Application of Zero-Bias Quasi-Optical Schottky-Diode Detectors for Monitoring Short-Pulse and Weak Terahertz Radiation

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***Abstract*—Schottky diodes are well-known nonlinear elements allowing for effective detection and mixing of electromagnetic radiation in the range through microwave to terahertz. Although less sensitive than their superconducting counterparts, they generally do not require cooling that makes them the devices of choice for applications where the ultimate sensitivity is not needed. In the emerging field of terahertz technology, there is a long-time quest for cheap and handy detectors for laboratory use, as well as for serial compact and midsize instruments. We describe the use of a quasi-optically coupled zero-bias planar Schottky-diode detector for monitoring picosecond pulses of synchrotron terahertz radiation and weak continuous-wave emission from an array of Josephson junctions.**

***Index Terms*—Planar Schottky diodes, terahertz radiation.**

I. Introduction

COMPARED to room-temperature calorimetric terahertz detectors, such as microbolometers [1] or Golay cell detectors, Schottky-diode detectors have a much shorter response time. The quest for larger bandwidth and lower noise drives the development of Schottky diodes in binary and ternary compounds [2] and heterostructure detectors [3]. According to the scheme of radiation coupling, these detectors are either waveguide-mounted or open-beam devices. In the latter case, the detector is either mounted in a corner-cube reflector or integrated into a planar antenna, which is usually combined with an immersion lens. Recent development of zero-bias low-noise detectors utilizing planar low-barrier InGaAs Schottky diodes [4] has made it possible to reduce drastically the sizes of diode chips and integrate them in different planar broadband antennas. Achieved level of miniaturization extends the detection capability of these devices well into the terahertz range where the diode performance is largely limited by its own parasitic capacitance. In this letter, we demonstrate the ultimate capabilities of such Schottky-diode detector by recording picosecond terahertz pulses and continuous nanowatt microwave radiation.

Coherent synchrotron radiation (CSR) is emitted by electron bunches in a storage ring at wavelengths that are equal to or larger than the bunch length [5]. CSR typically covers the frequency range up to approximately 1.5 THz and is limited at low frequencies due to a finite cross section of the beam line. The expected duration of CSR pulses (a few picoseconds) is associated with the time needed for an electron bunch to travel through the area where a gradient of magnetic field exists. Due to their picosecond intrinsic response time and relatively large sensitivity, Schottky-diode detectors appear to be good candidates for resolving CSR pulses and, hence, for studying physics of electron bunches.

Josephson junction arrays can potentially become an alternative for on-chip integrated local oscillators, e.g., flux-flow oscillators, in all-solid-state heterodyne receivers, where submicrowatt power is required. However, in the development stage, broadband control of the output power requires a dedicated detection system.

In the following, we describe a specific broadband design, which was implemented in a zero-bias quasi-optical InGaAs Schottky-diode detector. The same detector was used for monitoring coherent terahertz radiation from the synchrotron storage ring at ANKA [6], as well as nanowatt continuous-wave emission from an array of discrete synchronized Nb Josephson junctions [7].

II. Zero-Bias Schottky Diode

InGaAs/InP appears to be a very promising material system for the detection of millimeter and submillimeter waves. In comparison with GaAs, its lower Schottky barrier provides zero-bias detection ability that not only eliminates shot noise and hence improves crucially signal-to-noise ratio but also simplifies the detection system. Reducing chip dimensions makes it increasingly difficult to mount precisely the diode chip and to

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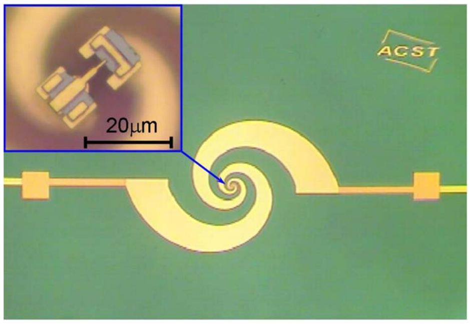

Fig. 1. Log-spiral antenna and zero-bias InGaAs Schottky diode form an ultrawideband detector. The inset shows the diode chip mounted onto the inner antenna arms.

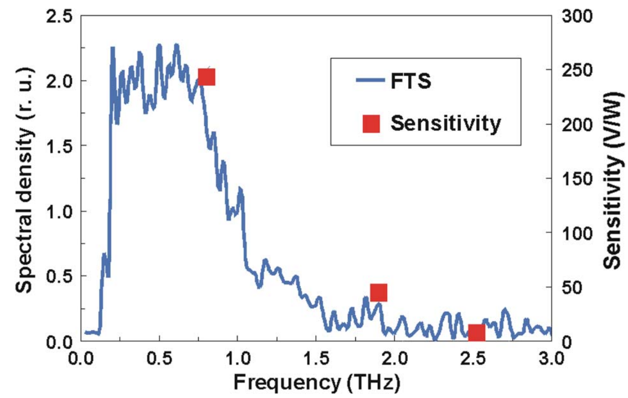

Fig. 2. (Solid line) FTS spectrum of the detector response and (symbols) the sensitivity, which was measured with different coherent radiation sources.

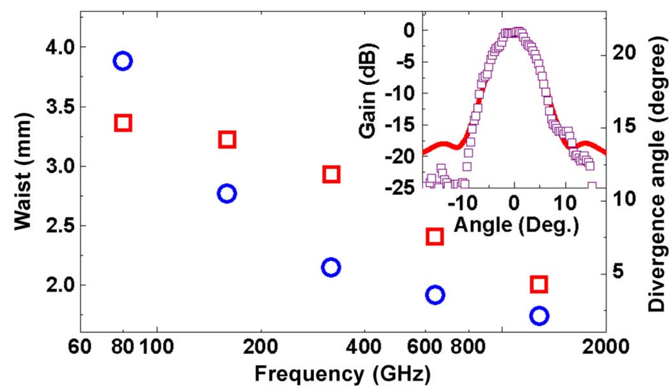

Fig. 3. (Circles) Far-field divergence angle and (squares) the waist of the directivity pattern for different frequencies. The waist is located at the tip of the lens. (Inset) (Line) Simulated and (symbols) measured patterns at 320 GHz. Asymmetry in the side lobes in the measured pattern is most likely due to a slight misalignment of the diode with respect to the lens axis.

achieve proper impedance matching at high frequencies. Monolithic integration can be implemented in order to overcome the highlighted problems. However, hybrid integration offers more flexibility because various antenna structures can be tested with the same type of diodes. A sophisticated approach was used at ACST GmbH to miniaturize discrete InGaAs diodes and hence make them suitable for ultrawideband detector applications at terahertz frequencies. The lateral dimensions of diode chips and their total height were reduced to approximately $15 \times 22\ \mu\text{m}^2$ and 3 μm, respectively. To integrate the chip in a circuit with matching contact pads, a dedicated mounting strategy has been elaborated, which ensures chip robustness during handling. Optical control enables precise chip positioning. Because the contact pads are as small as the chip itself, commonly used soldering and gluing are both inappropriate for contacting these diodes to the circuit. Therefore, the diodes were directly bonded by thermocompression to the substrate with either test electric circuit or antenna structure.

III. Assembling and Characterization

An ultrawideband detector was fabricated by combining the diode chip with a planar log-spiral antenna, as shown in Fig. 1. Although the gap between the antenna arms was as small as 10 μm, the diode structure could be positioned precisely and bonded by thermocompression. To the best of the authors' knowledge, this is the first feasibility demonstration of handling and mounting diode structures with such small dimensions. The antenna was produced by UV photolithography from a 300-nm-thick gold film on a 3×3 mm^2 GaAs substrate. The substrate with the antenna and the diode was glued to the flat rear side of a hyperhemispheric silicon lens, which has a diameter of 12 mm.

Preliminary characterization of the integrated diode detector was performed by Fourier transform spectroscopy and also by measuring the response of the detector at a few fixed radiation frequencies. Although the size of the diode chip causes the cutoff in the response spectrum (Fig. 2) at approximately 1 THz, the detector operates up to 3 THz with reduced sensitivity. The apparent cutoff at 0.1 THz is due to the lack of power of the FTS radiation source. Simulations of the antenna gain predict the lower spectral edge at $\approx$50 GHz. Fig. 3 shows the beam waist and the angle of the beam divergence of the integrated quasi-optical detector, along with the simulated and measured radiation patterns at 320 GHz. Relying on good agreement at this frequency and also on the fact that the beam pattern is defined to a large extent by the lens diameter and the distance between the detector and the center of the lens [8], we expect the directivity pattern of our detector to agree with simulations in the whole spectral range. To define the sensitivity of the detector, we adjusted the directivity pattern of a coherent radiation source with the known output power at 0.8 THz to the simulated directivity pattern of our detector. The detector signal was measured with a lock-in amplifier, which had an input impedance of 500 MΩ and an input noise of 100 nV $\cdot$ Hz$^{-1/2}$. The response of the detector was nonlinear; the sensitivity decreased from $\approx$200 V/W at low input powers to 120 V/W for input powers larger than 20 μW. Taking into account 30% reflection losses at the lens, polarization mismatch, and nonperfect impedance matching of the diode to the radiation resistance of the antenna, we arrive at an intrinsic diode sensitivity of larger than 10^3 V/W. This is comparable with theoretical estimates and sensitivities which were reported by other groups. With the aforementioned numbers, we found, for our detection system below 1 THz, a noise equivalent power (NEP) of 5×10^{-10} W $\cdot$ Hz$^{-1/2}$. We note that the system NEP was restricted by the noise of the lock-in amplifier. Taking this restriction into account, we estimated the upper limit for the NEP of the Schottky diode itself at 10^{-11} W $\cdot$ Hz$^{-1/2}$.

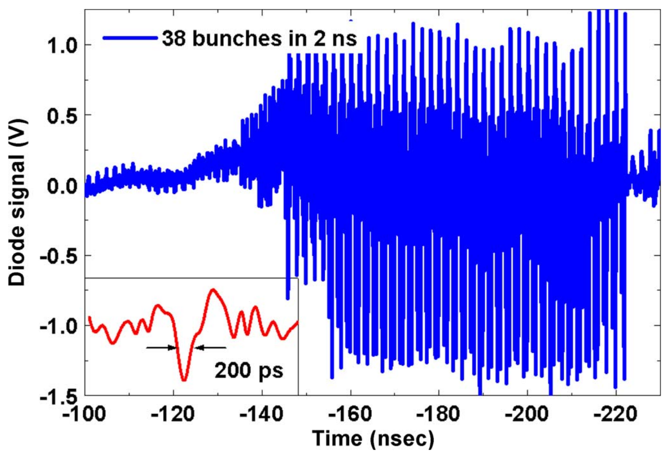

Fig. 4. CSR from a train of electron bunches as it was recorded with our Schottky-diode detector and amplifiers. Inset shows the portion of the signal associated with a single bunch.

This value is only a few times larger than the record numbers reported for heterostructure detectors.

IV. Applications

For measurements at the storage ring the detector was backed by microwave amplifiers. They provided a total gain of 64 dB and a noise temperature of 120 K in the frequency band from 0.1 to 4 GHz. Fig. 4 shows the single-shot signal transient, which was recorded after the amplifiers in response to radiation from 38 sequential electron bunches. Radiation from each bunch can be clearly distinguished. The single-bunch signal in the inset of Fig. 4 has a duration of ≈200 ps, which is close to the limit imposed by our readout electronics.

The same detector was used to measure nanowatt microwave emission from an array of Josephson junctions. The array containing 7500 discrete Nb junctions was mounted in a microwave resonator and cooled to 4.2 K in a transport Dewar. The junction emission was delivered to the room-temperature environment outside the Dewar via an oversized waveguide and was further launched into free space with a circular horn. The emission frequency was measured with a waveguide-mounted V-band mixer and a spectrum analyzer. An off-axis parabolic mirror and a TPX lens were used to collect radiation onto the detector. Although the maximum power coupled to the detector was only 55 nW, the signal-to-noise ratio was sufficiently large for measuring directivity pattern of the array emission. To do that, we move the detector at right angles to the optical axis and recorded the detector signal. Coupling of two offset Gaussian beams depends on their waist radii ω_0 and ω_{01} and the offset value x

$$K(x) = \frac{4\omega_{01}^2\omega_0^2}{\left(\omega_{01}^2 + \omega_0^2\right)^2} \exp\left(-\frac{2x^2}{\omega_{01}^2 + \omega_0^2}\right). \qquad (1)$$

The experimental profile of the array emission at 70 GHz is shown in Fig. 5. Taking the computed value $\omega_0 = 3.4$ mm for the beam waist of our detector at 70 GHz and using the

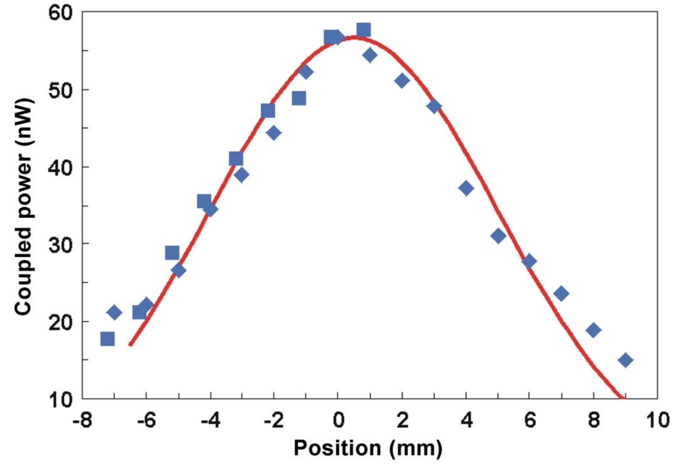

Fig. 5. Directivity pattern of the array emission at 70 GHz, measured with the Schottky-diode detector. Different symbols belong to different sequential scans. The solid line represents the best Gaussian fit.

beam waist of the array emission ω_{01} as the fitting parameter, we fit the experimental data in Fig. 5. The best agreement was obtained for $\omega_{01} = 17.7$ mm. With these two waist radii, we estimated $K(0) \approx 0.14$ and the total power emitted by the array in free space at 420 nW. Measurements were performed with the lock-in technique and a beam chopper installed a few centimeters before the detector. Since our detector is not sensitive to near-infrared radiation, we were able to register in this way a power that was orders of magnitude less than the background thermal emission at 300 K.

In conclusion, we have shown that quasi-optical Schottky-diode detectors suite well for broadband applications which require simultaneously moderate sensitivity and fast response in the spectral range from microwaves to terahertz waves.

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