imaging is very time consuming, as systems consist of one source and only one detector. With such setups, frequencies from hundreds of GHz to up to 8 THz and above can be achieved in the power range of microwatts.

The second is the microwave approach, where signals are generated at frequencies as low as 10 GHz with discrete RF components. With these techniques continuous wave signals with frequencies up to 1.2 THz can be generated. The typical power at 300 GHz can reach up to 20 milliwatts. Commonly used detectors are Schotkey diodes and bolometers with an antenna, where an incident wave causes a temperature change of the detector. Such detectors are small enough and can be merged into arrays, and can be integrated into systems used for imaging. It should be noted that spectroscopy is also emerging as a future application.

1.1. Time domain THz spectroscopy system

An optical approach of THz generation and detection is used in many different types of Time domain spectroscopy (TDS) THz systems. The common base of all is to split a femtosecond laser beam into two signals. One is used for THz wave generation and the second, also named a probing signal, is used for THz pulse reconstruction on the detector. For generation and detection of THz waves various methods are used, such as photoconductive generation and optical rectification. To reconstruct the whole THz pulse, the probing signal has to be time shifted over the whole THz pulse. This is done by a probing signal delay with a motorized optical delay line. When using photoconductive generation and detection, signals have to coincide directly on the detector itself. In the case when the optical rectification detection method is used, both signals have to coincide on the crystal, where the probing signal is polarized according to the incident THz pulse intensity. The difference in polarization gives THz signal strength information.

At first, THz time domain spectroscopy setups were mostly built on optical tables, where various optical components such as beam splitters and focusing parabolic mirrors could be easily adjusted. Such systems are very sensitive to mechanical stress and also the samples have to be small enough to fit into the measurement place in the system. They operated mostly in the transmission mode. To change to reflection mode usually big part of the setup had to be changed. To obtain a visual THz image, a sample had to be moved with implemented translation stages. Therefore, new systems were built using fiber optics to improve the flexibility of measurements. Now both main and probing laser signals can be transferred to a remote distance of few meters using fiber optics, and THz pulses are generated at the remote location. This allows THz response measurements of larger objects. Also, the reconstructing of a visual THz image can be easily done with transmitting and receiving THz heads mounted on to the translation stages.

1.2. Continuous wave THz systems

The main THz core of a continuous wave (CW) THz source is a few GHz voltage controlled oscillator with a precise PLL loop to achieve low phase noise and enough output power. Normally the chosen basic frequency is 12.5GHz, which can be easily multiplied to several hundreds of GHz. During multiplication, which means higher harmonics filtration and amplification, the main issue is to keep low phase noise and to achieve high output power. The power on the output horn antenna is usually up to 100 milliwatts and is highly dependent on number of multiplications. With electronics sources a frequency of up to 1THz can be reached, which is highly suitable for 2D and 3D imaging. For a detector, many sensors can be used, as the power is higher and the THz beam illuminates a larger area. Primary selection is the bolometer type sensor array, Schotkey diode array, pyro sensor array, etc. [1].

2. LMFE THz Sensor and System

The THz system in the Laboratory for Microelectronics (LMFE) is a CW THz-based system with scanning mechanic, THz lenses and a micro bolometer detection array [2], [3].

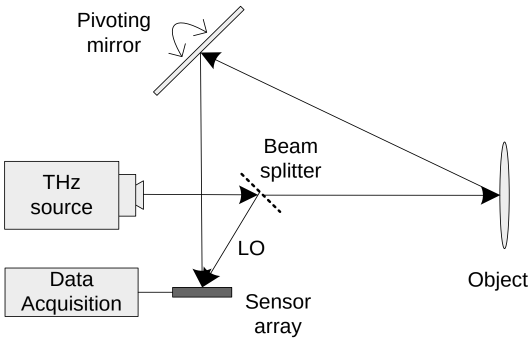

Fig. 1 Block diagram of a LMFE THz Imaging system

The THz source is a 12.5GHz source, multiplied by x4, x2, and x3- totally x24, which gives an output frequency of 300GHz with a peak power of 5mW. The THz beam is split in a ratio 40:60 with a silicon beam splitter. The larger part of the beam continues to the observed object. There it reflects and it is redirected to a sensor array by a pivoting mirror. The pivoting mirror scans through the vertical dimension of the object. The on sensor array, which gives the horizontal dimension, and both THz beams are merged to achieve a heterodyne detection. The core of the system is a 2x16 THz sensor array, fabricated and assembled in LMFE.

2.1. THz sensor and sensor array

Sensors used in a THz array [4]-[6] are designed and fabricated in LMFE. LMFE owns the CMOS technology, which is able to produce a sensor and systems on silicon down to 500nm. The technological procedure of the THz sensor fabrication was described in patent [7]. Materials for the sensor were evaluated with the equation

$$S_e(\omega = 0) = \sqrt{TC} \cdot \frac{R_{ho}}{G} \quad (1)$$

where S_e is sensitivity, TC is the temperature coefficient of the material, R_{ho} is sheet resistance, and G is thermal conduction [8]. From the several appropriate materials, Titanium was chosen.

The main goal of the design was to achieve the highest sensitivity (S_e), low noise equivalent power (*NEP*), and to match sensor and antenna impedances.

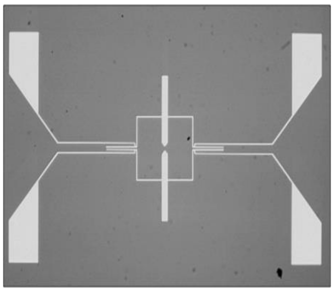

Fig. 2 LMFE THz sensor

As the detection principle is based on a Titanium thermistor, a double dipole antenna is attached to it to receive and transfer THz energy to the bolometer which is therefore heated, and consequently its resistance changes according to the energy received. On Figure 2, the realization of such sensor is shown. The sensors are fabricated from a Silicon wafer, which is partly etched on the thermistor-antenna area to achieve better parameters regarding thermal dissipation. Doubled contact pads allow connection from both sides. The antenna and connections material is Aluminum. Equation (2) describes power conditions on the bolometer:

$$P = {U_b^2}/{R} + {U_n^2}/{R} + {U_s^2}/{R} \quad (2)$$

As it can be seen from equation (2), three basic power components are present on thermistor – biasing power (U_b^2/R), noise power (U_n^2/R), and signal power (U_s^2/R) [9].

THz sensors fabricated at LMFE have a 300GHz central frequency, a sensitivity of up to 1000V/W, and NEP of up to 5pW/√Hz when in a vacuum and at room temperature. The sensors are fabricated as quadruples for easier handling and a simple array assembly. The sensors are biased with an $I_0/4$ current, where I_0 is a physical limitation of the electrical damage.

Fig. 3 THz sensor array

On Figure 3 THz sensor array (2 x 16 sensors) is presented. The opening under the sensor can be clearly seen – a 3um Silicon Nitride membrane is practically invisible – cavity under the sensors is λ/4 deep and acts as a resonator which gains the THz signal.

2.2. LMFE THz system

THz system was partly described in the block diagram on Figure 1. The real setup is shown on Figure 4.

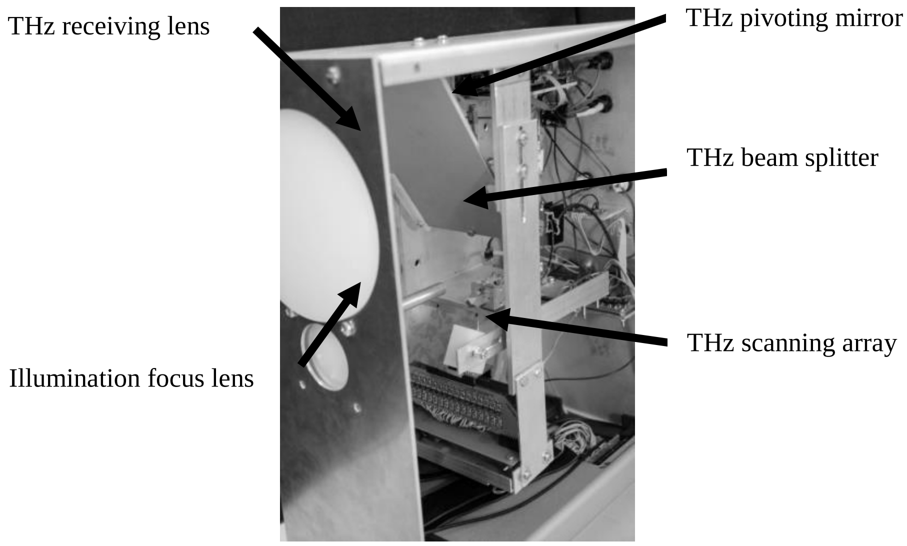

Fig. 4 THz sensor system

The image on Figure 4 presents a portable THz system which consists of four main blocks, as presented in the block diagram in Figure 1. Some other system parts can be seen in Figure 4, as the THz receiving lens and illumination focus lens. The system also needs additional low noise amplifiers, which are below the sensor array, the supply for each block and A/D converter for its operation. Digitalization is made with a 16-bit National Instruments A/D card with 32 channels, and a 2MHz total sampling frequency. Data collected and transformed is transferred to a PC and processed to produce the THz image of the hidden object.

3. IMAGING RESULTS

The THz system is capable of scanning through different materials which are invisible, but transparent for THz radiation as paper cardboard, plastics, paper, and packaging material. It covers approximately 0.1m x 0.1m area at a 1m distance with basic lenses and basic optical adjustments. With special stand-off lenses, a maximal area of 0.2m x 0.2m at 5m was achieved. The test setup of the system is presented in Figure 5 where the lenses, THz source, and THz detector array box are separated due to different tests, different observation distances, and different operation modes (reflection and transmission mode).

THz lenses are made of polystyrene and they have different diameter according to the distance of the observed object. In many cases, a lens can included in the THz source block and/or in the receiving block. Design of the lens is important as it can significantly influence image quality and the system resolution. For larger diameter of the lens a Fresnel principle is used and for the smaller diameters continuous lenses are choosen. For images three different objects were chosen to prove all operational modes and the stand-off operation.

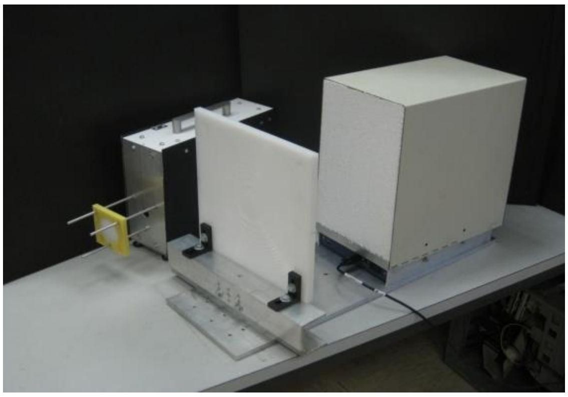

Fig. 5 Test THz system

In transmission mode Figure 6 was captured. The observed objects were plant leaves, where water vessels can be clearly seen in the THz image. The visual image is added for better understanding.

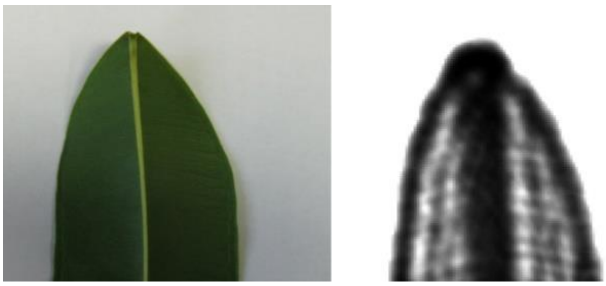

Fig. 6 Visual and THz image in transmission mode

The main vessel in the center is almost opaque due to high water content (THz waves are totally absorbed), meanwhile other parts of the leaf are semi-transparent according to the water content level. The next mode is the reflection mode, where two different objects at two different distances are presented. The first in Figure 7, the paper clip at a distance of 0.36m was scanned.

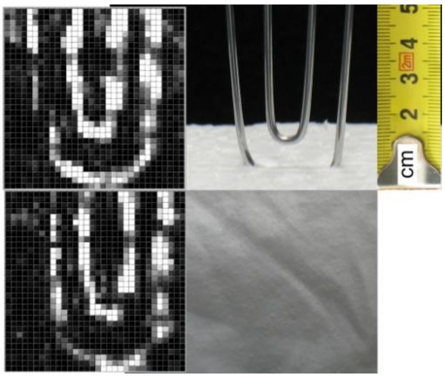

Fig. 7 Visual and THz image of a paper clip

The upper two images in Figure 7 presents a THz and visual image of a paper clip without a barrier cover material, and the images below present the same clip with an additional two layers of textile cover, to prove the THz waves penetration.

Figure 8 presents the imaging result of the THz system of a small carpenter knife taken at a 5m stand-off distance.

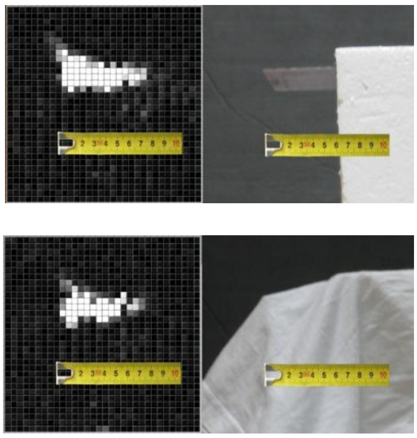

Fig. 8 Visual and THz image of a carpenter knife

The upper image couple in Figure 8 presents the uncovered object, and the bottom couple show the object covered with two layers of textile. The knife is clamped in expanded polystyrene, which is transparent for THz radiation.

4. CONCLUSIONS

In the paper the THz vision system developed in the University of Ljubljana Laboratory for Microelectronics is described. Both transmitted and reflected images are shown giving excellent resolution at up to a 5m stand-off distance. The core of the system is the THz thermistor sensor, which is fabricated in LMFE, and achieves one of the best reported results in sensitivity (Se=1000V/W) and noise equivalent power (NEP=5pW/√Hz) at room temperature.

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