A Broadband Quasi-Optical Terahertz Detector Utilizing a Zero Bias Schottky Diode

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***Abstract*—A quasi-optical broadband terahertz detector using a zero bias Schottky diode mounted on a self-complimentary sinuous antenna has been developed. Design and characterization of this detector are described. Measurements show that a responsivity of 300–1000 V/W covering the frequency range of 150–440 GHz has been achieved. The detector performance has been compared to waveguide detectors covering four frequency bands up to 600 GHz. A recent measurement at 600–900 GHz yielded the same output voltage as a waveguide detector. The noise equivalent power level of this detector is estimated to be 5–20 $\mathrm{pW}/\sqrt{\mathrm{Hz}}$ based on the measurements of similar detectors.**

***Index Terms*—Broadband, sinuous antenna, terahertz (THz) detector, zero bias Schotky diode.**

I. Introduction

SCHOTTKY diode detectors have long been used at millimeter and sub-millimeter wavelengths because of their high sensitivity, ability to operate at an ambient or cryogenic temperature and fast response time compared with other room temperature detectors, such as Golay cells, pyroelectric detectors, or bolometers [1]. Waveguide-based Schottky diode detectors have typical responsivities ranging from 1000–4000 V/W over the frequency range of 100 GHz to 1 THz. However, the frequency bandwidth of waveguide-based detectors is limited by fundamental mode waveguide operation to approximately 50% fractional bandwidth. For many applications such as terahertz (THz) spectroscopy, it is desirable to achieve wider operating bandwidth. This letter describes a quasi-optical detector using a zero bias Schottky diode (ZBD), and a self-complementary broadband sinuous antenna mounted on a silicon substrate lens [2]. The antenna has directive beam patterns with decade or wider bandwidth and sidelobe levels below -15 dB. Design and characterization of the broadband quasi-optical Schottky detector, and measurement results including antenna patterns, responsivity, and noise-equivalent power (NEP) are presented.

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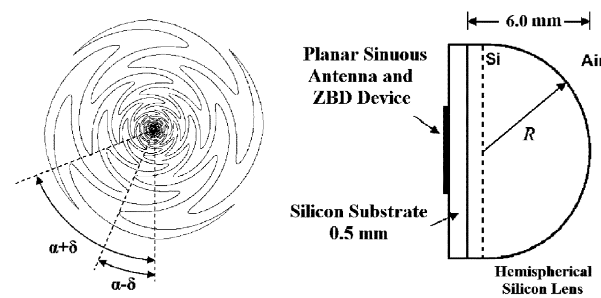


Fig. 1. Broadband THz detector design: (a) the four-arm planar sinuous antenna with self-complementary structure, and (b) the planar sinuous antenna mounted on an extended hemispherical silicon substrate lens with radius R, of 5 mm.

II. Detector Design

A. Quasi-Optical Design

For this work, planar sinuous antennas covering the 50 to 900 GHz frequency band were designed and fabricated on high-resistivity silicon substrates. As shown in Fig. 1(a), the four-arm sinuous antenna has a self-complementary log-periodic structure, leading to a frequency independent input impedance of 74 Ω. For each sinuous curve defining the antenna arms, the angular breadth α and offset parameter δ are 45° and 22.5°, respectively. The antenna is photolithographically fabricated on a silicon substrate with 0.5 mm thickness and mounted on an extended hemispherical high-resistivity silicon lens ($\geq 1E5\ \Omega\cdot\mathrm{cm}$, $\epsilon_r = 11.8$). As shown in Fig. 1(b), the lens radius is 5 mm and the total extension length is 1.5 mm. Because the ratio of power radiated into the two half-spaces of the antenna is related to the dielectric constant by ${\epsilon_{r_{Si}}}^{1.5}/{\epsilon_{r_{air}}}^{1.5}$ [3], the use of a silicon substrate enhances the power coupling efficiency for a receiving antenna. In addition, using the same material for both the substrate and lens eliminates the power loss to substrate modes [2].

In this detector design, as shown in Fig. 2, two of the antenna arms are connected to dc outputs and the remaining two arms are unused but present to maintain a self-complementary geometry. DuHamel has shown that the active region for sinuous antennas is given by [4], $r \approx \lambda_e/(4(\alpha+\delta))$, where λ_e is the effective wavelength and the angles α and δ are in radians. From this relation, the sinuous antenna designed for this work is expected to cover the frequency range of 50 to 900 GHz. Compared to other broadband planar antenna designs such as log-periodic antennas and spiral antennas, the polarization of the sinuous antenna is linear with only a slight polarization wobble with frequency

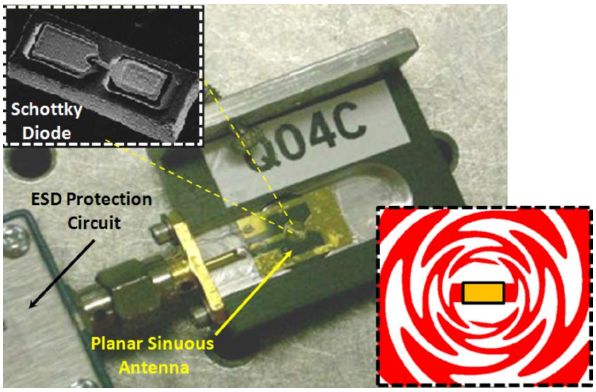


Fig. 2. Photograph of a planar four-arm sinuous antenna mounted in a housing with a SMA output and a silicon substrate lens. The zero bias Schottky diode is flip-chip mounted at the feed point of the antenna.

($\pm 4^{\circ}$). This greatly simplifies use of the detector as the polarization is not strongly dependent on the operating frequency.

B. Zero Bias Schottky Detector

The ZBD diodes used in this research were fabricated at Virginia Diodes, Inc. (VDI), in a flip-chip configuration. As shown in Fig. 2, typical chip dimensions are 180 μm$\times$ 80 μm$\times$ 40 μm (length $\times$ width $\times$ thickness), with device electrical parameters of $I_{sat} = 11\ \mu$A, $R_s = 19\ \Omega$, ideality factor, $\eta = 1.13$, and zero bias junction resistance, $dV/dI = 1 - 3\ \mathrm{k}\Omega$ [5].

The detector circuits were fabricated and assembled in the Microfabrication Laboratory at the University of Virginia (UVML). During assembly, the Schottky diode was mounted across the feed point of the sinuous antennas (two opposite arms), and the antenna was subsequently mounted onto a 10 mm diameter high resistivity silicon substrate lens. In this research, an extension length of 1.5 mm was chosen to provide a reasonable antenna directivity (30 dB) while maintaining a good Gaussian coupling efficiency (85%) [6]. For broadband operation, the silicon lens is not coated with a quarter-wave matching layer, which causes a reflection loss at the air-dielectric interface of 1.6 dB, thus reducing the overall detector responsivity.

III. Detector Characterization and Results

A. Antenna Characterization

To demonstrate the broadband properties of the detector, the far-field radiation patterns of the sinuous antenna mounted on the hemispherical silicon lens were measured at 196 and 585 GHz. As shown in Fig. 3, the patterns show a directive pattern with a main beam that scales with the frequency and side-lobe level less than -13 dB. The 3 dB beam width at 196 GHz is 10.4°, and decreases to 4.6° at 585 GHz. The antenna directivity is estimated to range from 24 dB at 150 GHz to 32 dB at 600 GHz. The sinuous antenna pattern within the dielectric half-space should be frequency-independent. However, the silicon lens utilized acts as an aperture with a fixed dimension, resulting in narrower antenna beams at higher frequencies. The measured H-plane radiation pattern is slightly broader than the pattern in the E-plane, for both 196 GHz and 585 GHz.

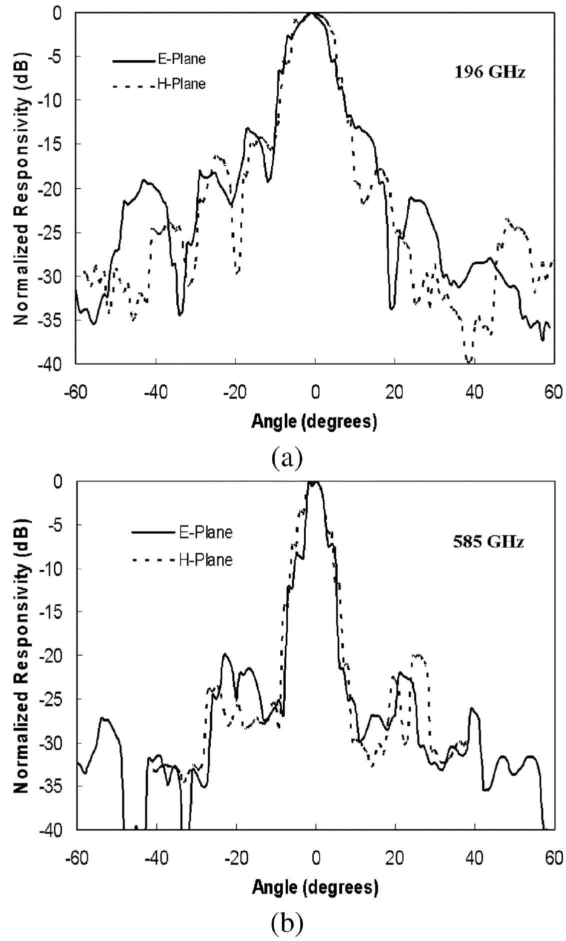


Fig. 3. Measured far-field radiation patterns for the planar sinuous antenna on extended hemispherical silicon lens: (a) antenna patterns measured at 196 GHz, and (b) antenna patterns measured at 585 GHz.

B. Detector Responsivity Measurement

The detector responsivity measurement setup is shown in Fig. 4. An Agilent microwave source (E8257D) together with a VDI broadband amplified multiplier chain were employed to provide the terahertz power (P_{out}) through a diagonal horn antenna. A waveguide directional coupler is placed between the VDI multiplier chain and the horn antenna to monitor the output power (P_{RF}) with an Erickson power meter (P_{meter}). The coupling coefficient C of the coupler

$$C = \frac{P_{Meter}}{P_{RF}} \tag{1}$$

is 10 dB. Two off-axis parabolic mirrors ($f = 76.4$ mm) are utilized to couple the terahertz signal onto the broadband detector. The terahertz signal is AM modulated at 100 Hz, and the dc output signal from the detector is measured using a lock-in amplifier.

The responsivity of the broadband quasi-optical detector is determined by $R = V/P_{RF}$, where V is the r.m.s. voltage detected by the lock-in amplifier and, P_{RF} is the incident RF power calculated from (1) and the Erickson power meter reading. From this, the responsivity of the quasi-optical detector is estimated to range from 300–1000 V/W over the frequency range from 150–400 GHz, as shown in Fig. 5(a).

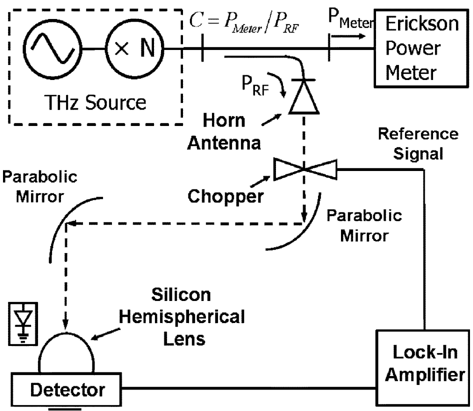
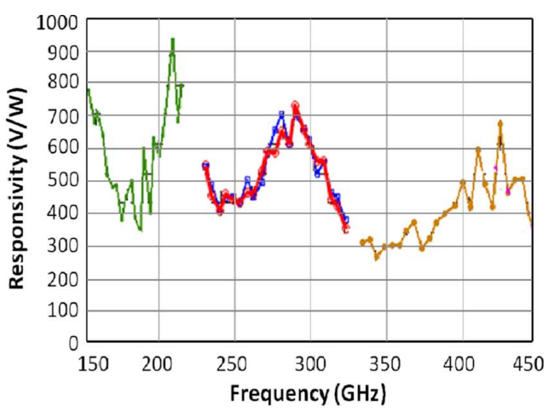
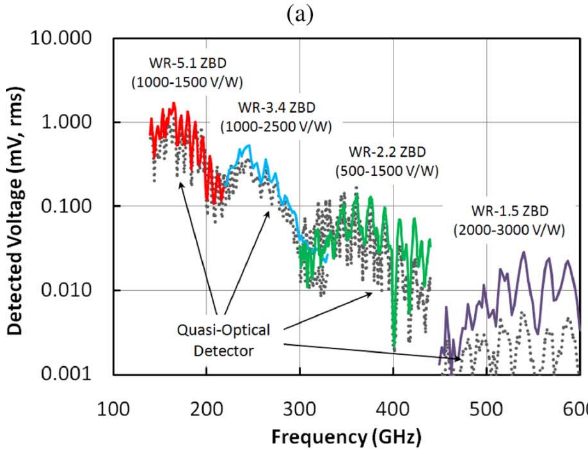


Fig. 4. Diagram of the responsivity measurement setup for the ZBD broadband THz detectors.



(a)



(b)

Fig. 5. (a) Measured responsivity of the quasi-optical ZBD detector. The red and blue lines for 220–330 GHz represent two measurements showing the experiment repeatability; (b) measured voltage response of the quasi-optical detector (dashed lines) compared with a series of four different waveguide detectors (solid lines). The frequency step size is 5 GHz.

In Fig. 5(b), the performance of the quasi-optical detector is compared to a series of waveguide diode detectors based on the same Schottky diode. For this measurement, the frequency dependence of the voltage response of the quasi-optical detector was measured by illuminating the detector in the far field of a broadband frequency multiplier-based source ranging in frequency from 150 up to 600 GHz. The detected video response voltage was measured as a function of frequency. To provide a point of reference, four waveguide detectors covering the frequency bands of WR-5.1, WR-3.4, WR-2.2 and WR-1.5, respectively, were also placed at the same location in the source beam and the resulting voltage responses measured. Fig. 5(b) shows the measured voltages for the quasi-optical detector compared with the four individual waveguide detectors. The waveguide detectors employ simple diagonal horns with directivity of 22–25 dB to couple the power from free-space. Taking into account the effective aperture of the quasi-optical detector at high frequencies, the detector described in this letter has comparable performance to waveguide detectors to 600 GHz. The reduced response at frequencies above 450 GHz is not expected, and further measurements are underway to determine the mechanism of the roll off. Recent measurements also show that the quasi-optical ZBD detector works well in the frequency range of 600 to 900 GHz, with a measured response comparable to a WR-1.2 waveguide detector, using the same method described above. The NEP of this detector is estimated to be 5–20 $\mathrm{pW}/\sqrt{\mathrm{Hz}}$ based on the responsivity measurements of similar detectors [5]. In this work, the upper operation frequency of the detector is limited by the dimensions of the diode chip. By integrating zero bias Schottky diodes directly onto the antenna feed point, the operation frequency of the detector can be extended to 2 THz and higher according to [4].

IV. Conclusion

A broadband quasi-optical ZBD Schottky detector based on the sinuous antenna has been designed, fabricated, and demonstrated. A responsivity of 300–1000 V/W has been measured over a frequency range from 150–400 GHz, with good performance to 600 GHz. Recent experiments also verify that the detector works comparably to a WR-1.2 waveguide detector at 600–900 GHz. The noise equivalent power (NEP) level of this detector is estimated to be 5–20 $\mathrm{pW}/\sqrt{\mathrm{Hz}}$. Similar performance is expected up to about 1 THz using flip-chip mounted zero bias detector diodes. Extension of these results to 2 THz and higher is possible by integration of the diode with the antenna during fabrication.

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References

[1] P. R. Griffiths and C. C. Homes, "Instrumentation for far-infrared spectroscopy," in *Handbook of Vibrational Spcectoscopy*. New York: Wiley, 2001, vol. 1, Theory and Instrumentation.

[2] D. B. Rutledge and M. S. Muha, "Imaging antenna arrays," *IEEE Trans. Antennas Propag.*, vol. AP-30, no. 7, pp. 535–540, Jul. 1982.

[3] D. B. Rutledge, D. P. Neikirk, and D. P. Kasilingham, "Integrated circuit antennas," in *Infrared and Millimeter Waves*, K. J. Button, Ed. New York: Academic Press, 1983, vol. 10, pp. 1–90.

[4] R. H. DuHamel, "Dual Polarized Sinuous Antennas," European Patent Application 0198575, Feb. 19, 1986.

[5] J. L. Hesler and T. W. Crowe, "Responsivity and noise measurements of zero-bias Schottky diode detectors," in *Proc. 18th Int. Symp. Space Terahertz Technol.*, Pasadena, CA, Mar. 2007, pp. 89–92.

[6] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, "Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses," *IEEE Trans. Microw. Theory Tech.*, vol. 41, no. 10, pp. 1738–1749, Oct. 1993.