The backward wave oscillator as a radiation source in terahertz imaging

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Abstract

We demonstrate a terahertz (THz) imaging system using a backward wave oscillator (BWO) as the source. 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.

Introduction

THz imaging, after the first steps in the seventies[1] and rapid development in the recent years,[2] is expected to allow new applications such as in technology, medicine,[3] and fundamental research.

BWOs have a relatively long history in spectroscopic applications in the microwave and THz range. They are highly monochromatic sources, with an excellent stability, and their tunability although limited can also be exploited. We report here an application of the BWO in THz imaging. The specific problems that arise from such utilization and the advantages that can be drawn will be discussed in detail. A number of applications will follow.

Imaging setup

The imaging system that we built consists of the BWO as the source, off-axis parabolic mirrors to manipulate the THz wave, an *xy* motor stage to scan the sample, and a pyroelectric sensor, as shown in Figure 1. For alignment purposes and for an easy positioning of the sample the THz beam is superimposed with a visible light beam by use of a dichroic mirror, which is an indium-tin oxide layer deposited on a glass substrate. Since we used only reflection optics the propagation of the two beams is practically identical despite their very different wavelengths.

The sample is placed on an *xy* motor stage so that a rectangular area is scanned. The signal from the detector is fed to a lock-in amplifier, which is synchronized with an optical chopper that modulates the BWO beam. A computer controls the BWO, the *xy* stage, and the lock-in amplifier, and also reads the detected signal, providing an image that corresponds to the transmission value map of the sample.

Typical for radiation sources with narrow bandwidth is the development of standing waves propagating back and forth between reflecting surfaces in the optical path. This etalon effect produces artifacts in the images, in the form of fringes, which can compromise the quality of the measurements and hence have to be removed. We have implemented several ways to cancel, at least in part, the etalon effect. An effective method consists in placing a partially absorbing medium in the beam, between the surfaces that support the standing wave. Another method consists in tilting one of the surfaces involved in the etalon effect, as can be seen in Figure 1 for the detector. We have also obtained a good cancellation using this method for reducing the etalon effect resulting from reflections on the sample, by tilting it. The best results were obtained by modulating the wavelength of the BWO source. This can be done electronically by adding a triangular *ac* component of controlled amplitude to the BWO high voltage. Figure 2 shows the result on a tilted plastic sheet used as sample.

Image resolution

One of the most important parameters in judging the image quality is the spatial resolution. We have measured the THz spot size at the sample position by using the knife-edge-method. The full width of the focal spot at half maximum is 561 μm and 534 μm respectively in the x and y direction. The BWO output beam has an approximate Gaussian profile, which allows the theoretical estimation of the spot size; this turns out to be 477 μm. The difference is explained by an imperfect alignment, the finite size of the parabolic mirrors, and the non-Gaussian distribution of the BWO output wave.

The depth of focus, defined as the axial region where the spot size is at most $2^{1/2}$ times its minimum, is about 2 mm, which allows relatively thicker samples to be imaged, as well as a certain margin in the sample placement accuracy.

Noise and imaging speed

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. The trade off between the signal-

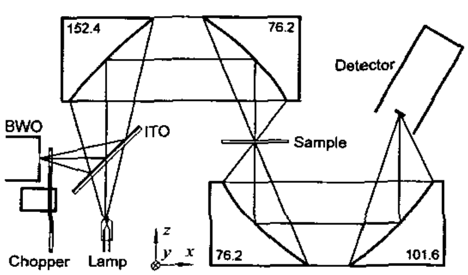

Fig. 1. Schematic of the optical setup. The numbers on the parabolic mirrors represent their effective focal lengths in millimeters. Their diameters are all 76.2 mm.

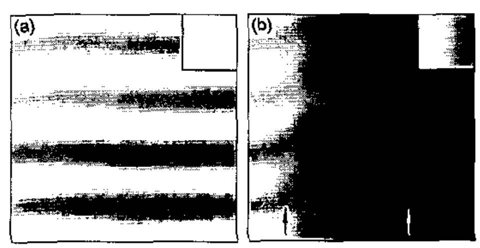

Fig. 2. Removal of the etalon effect by frequency modulation of the BWO output. A plastic sheet was scanned with no wavelength modulation (a) and with linearly growing modulation amplitude from left to right (b). The arrows show where the etalon effect is canceled.

to-noise ratio and the imaging speed can be changed as needed.

The source output level was found to have an instability that behaves as a Brown noise. At a 1 s time scale the instability is approximately 0.3 μV rms, and increases 10 times for each decade of time scale. This instability can pose a problem only for precise measurements that take a long time. The BWO output power measured during a 30-minute interval varies within ±2% of the mean value.

Applications

Technical and medical applications have been found for this BWO imaging system. Figure 3 is a demonstration of the possibility of using THz waves to penetrate materials such as cardboard and Teflon.

Figure 4 shows an opaque polyurethane tube with a defect inside that cannot be detected optically. An industrial application can be imagined, in which the tube is passed through a THz beam for testing.

Figure 5 is the THz image of a "touch and go" payment card used in the Japanese railway system. It shows in good detail the internal structure of the card, including a 6-loop antenna whose wires have a transversal period as small as 0.8 mm.

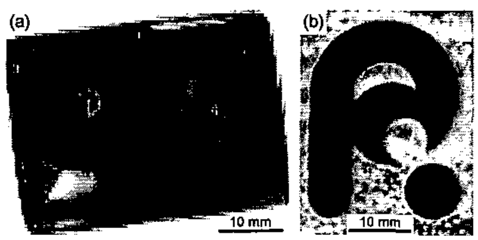

Fig. 3. (a) Metallic objects in a cardboard box. (b) The RIKEN logo made of aluminum foil, imaged through an 18 mm thick block of Teflon.

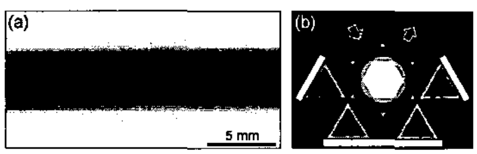

Fig. 4. A polyurethane tube with a defect. (b) Schematic of an optical adapter consisting of mirrors, which would allow the detection of defects in the tube, during production, by a single axial scan. Cracks, inclusions, deformations can be detected.

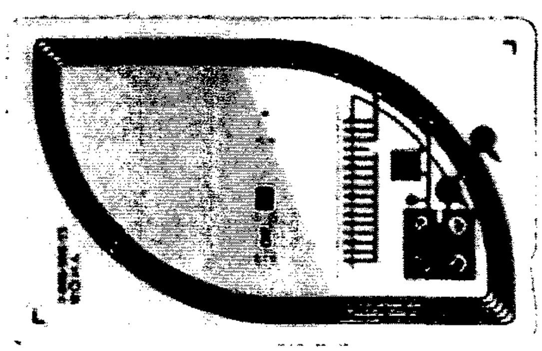

Fig. 5. THz image of a railway payment card. The large loop made of 6 thin wires is the antenna that allows the card to be used by just placing it near the reading/writing machine. Other elements of the circuitry can be seen. Card length: 85 mm.

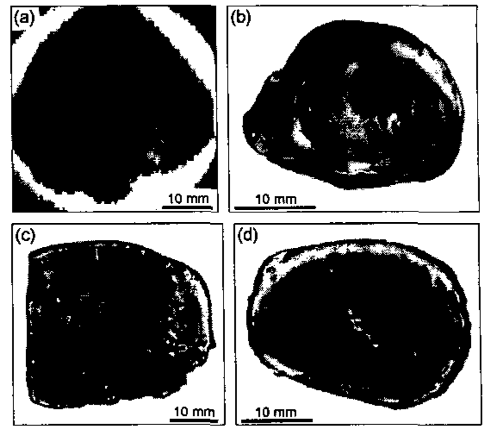

Fig. 6. Biological samples. (a) Frozen pig tongue; (b-d) freeze dried samples: chicken heart, pig tongue, and pig uterus, respectively.

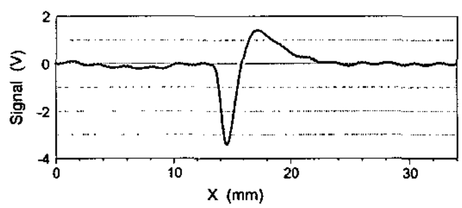

Fig. 7. Detection of sealing defects in plastic packages. The defect seen as a peak in the middle of this graph was a 100 μm diameter channel filled with water. The scanning speed was set to 800 mm/s. Air-filled defects can be detected as well.

In Figure 6 we show a few tests on overcoming the strong absorption of water in biological samples. It is known that ice has a lower absorption coefficient than water and the image in (a) shows such a measurement. 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, as shown in the remaining three scans.

Industrial applications are also possible as shown in Figure 7, where a channel-shaped defect in the seal of a plastic package produces a clear signal. Heat-sealed plastic packages for foods and medicines can contain flaws that have negative effects on the package contents, such as by letting the product inside leak out, or by allowing matter from the outside penetrate the package. We found out that a single scan of the seal through a focused THz beam can reveal the presence of a defect as small as a few tens of micrometers, both for water-filled and air-filled defects, in a practical range of scanning speeds.

References

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