Performance Evaluation of High-Capacity RTD Transmitters for THz Microscale Applications

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Abstract: This work addresses a transmitter based on a RTD oscillator operating at 1.03 THz supporting output power and capacity as high as 0.84 mW and 0.15 Tb/s whilst achieving a 7-meter THz link reach. © 2021 The Author(s)

1. Introduction

Next generation wireless systems based on terahertz (THz) communication will most likely be based on commercial off-the-shelf (COTS) solutions along with custom-made traditional silicon and silicon photonics devices. Suitable power levels, COTS transmitters and higher extension reach remain constant challenges in THz communications. The THz region allows for extensive capacity in the order of terabits per second (Tb/s). Several different THz solutions have been proposed for a myriad of networking applications, including microscale applications [1]. THz microscale applications might be part of the emerging wave of applications and meet well the consumer's demand for higher bandwidth at the microscale. Amongst several solutions, next generation wireless systems can be implemented with the help of resonant tunneling diode (RTD) devices. This particular class of device has a non-linear current-voltage (*I–V*) curve that occurs due to its double-barrier quantum-well (DBQW) structure, which gives rise to a negative differential resistance (NDR). This exciting feature compensates the ohmic losses of resistive elements, which enables its use as oscillating circuits. In addition, RTDs can be grown on III–V based semiconductors substrate to confer remarkable attributes such as high-speed response, low power consumption, and high frequency operation, hence becoming an ideal candidate to work as an oscillator. For example, an InGaAs/AlAs RTD operating as an oscillator at 1.98 THz working along with a slot antenna was proposed in [2]. Within this context, this work proposes a transmitter for THz microscale applications composed of an InGaAs/AlAs RTD oscillator and a single-dipole antenna with silicon (Si) lens substrates. The THz RTD-based transmitter is compatible with CMOS pilot-line fabrication process, supports high-speed modulation and operation at room temperatures (300 K), and has a compact footprint (280 μm²). A new analytical framework for investigating the performance of the system in terms of channel capacity and bit error rate (BER) taking account the load effects and RTD conductance degradation is derived. Results shown the THz transmitter operating at 1.03 THz can provide not only output power levels as high as ~0.84 mW, but also channel capacity as high as 0.15 Tb/s and for a 7-m link reach proving to be suitable for THz microscale aplications.

2. Device Structure and Performance Evaluation

The proposed THz transmitter is based on the integration of InGaAs/AlAs RTD with a single-dipole resonant antenna [3, 4]. The THz microscale application addressed here is illustrated in Fig. 1(a), where the transmitter can act as a THz access point whose data is sent to other devices. The designed RTD works as an oscillator feeding an antenna as illustrated in Fig. 1(b). The RTD-based transmitter has a DBQW structure formed by two undoped spacer layers of $In_{0.53}Ga_{0.47}As$, and two AlAs barriers (1.1 nm), separated by a quantum well of $In_{0.8}Ga_{0.2}As$ (3.5 nm). To transmit the signals, a full-wavelength single-dipole resonant antenna with Si lens substrates is used. This antenna [4] is formed by a metallic layer with a length of 94 μm and a width of 3 μm on a Si substrate. The Si substrate has a thickness of 472.5 μm, and from the substrate a hemispherical Si lens with a radius of 1350 μm is made. The main features of the antenna are resonance frequency of 1.03 THz, load impedance of 295 Ω, directivity of 28.4 dBi, radiation efficiency of 92%, and a gain of 26.13 dBi [4]. The single-dipole antenna has a relatively high gain value, which is essential for transmitters operating above 1 THz, considering that signals in the free-space will undergo considerable atmospheric attenuation [5]. The output power of the transmitter is evaluated considering the load effects of the antenna and the degradation of the RTD conductance for high frequencies. According to [6], the *I–V* characteristics of the RTD can be approximated as $I(V) = F(V) \approx G_{n0}V + bV^3$, where G_{n0} is the magnitude of the conductance, b is the positive parameter of cubic polynomial approximation. The RTD can be represented by a

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resistor R_s and an inductor L_s in series connected to a current source $F(V)$ in parallel to the RTD capacitance C_n. The capacitance (C_n) and the carrier transit time (τ) of the device can be obtained based on [7]. Generally, some methods consider the magnitude of G_{n0} regardless of the operating frequency [6]. However, the RTD conductance will decrease as the frequency increases, so as the capacitance. Hence, affecting the output power (P_{out}) of the system.

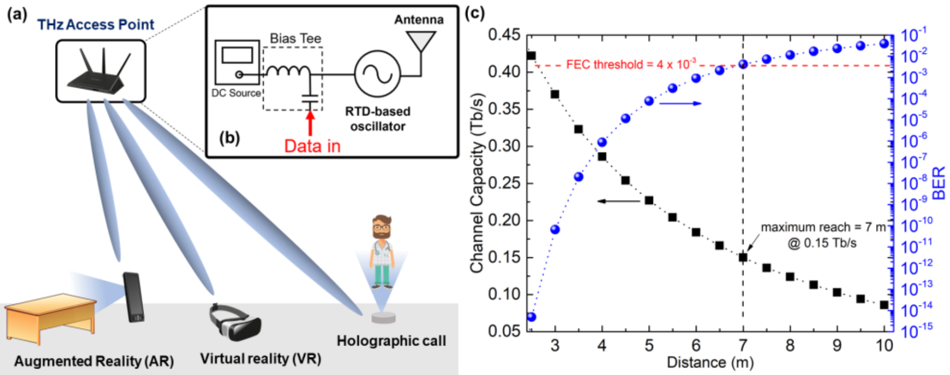

Fig. 1. (a) Terahertz microscale applications. (b) Block diagram of the THz transmitter based on RTD and single-dipole resonant antenna. (c) System performance evaluation: the channel capacity versus ditance and the BER versus distance.

3. Results

The device's *I–V* curve leads to peak and valley currents of the order of 42.8 mA and 8.82 mA. Their ordered pairs referring to the peak and valley voltages are of the order of 0.47 V and 0.67 V, respectively. These values allow one to obtain the magnitude of the RTD conductance G_{n0} = 255 mS and the positive parameter b = 8.5 S/V². Next, the following parameters associated to the RTD's model are considered: barrier length (L_b) = 1.1 nm, barrier effective mass (m_b) = 0.15m_0, barrier height (V_0) = 1.0 eV, and first energy level in the quantum well (E_1) = 0.286 eV. E_1 is calculated with the assistance of the transfer matrix method implemented to the RTD's DBQW model structure. By applying these parameters, the following values are obtained: τ = 92.2 fs, and C_n = 29.6 fF, which show a close agreement with [3]. Such value obtained for C_n is adjusted as 25.5 fF in order to support operation at 1.03 THz. Then, the RTD conductance as function of the frequency (G_n) is equal to 211 mS. Once the parameters C_n and G_n are known, the final requirements to achieve oscillation at 1.03 THz are to set the resistance (R_s) = 0.1 Ω and inductance (L) = 0.92 THz. An output power as high as ~0.843 mW is obtained for the antenna and RTD's device with matched conductance, i.e., G_L = 126 mS. We consider Tx and Rx antennas gain as 26.13 dBi [4], 3 dB noise figure, and FEC threshold set to 4 x 10^{-3} [1]. We evaluate the system performance along with the help of the THz propagation model [5] by addressing both the channel capacity and BER as a function of the wireless link transmission distance, whose values are plot in Fig. 1(c). Interestingly, the channel capacity decreases as the wireless link reach increases until achieving a maximum reach of 7 meters, which is the FEC limit for guaratting error free transmissions. Hence, under this FEC region (see red line in Fig. 1(c)), the system transmits error-free bits, supports channel capacity as high as 0.15 Tb/s and transmission reach up to 7 meters being suitable for THz microscale aplications.

4. Conclusions

A RTD transmitter capable of operating at the THz region was proposed. The high-capacity transmitter suits THz microscale applications and was characterized as well as evaluated. The transmitter supports 1.03 THz operation, error-free transmissions, high power levels (~0.84 uW) and capacity (0.15 Tb/s) whilst achieving a 7-m link reach.

5. References

[1] H. Elayan et al., "Terahertz band: the last piece of RF spectrum puzzle for communication systems," IEEE Open Journal of the Communication Society, vol. 1, pp. 1-32, 2020.

[2] R. Izumi, S. Suzuki and M. Asada, "1.98 THz resonant-tunneling diode oscillator with reduced conduction loss by thick antenna electrode," 42nd International Conference on Infrared, Millimeter, and Terahertz Waves, 2017.

[3] S. Muttlak et al., "InGaAs/AlAs resonant tunneling diodes for THz applications: an experimental investigation," IEEE Journal of the Electron Devices Society, vol. 6, pp. 254-262, 2018.

[4] T. Nguyen and I. Park, "Resonant antennas on semi-infinite and lens substrates at terahertz frequency," Convergence of Terahertz Sciences in Biomedical Systems. Springer, Dordrecht, 2012.

[5] C. Han, A. O. Bicen and I. F. Akyildiz, "Multi-ray channel modeling and wideband characterization for wireless communications in the terahertz band," IEEE Transactions on Wireless Communications, vol. 14, no. 5, pp. 2402-2412, 2015.

[6] A. Al-Khalidi et al., "Resonant tunneling diode terahertz sources with up to 1 mW output power in the J-band," IEEE Transactions on Terahertz Science and Technology, vol. 10, no. 2, pp. 150-157, 2020.

[7] R. Nobrega et al., "A semi-analytical approach for performance evaluation of RTD-based oscillators," 21st ICTON, Angers, France, 2019.