Chip-Size Double-Resonant-Tunneling-Diode Patch-Antenna Oscillators and their sub-THz Application

Petr Ourednik[1,*], and Michael Feiginov[1]
[1]Department of Electrical Engineering and Information Technology, TU Wien, Vienna 1040, Austria
[*]petr.ourednik@tuwien.ac.at

***Abstract*— To enable applications in the THz frequency range, chip-size room-temperature THz and sub-THz sources are required. We present here the concept and experimental results on such sources using double-resonant-tunneling-diode (RTD) patch-antenna oscillators. With these sources, we could cover the frequencies up to 1.09 THz, with the output powers between 70 to 10 µW from a single oscillator. These data demonstrate an order of magnitude improvement in terms of the output power and factor 2 improvement in terms of the fundamental operating frequency compared to the previous reports on patch-antenna RTD oscillators. Next, we show the possible direct application of these oscillators as a source for FMCW radar or optical coherent tomography working at a frequency of 680 GHz, with a bandwidth of 38 GHz (5.5 %), allowing 4 mm spatial resolution. The output power was 23 µW.**

I. Introduction

RESONANT-TUNNELLING-diode (RTD) oscillators are the highest-frequency active electronic devices nowadays [1,2]. However, as their technology is still not mature yet, they face several challenges, such as compactness, simplicity, and increase of their output power. Another challenge lies in incorporation of these sources into real-life applications. The possible applications are telecommunications, security, spectroscopy, or sensing. In this paper, we address one of the possible sensing applications.

II. Chip-Size RTD Oscillators

We address these challenges by developing double-RTD patch-antenna oscillators, see Figure 1. Such oscillators do not require a bulky Si lens. They emit upwards from the metalized chip surface. Additionally, they are simpler than other types of RTD oscillators radiating upwards from the substrate (they require multi-antenna/resonator configurations), since they use only a single patch antenna. The use of two RTDs in one oscillator enhances their output power. Moreover, the double-RTD configuration preserves the asymmetric ground eigenmode of the patch antenna with the node of the electric field distribution in the middle of the patch, see the inset in Figure 1. The connection of the biasing line at the node, allows one to decouple the THz resonator from the external bias circuitry efficiently. We have recently demonstrated two types of double-RTD patch-antenna oscillators [3,4].

The first type [3] was designed for fabrication solely by the optical lithography process. Therefore, we used RTDs with relatively thick barriers (1.6 nm) and the peak RTD current density of 5.8 mA/µm^2, which allowed us to use large mesa areas that were in the range 2-5.5 µm^2. The oscillators were operating at the frequencies 330-525 GHz with the output power of 70-10 µW, which is an order of magnitude higher, than in previous reports on patch-antenna RTD oscillators.

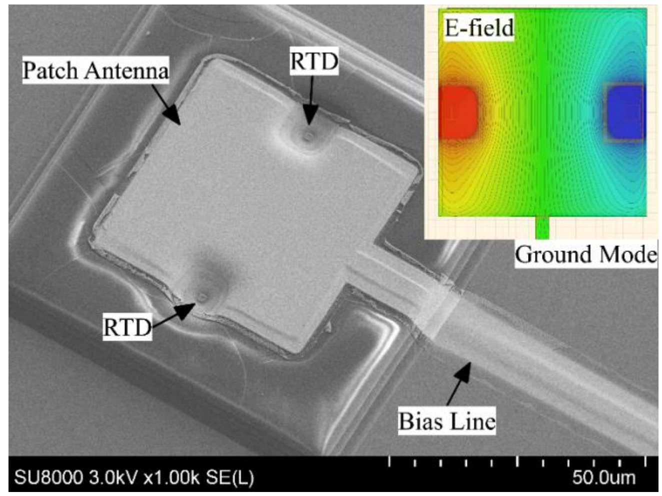

Fig. 1. SEM image of the double RTD oscillator. The inset shows distribution of the electric field for the asymmetric ground eigen mode.

In the second type [4] of the double-RTD patch-antenna oscillators, we have used RTDs with thin barriers of 1 nm and with the current density of 24 mA/µm^2 (see Fig. 2). Those RTDs exhibit record high peak-to-valley current ratio for RTDs with the current density in the range of ~20 mA/µm^2 (the current density in this range is required for the operation of RTDs at THz frequencies). Additionally, we have implemented conical vias for the connection of RTDs and the patch antennas, which has dramatically reduced the parasitic inductance of the antenna, e.g., the total oscillator inductance has been reduced approximately by the factor of 2 for a square 40 µm patch antenna. The active RTD mesa areas were in the range of 0.2-0.7 µm^2. The electron-beam lithography had to be used to fabricate these oscillators. The oscillators have been working in

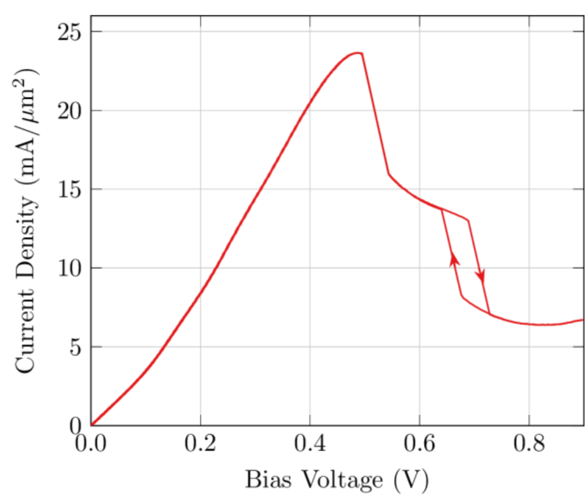

Fig. 2. Measured I-V curve of the RTD oscillator with 1 nm barriers.

© 2022 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

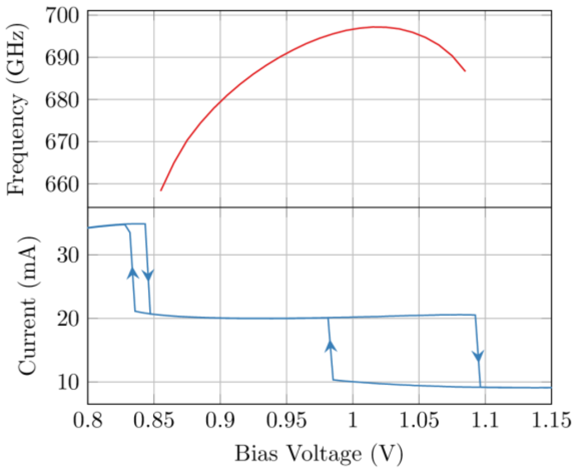

Fig. 3. The dependence of the oscillator operation frequency on the bias voltage. The frequency tuning shows the non-linear inflection character. The arrows indicate the backward and forwards sweeps of the relevant part of the I-V curve in the oscillation range.

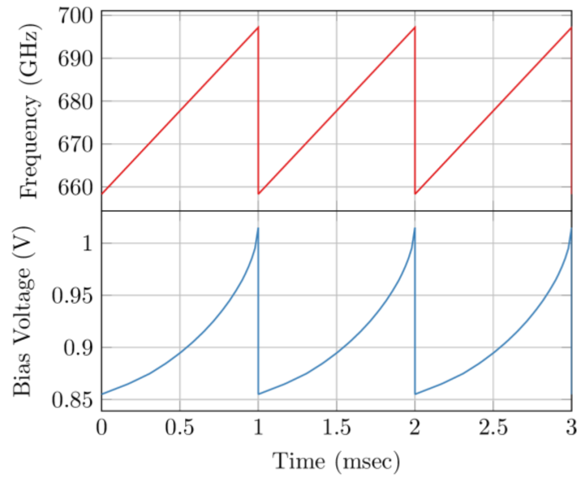

Fig. 4. Sequence of the linearized chirps for the first section of first frequency region and the corresponding sequence of the bias voltage sweeps, that are linearizing the response.

the range of 0.62-1.09 THz with the output power of 27-9 µW. The level of the output power of these oscillators is getting close to that of the other more bulky (slot antenna with Si lens) or more complex (double-antenna/resonator) types of fundamental RTD oscillators in the THz range [1,2].

For both types of oscillators, the measured data for the operating frequencies, output power, and RTD characteristics are in very good agreement with the simulations. Our analysis shows that the operation of double-RTD patch-antenna oscillators at significantly higher frequencies and with higher output power (per oscillator) is possible [4].

III. FMCW and OCT Application of RTD Oscillators

Next, we show the behavior of resonant-tunneling-diode (RTD) oscillators regarding their frequency tuning and investigate the possibility of employing the RTD oscillators in THz frequency-modulated continuous wave (FMCW) radars and optical coherent tomography (OCT) applications. The frequency tunability of RTD oscillators was addressed, e.g., in [5]. However, the behavior of fast linear frequency chirps was never shown. In this part, we use the above-described double-RTD oscillator with the nominal barrier thickness of 1 nm.

The oscillation frequency of an RTD oscillator depends on the bias applied to the RTD since the RTD depletion-layer and quantum-well capacitances are bias-dependent. Therefore, with the control of the bias, the RTD oscillator can be used as a voltage-controlled oscillator. However, the frequency response of the oscillator is not linear with a linear bias voltage sweep. In FMCW radars, to reliably determine the target's distance and speed, it is required from the source to generate linear frequency chirps in time.

The measured frequency response as a function of the bias voltage of our RTD oscillator is shown in Fig. 3. The inset shows details on the I-V curve zoomed in the oscillation region. The I-V curve is striped of the shunt resistor contribution, which is needed to suppress the low-frequency parasitic oscillations. The oscillation region is between the two hysteresis regions. The data shows two regions of possible operation, before and after the maximum. The first part gives a higher tunability range, which was 38 GHz in our case. The second part gives a lower tunability but an almost constant output power (for our device). We use the first part with a wider frequency range in this work. As the measurement has shown, the shape of the frequency vs. bias curve is not linear. The non-linear frequency sweep would cause a not constant FMCW-detection frequency, hugely decreasing the final resolution.

To linearize the frequency response in time, one needs to create a non-linear voltage sweep to compensate for the frequency non-linearity. The properly shaped voltage sweep with the duration of 1 ms was generated by an arbitrary waveform generator, it consisted of 50 segments with the duration of 20 µs each. The resulting linearized frequency sweep with the span of 38 GHz is shown in Fig. 4. The frequency-sweep rate is limited by the control equipment, by the external parasitics of the oscillator and by the RTD-resonator properties; the internal (inverse) time constants of RTD itself are in the THz range, they do not impose any relevant limitations. Much faster sweep rates are possible.

A control voltage was applied to the RTD oscillator, which corresponds to a continuous train of saw-tooth linearized frequency sweeps. The modulated RTD oscillator generates a nearly rectangular spectrum with the bandwidth of 38 GHz, which is shown in Fig. 5. A slight deviation of the spectrum from an ideal rectangular shape is due to the bias dependence of the output power of the RTD oscillators [4]. The output power of 23 µW was measured by a calibrated pyroelectric detector. The spectrum was measured with an interferometer in the Martin-Puplett configuration and with a Golay cell as detector. The interferometer basically corresponds to a typical OCT measurement configuration; given a linear frequency sweep with rectangular spectrum, the interferogram in Fig. 5 has a sin(x)/x shape, as expected. The peak of the interferogram corresponds to the configuration, when both interferometer mirrors have an equal off-set from the wire-grid interferometer polarizer. The peak width shows a 4 mm OCT resolution, corresponding to the 38 GHz bandwidth of the oscillator frequency sweeps.

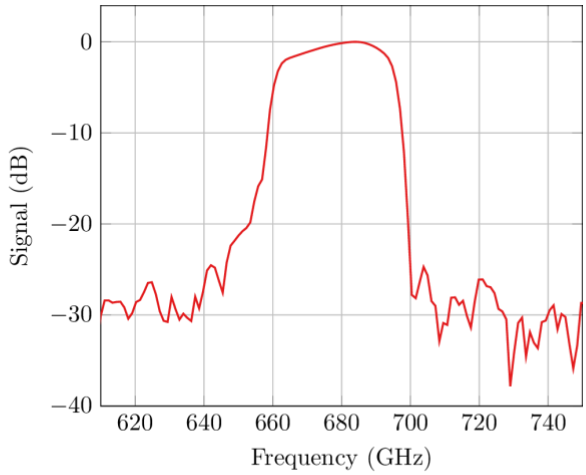

Fig. 5. Measured frequency spectrum of the RTD oscillator with applied linearized frequency modulation.

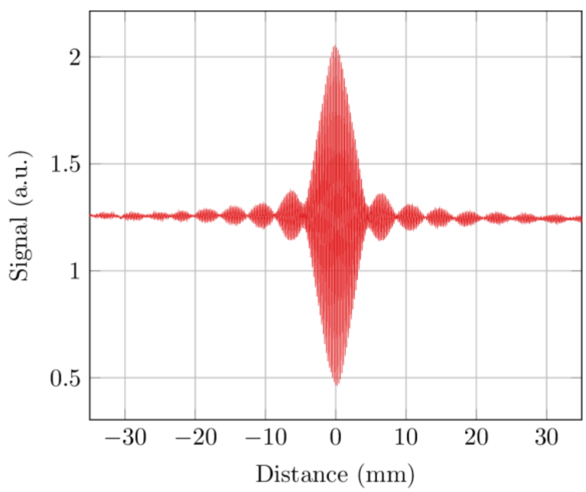

Fig. 6. Measured interferogram of the output oscillator signal with the applied linearized frequency modulation. The period of the sin(x)/x function (OCT resolution) corresponds to half of the reciprocal bandwidth.

To confirm the functionality of the source, we tried to build an FMCW radar. The mutual shift of the mirrors in the interferometer allows one to create two paths with different times of flight. The power detector then mixes the delayed responses due to the square-law detection. The output frequency is then equal to the difference of the input frequencies. The response time of the used Golay cell is 30 ms, and, therefore, for the expected range of the detected frequency, we used a chirp with a duration of 490 ms. Fig. 7 a) shows a comparison of the detected time domain signals for a simple linear bias chirp and a corrected chirp linearizing the frequency sweep. The target (static mirror in the moving arm of the interferometer) was at 23 mm. The linear chirp shows a frequency modulation in time. Meanwhile, the corrected chirps show a sinusoidal signal with a constant frequency. Fig. 7 b) then shows the corresponding range plots. The shape of the curve corresponding to the linear chirp shows a noticeable broadening of the peak, effectively decreasing the resolution and the signal strength. The corrected linearized chirp then shows a clear peak corresponding to the target's distance.

We should add, that for undisturbed operation of the RTD oscillator, the waves reflected back to the oscillator need to be sufficiently suppressed, in order to prevent frequency locking. The used interferometer inherently provides this isolation.

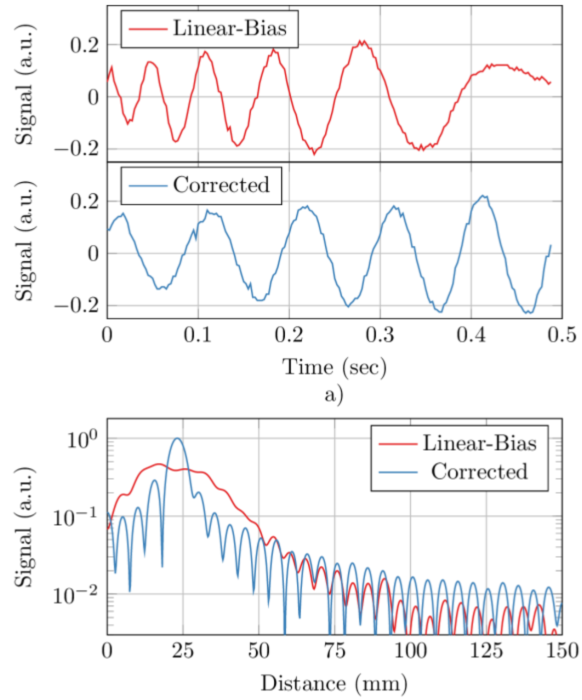

Fig. 7. Detected FMCW-radar signals for the linear bias chirp and the corrected frequency chirp for a target at a distance of 23 mm, in a) time domain, and b) in range plot.

IV. Conclusion

In this paper we have shown the true chip-size and simple RTD oscillator operating up to 1.09 THz, with output power ranging from 70 µW to 9 µW. Next, we have presented one possible real-life application: the functionality of RTD oscillators as sources for sub-THz and THz FMCW radars and OCT applications. The presented source provided spatial resolution of 4 mm with an output power of 23 µW with an average operation frequency of 680 GHz and 38 GHz (5.5%) bandwidth.

Acknowledgement

The work was supported by FWF project P30892-N30.

References

[1] M. Asada, and S. Suzuki, "Room-Temperature Oscillation of Resonant Tunneling Diodes close to 2 THz and Their Functions for Various Applications," *Journal of Infrared, Millimeter and Terahertz Waves,* vol. 37, no. 12, pp. 1185-1198, December, 2016.

[2] M. Feiginov, "Frequency limitations of resonant-tunnelling diodes in sub-THz and THz oscillators and detectors" *Journal of infrared, millimeter, and terahertz waves*, vol. 40, no. 4, pp. 365-394, March, 2019.

[3] P. Ourednik, T. Hackl, C. Spudat, D. Tuan Nguyen, and M Feiginov, "Double-resonant-tunneling-diode patch-antenna oscillators," *Applied Physics Letters*, vol. 119, no. 26, 263509, December, 2021.

[4] P. Ourednik, and M. Feiginov, "Double-Resonant-Tunneling-Diode Bridge-Less Patch-Antenna Oscillators Operating up to 1.09 THz," *Applied Physics Letters*, vol. 120, no. 18, 183501, May, 2022.

[5] S. Kitawaga, S. Suzuki, and M. Asada, "Wide frequency-tunable resonant tunnelling diode terahertz oscillators using varactor diodes," *Electronics Letters*, vol. 52, no. 6, pp. 479-481, March, 2016.