Terahertz imaging
- new steps toward real-life applications -

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Abstract

We are studying several novel steps toward real-life applications of terahertz and millimeter waves, such as, i) Non-destructive detection of illicit drugs using spectral fingerprints, ii) Laser-terahertz emission microscope for semiconductor device under test, iii) Real-time inspection system to detect micro-leak defects in the seal of flexible plastic packages, iv) Prism-shaped Fabry-Perot etalon for absorption measurement, v) Development of terahertz direct detector using superconducting tunnel junctions, vi) Water content measurement in plants and seeds, vii) Monitoring of water/ice state in food stuffs, viii) Non-thermal effect of millimeter wave radiation on cell membrane. In this paper, we introduce some of our recent activities.

Introduction

After more than a dozen years of basic research into the submillimeter and far infrared range, terahertz (THz) wave research has finally come into its own, and is recognized by the world scientific community as a new frontier [e.g. 1]. While femtosecond laser pumped THz wave sources have opened up a new vista in applied research, the ideal THz wave source will likely require high temporal and spatial coherence. When this level of quality is finally made available in a user-friendly device, there is little doubt that applied research efforts into the THz region will enjoy a true renaissance.

In this direction we have developed a widely tunable (0.7-2.4 THz, 125-430 μm, 23-80 cm^{-1}) injection seeded THz-wave parametric generator (is-TPG) that operates at room temperature [2]. The spectral resolution (100 MHz, 0.003 cm^{-1}) is the Fourier transform limit of the nanosecond THz wave pulses. The continuous scanning and the narrow spectral bandwidth of the is-TPG are verified in absorption spectra of low-pressure water vapor. The output has a high peak power (>200 mW) and a small beam divergence, which are suitable for applications such as spectroscopic imaging.

In our laboratory, THz- and MM- waves continue to broaden their range of applications as following.

Terahertz Spectroscopic Imaging

The absence of non-destructive inspection techniques for illicit drugs hidden in mail envelopes has resulted in such drugs being freely smuggled across international borders. We have developed a basic technology for THz imaging which allows detection and identification of drugs concealed in envelopes by introducing the component spatial pattern analysis. The spatial distribution and the composition of the targets are obtained from THz multispectral transillumination images, using absorption spectra measured with a tunable THz wave source [3, 4].

We further demonstrated a component spatial pattern analysis of chemicals using 2-dimensional electro-optic THz imaging which can capture real-time THz images [5]. By changing the optical delay of the pump beam, the CCD camera records time-dependent THz images. The multispectral images and the spectral data set were measured between 0.1 and 1.0 THz; the chemical composition, the spatial distribution, and the difference in concentration were clearly determined.

The actual mail detection system can be achieved using THz radiation in a simple two-step procedure: First, scattering of the THz waves is an indicator of the presence of powders in the envelope; second, the identification of the drugs is done by spectral fingerprinting [6].

Laser-Terahertz Emission Microscope

For inspecting electrical failures in large scale integration circuits (LSIs), we developed the laser-THz emission microscope (LTEM) [7], which records the map of THz emission amplitude in a sample upon excitation with fs laser pulses.

Commercial IC's were tested during operation. Clear two-dimensional THz-emission images of the IC chip are recorded as the chip is scanned with laser beam. The LTEM images of damaged chips show different patterns from those of normal chips. Also, by modulating the input signal of the IC chip, the signal lines can be traced. These results suggest that the LTEM could become a useful tool for inspecting and monitoring IC quality.

Further, we successfully observed the THz emission image of MOSFETs embedded in a test element group under zero bias voltage. This result suggests that the LTEM can be used not only for the defect localization in LSI failure analysis but also as in-line inspection and monitoring.

Real-time inspection system to detect micro-leak defects in the seal of flexible plastic packages

A method to detect production faults in plastic packages using THz radiation was demonstrated [8]. Relying on the large difference between the absorption coefficients of plastic and water (for water-filled defects), and on the refractive index difference between plastic and air (for air-filled defects), our technique consists in focusing and scanning a THz beam on the sealed area of the package.

Compared to previous methods such as visual and ultrasound inspection, our technique can be applied for optically opaque packages and doesn't require immersion in a matching liquid. We tested our system on defects fabricated as water-filled and air-filled channels imbedded in polyethylene films, with diameters in the range from 10 to 100 μm. The results show that detection is possible down to 30 μm for water-filled and 40 μm for air-filled channels. The movement speed of the samples were 800 mm/s, which is adequately fast enough to apply this detection system to real-world applications.

The backward wave oscillator in terahertz imaging

We demonstrate a THz imaging system using a backward wave oscillator (BWO) as the source [9]. The main imaging characteristics are reported, such as near diffraction limit resolution and low noise, as well as aspects specific to essentially monochromatic and continuous wave operation. Applications in nondestructive testing, biology, medicine, and fundamental research are presented.

The image quality is also determined by noise. The detector noise and the source stability were measured. The non-attenuated BWO beam gives a 20 mV signal, while the detector dark signal is 2 µV. These values yield a signal-to-noise ratio of 10,000:1. The time constant of the lock-in amplifier was set to 10 ms for these measurements. Allowing a factor of 3 between the pixel time and the time constant, this means a scanning speed of 33 pixels/s.

We show a few tests on overcoming the strong absorption of water in biological samples. Better than freezing the sample, we found that the freeze-drying process leads to a much better contrast, as it completely removes water from the sample.

Prism-shaped Fabry-Perot etalon for absorption measurement

A solid-state prism-shaped Fabry-Perot interferometer allows absorption measurements using a BWO [10]. When a liquid sample is placed on the prism surface it affects the total internal reflection, thus it can be considered as being optically inside the cavity. The wavelength is scanned and the spectra obtained are Fourier analyzed for the absorption determination.

As samples we have tested a series of mixtures of water and ethanol. The accuracy of concentration determination is under 5% for the most part of the range, with errors increasing when the mixture contains more than 70% ethanol. Similarly, solutions of 2-deoxy-D-glucose were tested, and the accuracy of determining the concentration of an unknown solution is about 1% in the present measurement conditions.

This method has the advantage that the thickness of the sample doesn't matter, provided that it is above a certain limit. Also, the etalon effect inside the sample, so often a problem in other setups, does not occur in the configuration we proposed.

Terahertz Detector using Nb-based Superconducting Tunnel Junction

We have developed a terahertz (THz) radiation detector using a Nb-based superconducting tunnel junction (STJ). The detector consists of a $LiNbO_3$ substrate on which the STJ is fabricated. The incident THz photons absorbed by the substrate generate THz phonons, and a substantial amount of the phonons are detected by the STJ [11]. The detector is expected to be sensitive to a wide-band THz/far-infrared radiation above the energy gap of Nb superconductor. We radiated monochromatic nanosecond THz pulses from a THz parametric oscillator (TPO) with the repetition of 49 Hz, and detected the corresponding periodic signals for the 1.1-1.9 THz radiation.

Monitoring of water/ice state using millimeter waves for the agricultural field

Research results aimed at industrial application of millimeter waves (MMW) are presented. We have checked that the absorption of a leaf is directly proportional with its water content; consequently, we suggested a nondestructive technique for monitoring the leaf moisture level by measuring its transmission in the millimeter wave region. This method can be applied in plant factory for monitoring the growing process.

Another direction of research consists in discriminating between the liquid state and the solid state of water. The difference in absorption coefficients for water and ice in the millimeter range is significant (ice absorbs three order of magnitude less than water), which allows the detection and monitoring of the water/ice state in foodstuffs [12].

Non-thermal effect of MMW on cell membrane (Frohlich Hypothesis)

Health related effects of MMW have attracted the attention of many research groups for quite some time. The question of whether low power MMW can affect biological systems is still not clear, and the theoretical consideration of such an interaction in the cell is under way. H. Frohlich [13] suggested effects by MMW might occur through a resonance-type interaction, since structural elements of the cell membrane have their own theoretically calculated resonant frequency around 10^{11} Hz. MMW is already used in industrial and medical applications, therefore the effects of MMW exposure need scientific clarification.

We are studying non-thermal effects of MMW on Pheochromocytoma (PC12) by potential measurement with a voltage sensitive dye (DiBAC4(3)) [14]. Cells were irradiated with fixed frequencies 30, 40, 60, 76GHz as well as sweeping frequency between 10 and 100 GHz by a generator based on a Uni-Traveling-Carrier Photodiode (UTC-PD), the most widely tunable MMW source.

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