Real-time nondestructive imaging with THz waves

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Abstract— The aim of this report is to present potential interest of a new technology of sensor for measuring terahertz radiation at room temperature and its application in imaging systems as a volumetric, safe, contact free and real-time Non-Destructive Testing systems. These imaging systems could be easily integrated in industrial facilities allowing the detection of surface, subsurface and in-depth defects for a large variety of materials with high precision and sensitivity.

Index Terms—optical non-destructive testing, High-Electron-Mobility transistors, imaging, material characterization

Introduction

The terahertz (THz) region of the electromagnetic spectrum lies between the microwaves and infrared ranges. With frequencies spanning from 0.1 THz and 10 THz and wavelength from 3 mm to 30 µm, it separates the electronic and photonic domain of the spectrum. On the one hand, the THz region is the frontier area of research on high-frequency electronics. At these frequencies, operation of classic electronic devices is limited by transit-time effects. On the other hand, the THz range poses a substantial challenge to the photonic research with its phonon energies being lower or roughly the thermal energy. The technological gap between microwaves and infrared frequencies is historically called the THz gap.

The energy of the terahertz photons is of the order of meV. This is a very low power, about 1000 times smaller than that of transitions between electronic levels of atoms, and even lower than the thermal energy at room temperature ($k_B T \approx 27$ meV, k_B the Boltzmann constant $\approx 1.38 \times 10^{-23}$ J / K). These waves have the characteristic to penetrate a large number of opaque materials for visible and infrared wavelengths and be absorbed by the conductive materials and polar liquids such as water. Many molecules have a specific spectral signature that often does not exist in other regions of the electromagnetic spectrum, such as near or mid infrared. Furthermore, the terahertz waves are non-ionizing, unlike X-rays and they are able to penetrate the organic or inorganic material without causing any damage. All these characteristics are suitable in spectroscopy and imaging methods. In spectroscopy, data on the structural properties of the material and identification of chemical compounds in the materials can be obtained. In imaging analysis, we can get data both about the surface and volume.

NDT (non-destructive testing) techniques, used over 35 years, are analysis techniques used in science and industry to evaluate the properties of a material, component or system without causing damage to the samples. Currently, widely used NDT methods include ultrasonic, eddy current, microwave and acoustic emission, *etc*. However, these methods have limitations in regards to the type of objects that can be inspected or to the type of defect to be detected. Recent developments in optical NDT technology give higher detection accuracy and sensitivity, plus ease of signal multiplexing and resistance to electromagnetic interference. Main types of optical NDT are surface measurements, such as infrared thermal imaging, endoscopic and speckle imaging for component surfaces and subsequent image analysis to determine the presence of a defect. Optical fibre sensing is used for dynamic parameter measurements. Compared with other NDT techniques, THz imaging has unique advantage in the detection of internal defects for non-metallic material. The THz waves can pass through opaque materials (such as fabrics and plastics) and detect internal defects which visible light cannot detect. It can also be used for insulating materials, unlike IR thermography.

Terahertz imaging and spectroscopy have strong potential applications in areas such as security, defense, environment, health, agronomy, food, biology, aircraft industry, *etc*. THz waves can indeed be used to study genetic mutations, to identify drugs and medicines, identify cancerous tumors and dental caries, studying plant water stress and vibration of cell membranes and microtubules.

The company, T-Waves Technologies, is the result of a technological partnership started early in 2012 with the Charles Coulomb Laboratory (L2C). This partnership was

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initiated with the technological maturation of a new type of sensor based on plasma waves [1] nano-transistors in the terahertz domain and extended to development of 2D and 3D imaging systems. The technology of sensor, compared to those already existing (micro-bolometers [2], Schottky diodes, Gunn and Impatt [3], pyroelectric [4]) presents adequate advantages to its use in compact imaging systems, inexpensive, operating at ambient temperature for real time and sensitivity inspection of materials. In addition, this new technology holds the world record of sensitivity at 0.3 THz since 2011 [5].

Theory

The channel of a FET (Field Effect Transistor) can act as a resonator for plasma waves, the charge-density waves of collectively excited 2D electrons. The plasma frequency of this resonator depends on its dimensions and the density of 2D electrons and can reach the sub-THz or even THz range for gate lengths of a micron and submicron (nanometer) size. When an incoming terahertz radiation excites the plasma waves, the local carrier density as well as the local carrier drift velocity is modulated by the radiation frequency components, resulting in generation of the quadratic plasma-wave current in proportion to the product of the modulation components of the local carrier densities and velocities. As a result, the plasma-wave current includes a rectified component, giving rise to a photovoltaic effect at the high-impedance drain terminal under a source-terminated and drain-opened asymmetric boundary condition. All of these ideas were proposed by Dyakonov and Shur [6]. More details are reported by the same authors on [7] where they gave a complete description of the resonant as well as the non-resonant (overdamped) plasma oscillation regimes.

The plasma resonances allow FET-type transistors to operate beyond their cutoff frequency emitting or detecting THz radiation [8]. So with the improvement of nanotechnology it was possible 10 years after the theoretical work of Dyakonov and Shur to prove experimentally these ideas. Indeed, in 2002, Knap et al. [9] demonstrated successively the resonant and non-resonant detection of THz signal in nano-transistors. Many publications have attested to the possibility of designing nano-transistors from different technologies to achieve rapid and sensitive THz radiation. Today, the development of manufacturing processes and new transistor structures [10] enable the detection of terahertz waves over a broad spectral range from 0.2 THz to 4.3 THz [11], with sensitivities up to 80 kV / W [12]. These detectors are now used in communication systems and terahertz imaging [5, 13]. They are low cost, operate at room temperature and easily integrated into more complex and fast systems. Given their frequency modulation (on/off) of the order of tens of GHz, their response time is very short, on the order of tens of ps.

Imaging systems

We have developed 2D (figure 2) and 3D (figure 4) versions of imaging systems based on nano-transistor sensor whose responsivity is about 40 KV/W at 0.3 THz, NEP (Noise Equivalent Power) of 50 Pw/√Hz (calculated from the formula mentioned in [5]) and acquisition speed about 3 kHz. The amplitude of the photovoltaic signal for 280 GHz versus polarization angle and the layout of a commercial FET device used in our experiments are shown in figure 1.

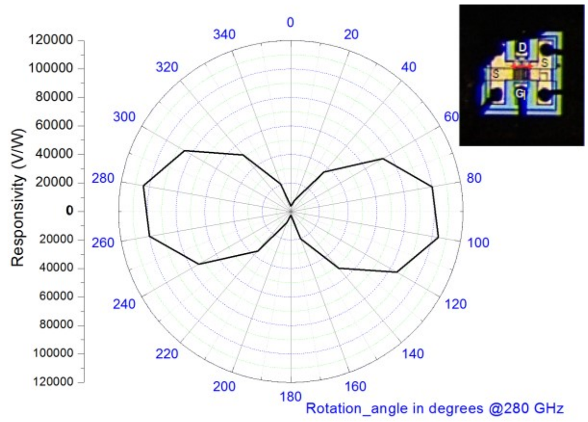

Figure 1. Responsivity of T-Waves sensor @280 GHz, picture of FET device. S, G and D denote source, gate and drain, respectively.

The 2D version can be used for transmission and reflection analysis. Imaging is based on point to point acquisition of detected terahertz signal. The 2D image is acquired by XY movement of a sample located between a source and a terahertz sensor. This displacement is provided by translation stages with steps ranging from 100 µm to 500 µm. The terahertz radiation is penetrating; 2D images can be interpreted as volume density maps of the matter, and some properties can then be revealed as the water content or the presence of contamination or defects.

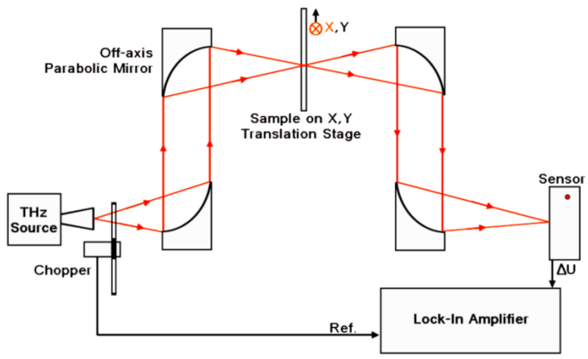

Figure 2. 2D imaging system, transmission method.

We report in figure 3 several terahertz images obtained by our 2D set up. Each image is associated with a defined area of the sample.

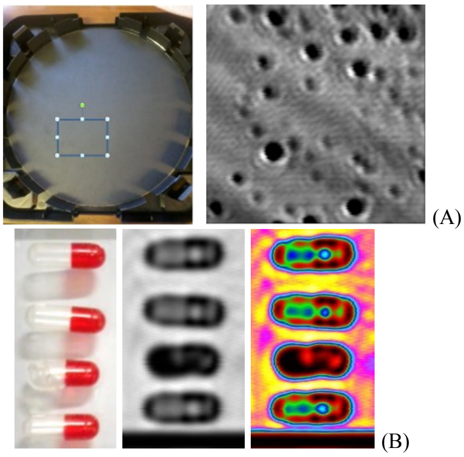

Figure 3. (A) Detection of silica beads in a wafer,
(B) Presence of water in pharmaceutical products.

The 3D version of our imaging system is showed on figure 4. The sample is placed on a rotative stage. It is based on the acquisition of several 2D images of the object (typically 18 or 36 projections). Each 2D image corresponds to a defined degree angle. In figure 4, we report 2 examples of 3D terahertz images.

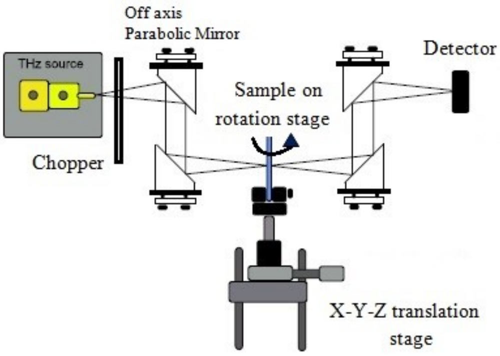

Figure 4. 3D imaging system, transmission method.

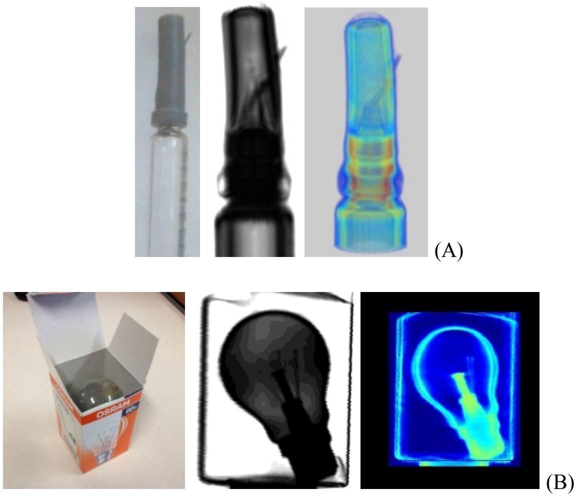

Figure 4. 3D térahertz images, (A) Detecting needle defects in syringes,
(B) Observation of bulb in a box.

Conclusion

We continue our efforts on improving the resolution of our terahertz imaging systems and extension of the variety of optical configurations associated to respond to the greatest number of potential applications in academic and industrial scale. We note also that our developments at different possible configurations for terahertz spectroscopy are also under development. We want to develop a complementary analysis from spectroscopy and imaging in the terahertz range for non destructive testing in the volume of the materials.

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