The Study of Harmonic-Mode Operation of GaAs TUNNETT Diodes and InP Gunn Devices Using a Versatile Terahertz Interferometer

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Abstract

A simple Fourier transform terahertz spectrometer was constructed to evaluate the transmission and reflection spectra of materials as well as the emission spectra of pulsed broadband and continuous-wave narrowband sources. It works as a Michelson interferometer without a beam splitter and operates at room temperature with a Golay cell as the detector. This interferometer was employed to study the extraction of power from GaAs TUNNETT diodes and InP Gunn devices at the second or higher harmonic frequency above 325 GHz. As initial results, output power levels of more than 80 μW were generated with a GaAs TUNNETT diode at 355 GHz in a third-harmonic mode, more than 0.6 mW at 328 GHz, with an InP Gunn device in a second-harmonic mode, and more than 5 μW at 415 GHz, with an InP Gunn device in a third-harmonic mode.

1. Introduction

Compact fundamental solid-state sources of coherent continuous-wave (CW) radiation are instrumental in many systems applications at submillimeter-wave frequencies [1]. Tunneling as a fast and "quiet" carrier injection mechanism makes the tunnel-injection transit-time (TUNNETT) diode one of the prime candidates for such sources and its CW operation has been demonstrated already up to 400 GHz [2], [3]. The InP Gunn device is another prime candidate for such sources since it is the most powerful fundamental solid-state source above 290 GHz. Predictions also indicate that substantial amounts of power can be generated up to at least 450 GHz [4]. Both types of two-terminal devices are mounted on diamond heatsinks and were operated in an efficient second-harmonic mode when they yielded radio-frequency (RF) output power levels comparable to those from frequency multipliers in the frequency range of 190–325 GHz [4], [5]. The strongly nonlinear nature of most two-terminal devices also causes higher harmonic frequencies to be present, but the extraction of higher harmonic frequencies has not been studied in greater detail. Some initial experimental results at submillimeter-wave frequencies are known only from Si impact avalanche transit-time (IMPATT) diodes [6], whereas some output power at third-harmonic frequencies of 135 GHz and 270 GHz was reported from GaAs [7] and InP Gunn devices [8], respectively.

A spectrum analyzer with a harmonic mixer is used routinely to determine the output frequency and spectral purity of, for example, GaAs TUNNETT diodes [5] and InP Gunn devices [4], [5]. However, its limitations, a high noise floor and long scan times, become more and more evident at higher submillimeter-wave frequencies and, in particular, when one tries to scan a large frequency range for different harmonics in the output signal from an oscillator. In addition, many commercially available spectrum analyzers are limited to displaying results with an external mixer only up to center frequencies of 325 GHz.

2. System Description

The Fourier-Transform terahertz interferometer was developed originally to study the emission spectra of broadband THz sources such as, for example, photoconductive switches [9], and the transmission (or reflection) spectra of materials [10]. Its configuration is shown schematically in Figure 1. The THz radiation is collected and collimated by a 2" gold-coated off-axis parabolic mirror (90°, numerical aperture = 1). The collimated beam is directed onto a movable split mirror (shown in the insert), which divides the beam into two halves and introduces a variable phase shift between the two reflected beams of nearly equal power. This phase shift is proportional to the differential delay. The reflected beams are then directed onto the second identical off-axis parabolic mirror, which focuses and combines them to form an interference pattern at the location of the THz detector. For material transmission measurements, a horizontal slit can be placed at the focal plane of the second mirror to increase the sensitivity at higher frequencies. A calibrated Golay cell (QMC Instruments Ltd., UK) with an aperture of 6 mm and a virtually flat responsivity curve in the frequency range 0.1–2 THz is placed directly at the focal plane (and directly behind the slit) and used as the THz detector. It is connected to a computer-controlled lock-in amplifier, which receives the synchronization signal from the mechanical beam chopper with a crystal-controlled chopper frequency of 8–16 Hz. A motorized and computer-controlled translations stage with a total travel distance of 25 mm moves the top half of the split mirror back and forth with respect to the other half. This motion causes a precise and variable time delay between the two halves of the THz beam and thus produces the interferogram.

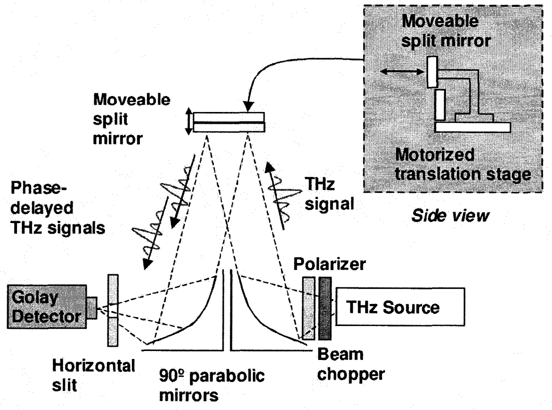

Figure 1: Schematic diagram of the Fourier transform THz interferometer.

This type of interferometer was originally proposed in the 1960s for wavelengths in the infrared (IR), but has never been employed at submillimeter-wave frequencies. The prime advantage of this design is that it does not require a 45°-beam splitter and therefore avoids the loss and frequency dependence introduced by such a beam splitter. Figure 2 compares the transmission spectra of two different fabric materials, whereas Fig. 3 compares two transmission spectra of a 0.75-mm thick cellulose sample, one from the Fourier transform THz spectrometer of Fig. 1, the other from a THz time-domain spectroscopy system with a femtosecond-pulse IR laser [11], [12]. Both figures show the versatility of this type of interferometer and illustrate a very useful application in the area of material characterization [10].

3. Harmonic power extraction from active two-terminal devices

Initial work in the area of CW electronic sources focused on identifying favorable conditions particularly for the extraction of the third and fourth harmonic frequencies from GaAs TUNNETT diodes and InP Gunn devices above 300 GHz.

Figure 4 shows the example of a GaAs TUNNETT diode with an output power of more than 50 μW at 356 GHz, where both signals at the fundamental and second-harmonic frequencies were blocked by the output waveguide with a cut-off frequency of approximately 285 GHz. A power level of more than 80 μW was generated by the same diode at a slightly lower oscillation frequency of 345.5 GHz, which was confirmed with a spectrum analyzer and a harmonic mixer as shown in Fig. 5. To increase the sensitivity, an active frequency multiplier that doubles the original local-oscillator (LO) frequency of approximately 3–6 GHz had been inserted between the spectrum analyzer and the harmonic mixer. The output power levels were determined with a Thomas Keating quasi-optical absolute power meter and represent a significant improvement in the performance of GaAs TUNNETT diodes when compared with other results from GaAs TUNNETT diodes above 240 GHz [2], [3]. They are the highest output power levels reported to date from TUNNETT diodes.

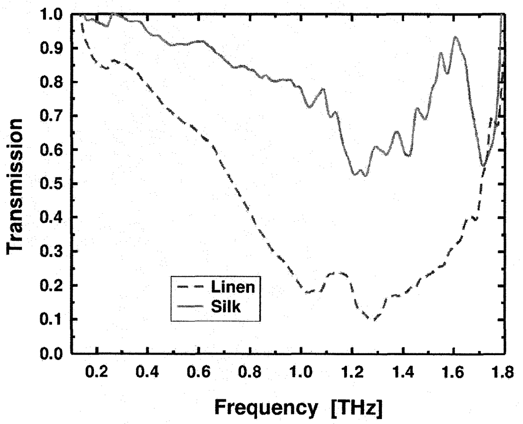

Figure 2: Transmission spectra of linen and silk fabrics.

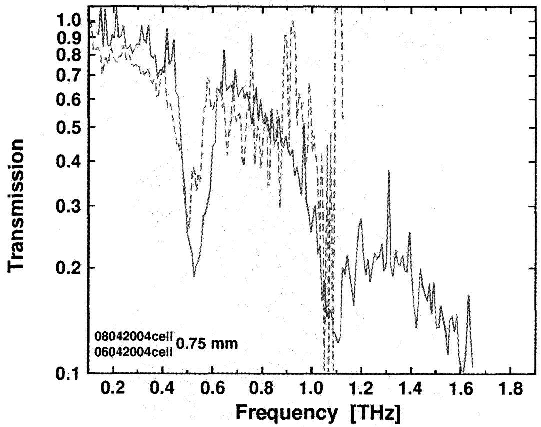

Figure 3: Comparison of the transmission spectra of a 0.75-mm thick cellulose sample measured with the THz interferometer of Fig. 1 (- -) and a THz time-domain spectroscopy system (—)[11], [12].

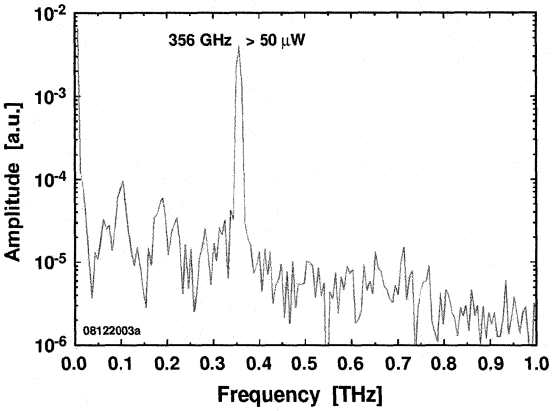

Figure 4: Spectrum of a 354-GHz oscillator with a GaAs TUNNETT diode operating in a third-harmonic mode.

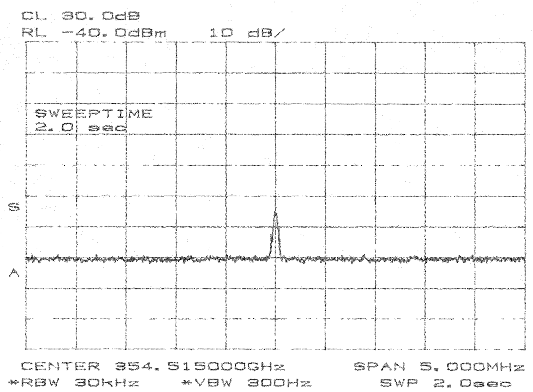

Figure 5: Spectrum of an oscillator with a GaAs TUNNETT diode in a third-harmonic mode recorded with a spectrum analyzer and a harmonic mixer (center frequency: 354.5 GHz, vertical scale: 10 dB/div., vertical scale: 500 kHz/div., resolution bandwidth: 30 kHz, video bandwidth: 300 Hz).

The operation at second-harmonic frequencies above 325 GHz as well as the extraction of higher harmonic frequencies was investigated with InP Gunn devices of two different doping profiles, one originally optimized for fundamental-mode operation [5], [13] and the other one optimized for second-harmonic power extraction [4]. Untested devices as well as those that had already yielded state-of-the-art results in a second-harmonic mode at *J*-band (220–325 GHz) frequencies [4], [5], [13] were employed in the experiments. Figure 6 illustrates an example of second-harmonic power extraction at 328 GHz as measured with the THz spectrometer of Fig. 1, whereas Fig. 7 shows the corresponding result from the spectrum analyzer with the harmonic mixer and the active frequency multiplier that doubles the original LO frequency of approximately 3–6 GHz. The output power level of more than 0.6 mW was determined with a Thomas Keating quasi-optical absolute power meter.

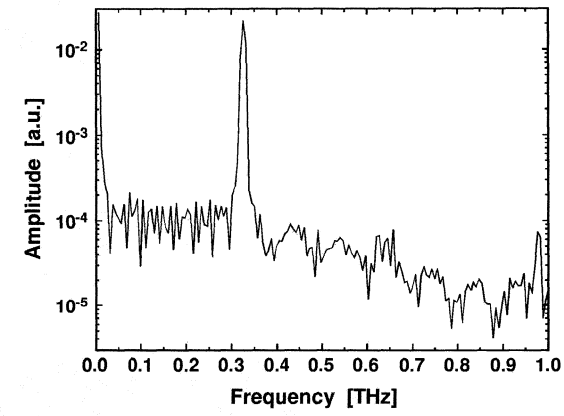

Figure 6: Spectrum of a 328-GHz oscillator with an InP Gunn device operating in a second-harmonic mode.

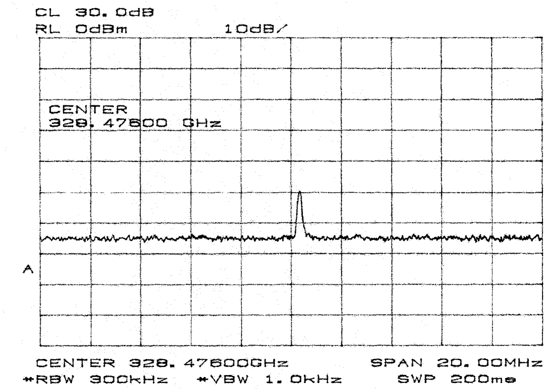

Figure 7: Spectrum of an oscillator with an InP Gunn device in a second-harmonic mode, recorded with a spectrum analyzer and a harmonic mixer (center frequency: 328.5 GHz, vertical scale: 10 dB/div., vertical scale: 2 MHz/div., resolution bandwidth: 300 kHz, video bandwidth: 1 kHz).

The device of Figs. 8 and 9 has the same doping profile as that of Figs. 6 and 7, but operates in a third-harmonic mode at 416 GHz. Its output power of more than 5 µW was estimated from a measurement with a *W*-band (75–110 GHz) thermocouple-based power meter. As can be seen from Fig. 9, power extraction at the third-harmonic frequency of 414.3 GHz with a similar output power was also confirmed with a different spectrum analyzer and a different harmonic mixer in a measurement setup that is much more sensitive than that of Figs. 5 and 7.

The THz spectrometer becomes the most suitable tool in a situation where several harmonic frequencies are present. This situation is illustrated with Fig. 10 where the second-harmonic frequency of 283 GHz is slightly below the cut-off frequency of the waveguide, and, therefore, the signal from the InP Gunn device [5] at the second-harmonic frequency is suppressed only partially and the second-, third-, and fourth-harmonic frequencies are present. The total output power is too low to be ascertained correctly with the Thomas Keating quasi-optical power meter, but it was estimated from the output voltage of the Golay cell that more than 1 µW is available at the third-harmonic frequency of 425 GHz. In a very similar experiment with a different InP Gunn device that had the same doping profile as those of Figs. 6–9, the interferogram indicated approximately three times higher output power levels at 436 GHz.

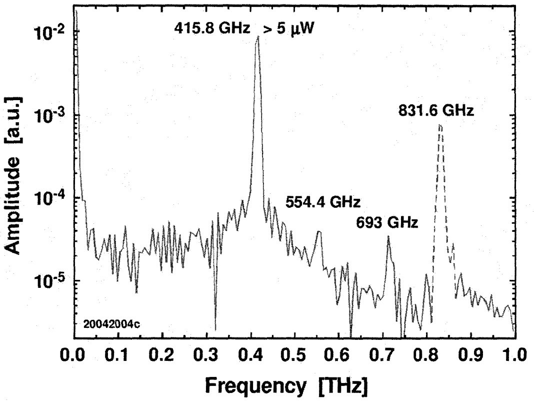

Figure 8: Spectrum of a 416-GHz oscillator with an InP Gunn device operating in a third-harmonic mode.

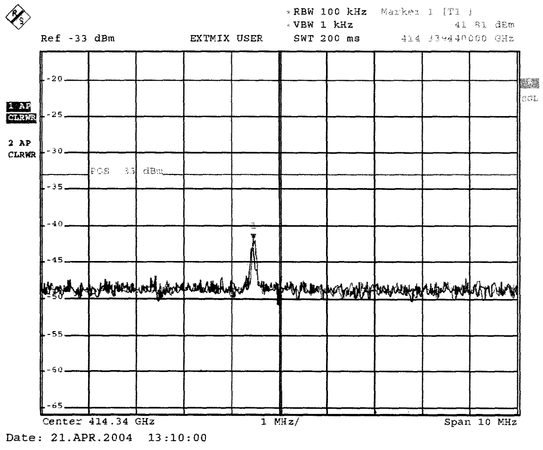

Figure 9: Spectrum of an oscillator with an InP Gunn device in a third-harmonic mode, recorded with a spectrum analyzer and a harmonic mixer (center frequency: 414.34 GHz, vertical scale: 5 dB/div., vertical scale: 1 MHz/div., resolution bandwidth: 100 kHz, video bandwidth: 1 kHz).

All output power levels from InP Gunn devices are not only the highest reported to date from any Gunn device, but also the highest reported from any fundamental source operated at room temperature. Further work is required to ascertain the output power levels at the fourth-, fifth-, and sixth-harmonic frequency.

4. Conclusion

The harmonic content in the output of GaAs TUNNETT diodes and InP Gunn devices was evaluated for the first time using a simple Fourier transform spectrometer without a beam splitter. The initial measurement of output power levels in the frequency range 325–475 GHz from GaAs TUNNETT diodes and InP Gunn devices indicate that the method of extracting higher harmonic frequencies from active two-terminal devices is promising and has a strong potential of reaching 1 THz. The bias conditions of the GaAs TUNNETT diodes and InP Gunn devices in these experiments were similar to those in a second-harmonic mode, which ensured low active-layer temperatures for long-term reliability.

Higher RF output power levels are expected from an optimization of the impedances seen by the device at the fundamental and harmonic frequencies, the coupling of the device into the output waveguide, and the device structures.

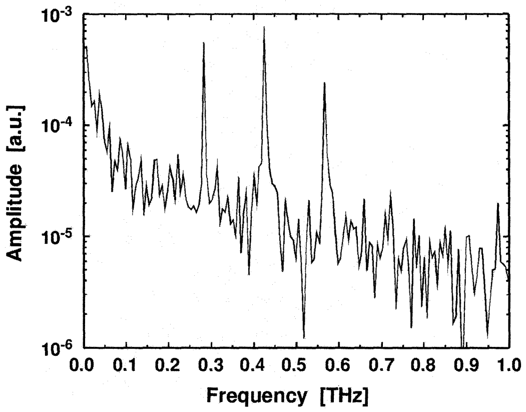

Figure 10: Spectrum of an InP Gunn oscillator with fourth-harmonic, third-harmonic, and partially suppressed second-harmonic frequencies of 566 GHz, 425 GHz, and 283 GHz.

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