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# Development and investigation of microwave radiation sources and detector sections using SBDs within the 220–400 GHz frequency range

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**Abstract.** A procedure of mm- and submm-wave devices simulation based on the up-to-date simulation techniques for bulk microwave structures is proposed. We demonstrate a possibility of making microwave radiation sources based on IMPATT diodes and frequency multipliers with frequency output of 280 GHz as well as detector sections with Schottky barrier diodes for the 220–325 GHz and 325–400 GHz frequency ranges.

**Keywords:** microwave radiation source, frequency multiplier, detector, Schottky barrier diode, waveguide to microstrip line transition, simulation.

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## 1. Introduction

In recent years, the number of fundamental and applied works dealing with 100 GHz÷3 THz radiation has grown considerably. This is because of intense development of solid-state sources and receivers of such radiation, which made it possible to make small-sized and highly-sensitive coherent radio-metering systems. These systems enable one not only to detect the radiation transmitted or reflected from an object but to measure its phase as well. This makes it possible to determine uniquely and concurrently (in the course of a single measurement) with high resolution the main characteristics and parameters of the object under investigation, namely, its permittivity, dielectric loss tangent and thermal radiation. The corresponding techniques find application in coherent THz tomography, biomedical technologies and pharmaceutics, nanotechnology, micro- and nanoelectronics, when checking food stuffs, monitoring environment and solving celestial problems as well as in space research, communication and many other areas [1].

The intensity of Rayleigh scattering of THz radiation is much below that of IR and visible radiation. For many media, the absorption coefficients in the THz range are much less than those for near-IR and visible radiation. Contrary to x-rays and γ-quanta, THz radiation has no factors detrimental to biological objects. All the above enables one to ensure an optimal combination of rather high spatial resolution and deep penetration of THz radiation into the object studied, thus making it a good instrument for diagnostics of various objects.

The problem of making the THz solid-state active oscillators involves a number of factors. The devices intended for THz frequencies are based on the principles of charge carrier transport. This fact imposes a fundamental restriction on the highest operational frequency that is specified by the time of charge carrier transit between the electrodes and the characteristic time related to the size and resistance of both the device in itself and its contact elements. The above reason limits in principle the generated power and sensitivity of solid-state active elements. In addition, the active oscillators with semiconductor structures of negative resistance have low $Q$ factor and, as a result, broad spectral characteristics. To make coherent systems, the transmitting and receiving sections have to be synchronized with an accuracy of several degrees. At the same time, both the radiation source and receiver should be small-sized, highly reliable etc. In this relation, the detectors and frequency multipliers with beam lead SBDs (Schottky barrier diodes) are of considerable interest.

## 2. Simulation

In this work, we consider devices operating in the fundamental mode of a rectangular waveguide line. The frequency multipliers and detector sections involve segments of waveguide and microstrip line, WGMLTs (waveguide to microstrip line transitions), filters for bias feed to SBD, rejection and harmonic filters. A beam lead SBD served as nonlinear element.

To simulate the impedance characteristics and conversion coefficients, we applied the method of harmonic balance, in particular, the Krylov subspace method [2]. It enables one to reduce essentially the computer memory capacity and increase calculating speed as compared to the standard approaches. The results of measurements of $C-V$ and $I-V$ curves for detector and frequency multiplication SBDs were taken as initial data for simulation.

Fig. 1 presents the measured $C-V$ curves of beam lead SBDs intended for signal detection. The inflection of $C-V$ curves at positive voltage is owing to current flow through the Schottky barrier [3]. Shown in Fig. 2 are $I-V$ curves of beam lead SBDs. Fig. 3 presents the $C-V$ curves of frequency multiplication beam lead SBDs.

The experimental data obtained were used for development of SPICE (Simulation Program with Integrated Circuit Emphasis) models of frequency multiplication and detector diodes. The calculations using the SPICE model gave the following values for conversion coefficient of detector diode: no less than 43 mA/V in the 220–325 GHz frequency range and 21 mA/V in the 325 – 400 GHz frequency range. The total resistance $Z$ was 8.1 – j63.4 Ohm (9.4 – j44.21 Ohm) in the first (second) of the above frequency ranges. The diode loss resistance lies in the 5–10 Ohm range. The conversion transconductance of the frequency multiplication diode (supplied voltage of 1 V at a frequency of 140 GHz and diode current at a frequency of 280 GHz) is 5.6 mA/V. The diode total impedance $Z$ is 11.96 – j35.2 Ohm (11.3 – j20.7 Ohm) at a frequency of 140 GHz (280 GHz).

The simulation of transmission lines, WGMLTs and filters was made using FEM (Finite Element Method) [4] that involved adaptive generation and space division into cells. The solutions for electromagnetic field of 3D structures determined from the Maxwell equations enable one to accurately find all the characteristics of a microwave device, with allowance made for appearance of waves of different types and their transformation into one another. This is of great importance for WGMLTs simulation. The method takes into account irregular structural nonuniformities and the losses in materials as well as ohmic and radiation losses. The initial types of single-mode waveguides were chosen as follows: 0.86×0.43 mm (0.72×0.36 mm) for the 220–325 GHz (325–400 GHz) frequency range and 0.8×1.6 mm for frequency multiplier pumping. RT duroid 5880 Laminates served as substrate material for filters, microstrip transmission lines and WGMLTs, with the following parameters: permittivity $\varepsilon_r = 2.2$, dielectric loss tangent $\tan(\delta) = 0.0009$, dielectric layer thickness of 50 μm and conducting layer thickness of 9 μm [5].

A filter for bias feed to the frequency multiplication diode should have the following properties. Its input and output resistances (RFIn and RFOut) should be 50 Ohm and the bias circuit (Ubias) must not affect considerably the wave impedance of transmission line at the frequencies 140 GHz and 280 GHz [6]. The topology of filter for bias feed to SBD is shown in Fig. 4. This filter is to be connected between WGMLT and a nonlinear element. A synthesis/analysis procedure shows that transmission losses are no more than 0.32 dB (0.42 dB) at a frequency of 140 GHz (280 GHz).

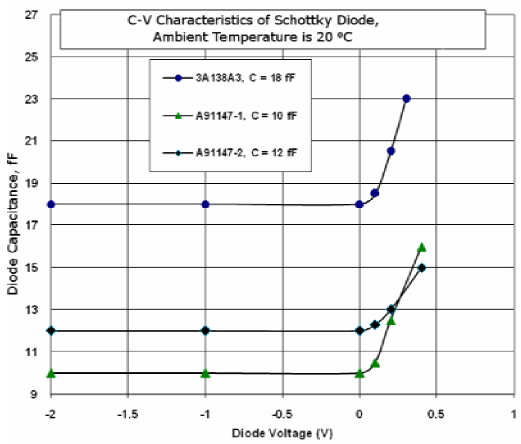



**Fig. 1.** *C–V* curves of three different SBDs.

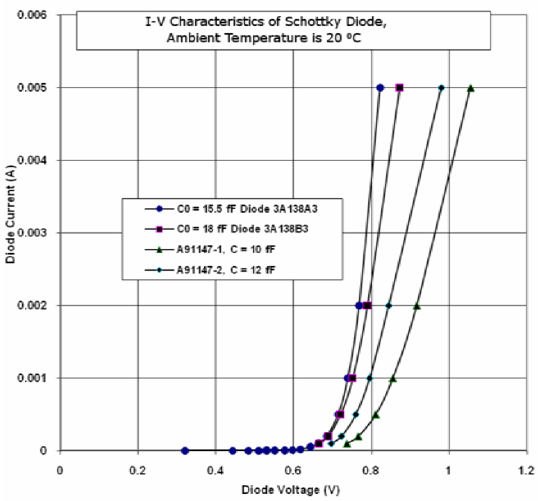



**Fig. 2.** *I–V* curves of four different SBDs.

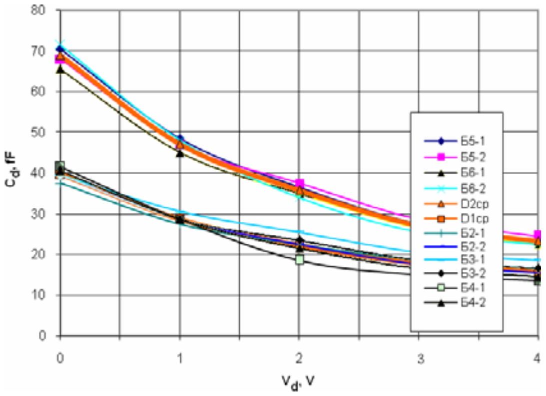



**Fig. 3.** *C–V* curves of twelve different frequency multiplication SBDs.

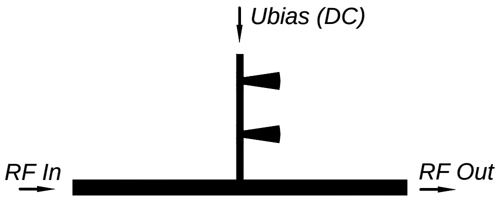



**Fig. 4.** Topology of a filter for bias feed to SBD.

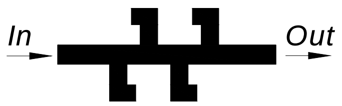



**Fig. 5.** Rejection filter topology.

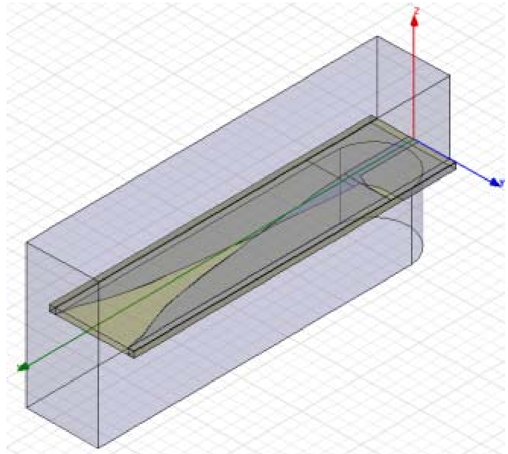


**Fig. 6.** A 3D model for a graded WGMLT.

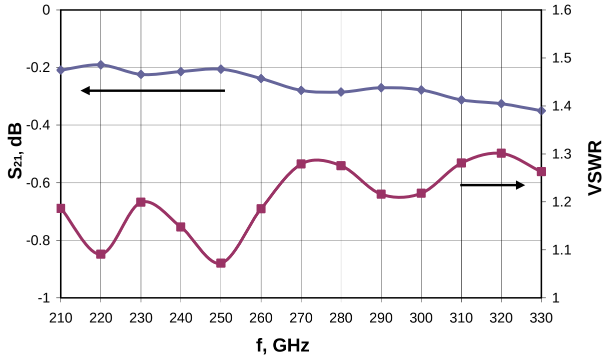



**Fig. 7.** The frequency dependence of transmission gain ($S_{21}$) and VSWR of a tapered WGMLT.

The rejection filters of the following three types were used in the detector sections and frequency multipliers:

- that rejecting 280 GHz and transmitting 140 GHz;
- 220–325 GHz rejection filter;
- 325–400 GHz rejection filter.

All the three rejection filters had the same topology (see Fig. 5).

The filter was placed in a below-cutoff (for the corresponding frequency range) waveguide. Such an approach excludes electromagnetic wave propagation in a space over the filter, and all the energy goes via a microstrip line from the input (In) to the output (Out). The simulation gave the following results: the transmission losses no more than 0.5 dB at a frequency of 140 GHz, isolation over 50 dB at a frequency of 280 GHz, suppression over 50 dB (45 dB) in the 220–325 GHz (325–400 GHz) frequency range.

A WGMLT for the 220–325 GHz and 325–400 GHz frequency ranges was synthesized on the basis of an unsymmetrical fin line. The transition space was divided into twenty sections whose impedance obeyed the exponential distribution law, depending on the transition length [7]. The wavelength dispersion was taken into account at each elementary section of the transition. A 3D model of a tapered transition is given in Fig. 6.

Fig. 7 presents the calculated frequency dependences of transmission gain ($S_{21}$) and VSWR (voltage standing-wave ratio) in the 220–325 GHz frequency range. One can see that the transmission gain does not exceed –0.4 dB, while VSWR is below 1.3 over the whole frequency range. Similar synthesis/analysis procedure was made for the 325–400 GHz frequency range. It showed that transmission gain did not exceed 0.5 dB and VSWR was less than 1.4. The feature of the tapered transition is that the microstrip line is connected to the broad wall of the waveguide.

To feed pumping power at a frequency of 140 GHz, one should use a transition in the frequency multiplier that is isolated from the waveguide walls, because the SBD bias is fed on the side of that transition. The 3D model of the transition is shown in Fig. 8. Such a transition ensures transmission gain $S_{21}$ (at a frequency of 140 GHz) of no more than 0.3 dB and VSWR of no more than 1.3. The operating frequency band is about 10%.

Fig. 9 shows the topology of a parallel-type frequency multiplier [8]. The frequency input (output) is 140 GHz (280 GHz). Pumping power is fed through the driving loop (1) in the waveguide and rejection filter (2) to SBD (3). The length of transition (5) is chosen in such a way as to bring low resistance to the diode plane.

Thus, the diode is connected in parallel to the microstrip line at a frequency of 140 GHz relative to the pumping input. At the same time, the filter (2) brings low resistance to the diode plane: the diode turns out to be connected in parallel to the microstrip line at a frequency of 280 GHz.

## 3. Experimental results

From the results of simulation, we designed and made a radiation source with the frequency output of 280 GHz. An oscillator with IMPATT (impact avalanche transit-time) diode was used as pumping source for frequency doubler. The frequency output and oscillator power were 140 GHz and 40 mW, respectively.

A waveguide isolator (isolation over 25 dB, transmission losses of 0.5 dB) is installed at the pumping oscillator output. The isolator is intended for exclusion of the effect of frequency multiplier VSWR on frequency and power of the pumping oscillator. Shown in Fig. 10 is a photograph of radiation source prototype. The radiation source ensured power output of 300 μW at a frequency of 280 GHz.

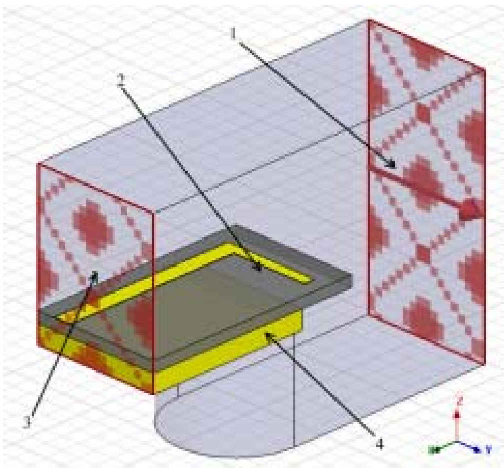



**Fig. 8.** A 3D model for a graded WGMLT isolated from the waveguide line walls: 1) rectangular waveguide section, 2) microstrip line–rectangular waveguide transition (a driving loop in the waveguide), 3) microstrip line section, 4) microstrip line.

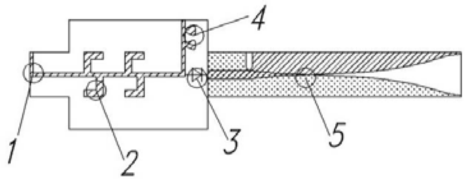



**Fig. 9.** Frequency multiplier topology: 1) a driving loop in the waveguide at the frequency multiplier input (140 GHz), 2) a rejection filter, 3) SBD, 4) a bias filter, 5) a WGMLT (280 GHz).

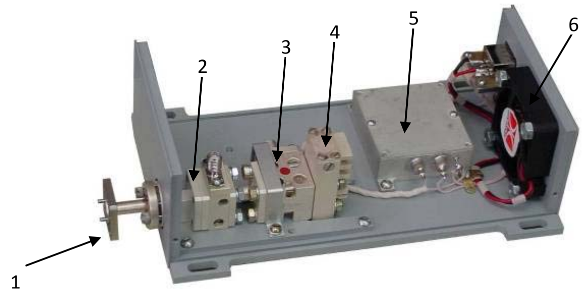
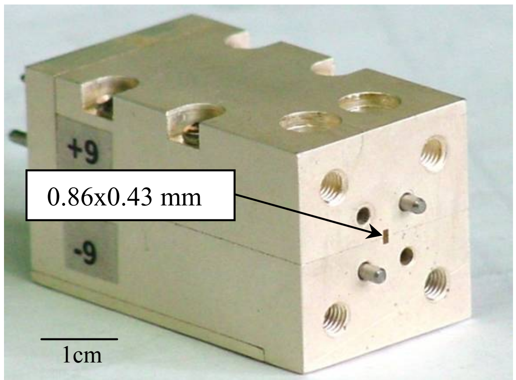



**Fig. 10.** Appearance of the radiation source with cover removed: 1) microwave signal output with a flange for connection to a waveguide, 2) frequency multiplier, 3) a ferrite isolator, 4) a master oscillator with IMPATT diode (operating frequency of 140 GHz), 5) power supply unit, 6) cooling fan.




*a*


*b*

**Fig. 11.** Appearance of detectors: a) 220–325 GHz frequency range, b) 325-400 GHz frequency range.

From the results of simulation, we made detector sections intended for operation in the 220–325 GHz and 325–400 GHz frequency ranges. The photographs of the detector sections are given in Fig. 11. The detector conversion coefficient in the 220–325 GHz (325–400 GHz) frequency range is no less than 60 V/W (55 V/W). The dependence of voltage output on power input remains linear at detector power input up to 0.5 mW. The maximal power at detector input at which the detector still retains its working capacity is no more than 15 mW.

## 8. Conclusion

We presented a simulation technique for microwave devices intended for operation in the mm and submm ranges. The technique is based on the up-to-date simulation packages for bulk microwave structures and nonlinear elements. As a result of application of the above simulation technique, we developed a microwave radiation source (frequency output of 280 GHz, power output of 300 μW) and detector sections with SBDs operating in the 220–325 GHz and 325-400 GHz frequency ranges with the conversion coefficient no less than 50 V/W.

## Acknowledgment

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