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Resonant Tunneling Diode Optoelectronic Circuits
Applications in Radio-Over-Fiber Networks

Horacio I. Cantú, Bruno Romeira, Anthony E. Kelly, Charles N. Ironside, and J. M. L. Figueiredo

Abstract—Phase-locked oscillators based on resonant tunneling diodes are used in this study to implement transceiver components that perform conversion between optical and wireless phase shift-keyed signals using injection-locked oscillator techniques. Three different links are demonstrated at frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz that are capable of locking to a phase-modulated signal that propagates from the optical to the wireless and back to the optical domains. The transmitter and receiver are evaluated through Gaussian minimum shift-keying modulation accuracy metrics. Deployment of the transceiver in radio-over-fiber architectures is also discussed.

Index Terms—Injection locking, phase modulation, radio-over-fiber (RoF), resonant tunneling diodes (RTDs).

I. INTRODUCTION

INJECTION locking of oscillators is a well-known phenomenon that has been thoroughly described in a number of situations. Adler’s paper [1] has been used by several authors [2]–[6] as a cornerstone and as a first-order approximation of the mathematical description of oscillators under locked conditions. Several approaches have been used to incorporate the highly nonlinear behavior of the oscillator active components by means of quasi-static, dynamic [2], and graphical analysis [3], circuit theory concepts [4], analytical simplifications [5], and numerical solution of second-order differential equations [6]. Accurate prediction of the relation between injected power levels and the frequency-locking ranges has been obtained from these studies. The improvement of the injection-locked oscillator phase-noise characteristics has been analytically described in [3] at the center and at the edges of the frequency-locking range. Applications such as precision quadrature generation have been proposed [3] and implemented [7] taking advantage of the first-order phase-locked loop (PLL) behavior exhibited by injection-locked oscillators.

The authors of [5] calculated the settling time of an injection-locked oscillator and its application in fast hopping systems. Their results showed that even for moderate values of locking range, the lock time can meet the hopping time of 9.5-ns requirement of some frequency-hopped spread-spectrum system specifications.

In this study, the possibility of implementing injection-locked resonant tunneling diode (RTD) based oscillators as transceiver components within picocellular [8] and femtocellular [9] networks is explored. The optoelectronic characteristic of the RTD is used to convert from optical to wireless domains and eventually for the deployment of radio-over-fiber (RoF) networks.

The deployment of picocellular networks enables the transmission of high data rates in advanced wireless communications for corporate and public users [8]. The reduction in cell size helps to maintain signal-to-noise ratio (SNR) with moderate transmitted power levels while limiting the number of users per cell. The authors in [9] recognize that the system capacity of a wireless link can be improved simply by placing the transmitter (Tx) and receiver (Rx) closer to each other. Reduced distances require lower transmit power, which consumes less battery life. An RoF picocellular link was implemented in [8] and the performance was evaluated with error vector magnitude (EVM) measurement techniques in the 2.4- and 5-GHz bands.

The demand of wireless high-bandwidth data delivery has made millimeter-wave frequencies attractive for the deployment of RoF networks with 1-Gb/s ultra-broadband capacity. The authors in [10] demonstrated the feasibility of a 60-GHz RoF link where the radio access points are limited to perform radio to optic and optic to radio conversion. They evaluated their link with EVM levels constrained by bit error rate (BER) values below 10^{-5}.

Room-temperature oscillations at 1 THz [11] and 1.1 THz [12] have been recently reported for RTD-based circuits, which makes them the fastest electronic devices currently available with proven optoelectronics characteristics [13] suitable for the realization of radio access points required for RoF-based picocellular networks operating in the millimeter-wave range of frequencies. The principle of injection locking of RTD oscillators is exploited here as the mechanism for conversion between the wireless and optical domains performed at each one of the radio access points within the network. The oscillator frequencies reported here fall within the microwave spectrum and are limited only by the hybrid circuit implementation of the technology. Scaling and monolithic integration of the radio access points would increase transmission applications to the V-band range of frequencies.

A demonstration of RTD-based communication links operating at frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz is presented in this study and organized in the following way:
Section II shows the RTDs structure, hybrid circuit design, and frequency tuning. In Section III, the oscillators are injection locked with phase-modulated signals and tested for signal transmission with modulation accuracy reports. The basic transceiver design is presented and implemented in Section IV and then used for measurements of modulation accuracy after signal broadcast in Section V. Implementation of RTD relaxation oscillators at $-\text{band}$ frequencies is briefly discussed in Section VI. A summary and conclusions are included in Section VII.

### II. RTD OSCILLATOR CHARACTERISTICS

#### A. RTD Epitaxial Structure

The active devices used in this study consist of AlAs/InGaAs/AlAs double-barrier quantum-well structures grown on semiconducting InP substrates. The epitaxial structure includes InGaAlAs layers that in previous study [14] helped to implement RTD devices as electro-absorption modulators and waveguide photo-detectors (PDs). In this study, the RTDs have been processed as pillars where the InGaAlAs layers are used to improve the absorption of light at a wavelength of 1550 nm. A description of the epitaxial layers is shown in Table I.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness</th>
<th>Doping Type</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>In$<em>{0.35}$Ga$</em>{0.47}$As</td>
<td>30 nm</td>
<td>$\delta$</td>
<td>$2\times10^{19}$ cm$^{-3}$</td>
</tr>
<tr>
<td>In$<em>{0.37}$Al$</em>{0.48}$As</td>
<td>300 nm</td>
<td>n</td>
<td>$2\times10^{18}$ cm$^{-3}$</td>
</tr>
<tr>
<td>In$<em>{0.37}$Ga$</em>{0.42}$Al$_{0.05}$As</td>
<td>500 nm</td>
<td>n</td>
<td>$5\times10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>AlAs</td>
<td>2 nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>In$<em>{0.35}$Ga$</em>{0.47}$As</td>
<td>6 nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>AlAs</td>
<td>2 nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>In$<em>{0.37}$Ga$</em>{0.42}$Al$_{0.05}$As</td>
<td>500 nm</td>
<td>n</td>
<td>$5\times10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Substrate InP</td>
<td>380 $\mu$m</td>
<td>n+</td>
<td>-</td>
</tr>
</tbody>
</table>

Single devices with an active area of $13.2 \mu m \times 13.2 \mu m$ were fabricated with this epitaxial structure and diced to form single chips. The RTD electrodes were formed with gold metallization that allows wire bonding to off-chip hybrid circuit components. Microphotography of the device is shown in the inset of Fig. 1.

#### B. Measured Current–Voltage (I–V) Characteristics

A bias voltage ($V_{\text{Bias}}$) was applied across the electrodes of three different RTD devices grown with the structure described in Section II-A. Each device was used as the active component of three hybrid circuit oscillators operating at different frequencies. The RTDs $I–V$ characteristics are shown in Fig. 1. A peak voltage of 0.8 V and peak current of approximately 12 mA is exhibited by all the devices, which also show a significant variation on the width of the negative differential resistance (NDR) region. The peak current density has been calculated to be 7 kA/cm$^2$ and the measured peak ($V_{\text{Bias}} = 0.8$ V) to valley ($V_{\text{Bias}} = 1.8$ V) ratio was 6, 5, and 5.2 for the devices used for oscillator frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz, respectively. The three different devices characterized in Fig. 1 were obtained from the same InP epiwafers. The difference in $I–V$ characteristics has been attributed to electrode contact process variations that lead to different electric field distribution across the active layers described in Table I. The plateau features observed in Fig. 1 are known to be originated by low-frequency oscillations within the $I–V$ measurement equipment network. These oscillations are extrinsic to the operation of the RTD device illustrated by the physics model [6] shown in Fig. 1.

#### C. Oscillator Design and Frequency Tuning

Relaxation oscillators [15]–[17] were used in this work as the basis of the Tx and Rx circuits that perform optical to wireless and wireless to optical signal conversion. The oscillators consist of an RTD connected in parallel with a 1-$\mu$F shunt capacitor. The diode illustrated in Fig. 1(b) was mounted on a metal carrier and wire bonded to a 50-$\Omega$ printed circuit board microstrip line. The line is used to interconnect with the off-chip 1-$\mu$F shunt capacitor and is also used to provide an output port for the generated RF power. A photograph of the oscillator circuit module is shown in Fig. 2. When the diodes are biased into the NDR region, the shunt capacitor works as a feedback element that helps sustain a steady-state oscillation whose frequency is determined mainly by the RTD parasitic reactance. Three fundamental oscillation frequencies were obtained in three different circuits by varying the length of the on-chip gold pads that are used to wire bond the RTD upper mesa to the external components. The length of the pad was estimated to be 350, 250, and 100 $\mu$m for the cases of the Tx oscillators used at the frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz, respectively. The upper mesa gold pad was 60-$\mu$m wide for all cases.

Fig. 3 shows the measured frequency tuning characteristics and power output generated by the fundamental oscillation of three different RTD circuits that have been biased into the NDR region ($V_{\text{Bias}} > 0.8$ V). The tuning ranges varied between 55, 250, and 500 MHz depending on the frequency band of their fundamental oscillations. The voltage tuning range is commensurate with the width of the NDR region, shown earlier in Fig. 1. The RF output power level of the oscillators varied from −4 to
III. INJECTION LOCKING WITH PHASE-MODULATED SIGNALS

The authors in [18] and [19] have investigated the settling times of injection-locked oscillators coupled to antenna arrays. In [18], the data rate of an injected phase-modulated carrier was shown to be limited by the resynchronization time required by large phase transitions between data symbols. The work in [19] reported that undesired frequency modulation of the carrier affects radiation patterns adversely due to different antenna gains around the nominal center frequency.

In order to minimize abrupt phase transitions from the injected signal, as well as to achieve spectral efficiency at the carrier frequency, a Gaussian minimum shift-keying (GMSK) signal has been implemented in this study as the scheme for data conversion and transmission. GMSK is widely used as one of the Global System for Mobile Communications (GSM) modulation standards for voice and data transmission in cellular networks. GSM operates in 124 channels that are 200-kHz wide occupying a total frequency band of 25 MHz. RTDs can be injection locked within frequency ranges as wide as 24 MHz [20], but the present work is concentrated on the operation of a single GMSK modulated GSM channel.

Signal bursts containing GMSK modulation were used in this study to injection lock the free-running oscillations from the circuits described in Section II. The bursts are injected to each oscillator by means of a microwave circulator that couples the output locked signal to a vector signal analyzer (VSA). A photograph of the experimental setup is shown in Fig. 4 and the general characteristics of the bursts are summarized in Table II. There was no impedance-matching network between the oscillator module and the microwave circulator in Fig. 4. A modulation accuracy report was generated for these measurement conditions. The report contains measured parameters such as EVM, magnitude error, phase error, and a constellation diagram. All reported numerical parameters are given as root mean square (rms) values calculated from the constellation diagrams.

The effect of different power levels of the injected signal on the oscillator locked signal measured modulation accuracy parameters was investigated. Fig. 5 shows measured EVM, magnitude error, and phase error for the case of the three different oscillators described in Section II. The carrier frequency of the bursts is set to lock the free-running oscillators at frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz.

For the case of the circuit with the fundamental oscillation frequency of 940 MHz ($V_{\text{Bias}} = 0.92 \, \text{V}$), the free-running power level of $-8 \, \text{dBm}$ was injection locked with bursts power levels varying from $-52$ to $-20 \, \text{dBm}$. The modulation accuracy results in Fig. 5(a) show that the EVM is higher than 5% only when the injected-locking signal power is below $-50 \, \text{dBm}$. This
means that it is possible to achieve a considerable amount of gain (40 dB) while keeping relatively low levels of error within the modulated-locked signal.

Fig. 5(b) shows modulation accuracy results for the oscillator with fundamental frequency of 1.3 GHz ($V_{\text{Bias}} = 0.83 \text{ V}$). The free-running power of the oscillator is $-13 \text{ dBm}$ and can be locked with a signal that is $27 \text{ dB}$ below that level while maintaining an EVM of less than 6%.

Modulation accuracy results for the 3.2-GHz oscillator are shown in Fig. 5(c). The power of the oscillator was $-12 \text{ dBm}$ ($V_{\text{Bias}} = 0.87 \text{ V}$) and the injected power level of $-50 \text{ dBm}$ was able to lock the oscillator with an EVM of less than 7%.

Using Adler’s equation, it was possible to obtain an estimation of the external quality ($Q$) factor of the oscillators after measurements of the injected power level and the locking ranges. For the case of the 940-MHz oscillator, an external $Q$ factor of 20 gives a cold cavity bandwidth of 24 MHz, which is commensurate with the observed frequency locking ranges. External $Q$ factors and locking ranges within the same order of magnitude ($10 < Q < 20$) were obtained for the oscillators operating at 1.3 and 3.2 GHz.

The hybrid circuits implemented for each oscillator module had assembly variations on the position of the shunt capacitor component and wire-bond lengths. A consequence of these variations is a difference on the value of the input impedance of each oscillator module, as well as their external $Q$ factor. The lower gain obtained from injection locking of the 1.3-GHz oscillator can be explained as a consequence of these variations; in other words, the impedance mismatch prevents a more efficient coupling of the injected power to the RTD device. Variations on the external $Q$ factors of the oscillator circuits have also an impact on phase noise performance for each module. In this study, there was no attempt to optimize impedance matching or the $Q$
Fig. 6. Technique used for coupling light into RTD-PD. (a) Micro-photograph of lens fiber and RTD substrate. (b) Schematic representation.

TABLE III

<table>
<thead>
<tr>
<th>TX SYSTEM COMPONENTS OPTICAL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTD-PD/Photodetector</td>
</tr>
<tr>
<td>-----------------------</td>
</tr>
<tr>
<td>Responsivity</td>
</tr>
<tr>
<td>Coupling Losses*</td>
</tr>
<tr>
<td>Spot Diameter</td>
</tr>
<tr>
<td>Working Distance (WD)</td>
</tr>
</tbody>
</table>

* Estimated from the product of the coupling factor reported in [20] and the transmission coefficient calculated from Fresnel equation ($\theta = 45^\circ$).

factors of the oscillators modules. Instead, there was an effort to demonstrate the principle of signal amplification and conversion between optical and wireless domains.

IV. RTD-BASED Tx AND Rx OPERATION

A. RTD Photo-Detector (RTD-PD)

It has been demonstrated in [15] and [17] that an RTD can be optically controlled using a beam of light incident on the active epitaxial structure of the device. In this study, the subcarrier of a modulated optical signal with a wavelength of 1550 nm has been used to injection lock the oscillations of the circuits described in Section II. The RTD works in this format as a PD that has the capacity to convert an optical subcarrier into an enhanced RF signal. The device illustrated in Fig. 2(b) was illuminated with a beam of light that is incident on the plane of the RTD active mesa at an angle of approximately $45^\circ$. The light is coupled to the device by means of a lens fiber, as shown in the illustration of Fig. 6. The optical characteristics of the RTD-PD and the lens fiber used in the setup are shown in Table III.

The experimental setup in Fig. 7 was used to produce the optical subcarriers that injection lock the RF oscillations of the circuits described in Section II. The output RF port of the oscillators was connected directly to an antenna used to broadcast the locked signal. The antenna used was a monopole based on the design in [21] for the cases of the 940- and 1.3-GHz oscillators. A rectangular patch antenna was used for the 3.2-GHz oscillator broadcast. A photograph of the setup in Fig. 8 shows the physical position of the Tx system components.

An optical power of 3 dBm was applied to the lens fiber shown in Fig. 6. A substantial amount of the power is consumed by the coupling losses to the RTD-PD and its limited responsivity. The power absorbed by the RTD-PD, however, was sufficient to injection lock the oscillations of the device used in the setup of Fig. 7. The subcarrier is converted by the RTD to an RF signal with a power level approximately 30 dB below the free oscillating power of the devices. This injected power level has been estimated from Adler’s equation using the external factors obtained in Section III and the measured frequency-locking ranges of the oscillators.

Injected photo-detected power is dependent on the responsivity parameter shown in Table III. However, under oscillation conditions, further amplification of the photo-detected signal takes place around the fundamental oscillation. An estimation of the photo-detected power under this condition was made based on optical control results and the observed locking ranges. The estimated power levels were -35, -40, and -40 dBm for the cases of oscillators working at frequencies of 940 MHz ($V_{bias} = 0.93$ V), 1.3 GHz ($V_{bias} = 0.83$ V), and 3.2 GHz ($V_{bias} = 0.88$ V), respectively.

Phase-modulated signals as those described in Section III were mounted on the subcarrier of the optical beam illuminating the RTD-based oscillators. The output RF locked signal is broadcast through a patch antenna that performs the final step required for the conversion from the optical to the wireless domain. The setup in Fig. 7 was used as the Tx part of the communications link presented in this study and was implemented at a frequency of 940 MHz, 1.3 GHz, and 3.2 GHz. Experimental results of modulation accuracy after signal broadcast...
are presented in Section VI, where demodulation and analysis take place after wireless reception of the GMSK bursts.

**B. RTD and Laser Diode (RTD-LD)**

The Rx part of the communications link was implemented with an RTD-based oscillator, a microwave circulator, an antenna, and a laser diode (LD). It converts the wireless propagated signal back to the optical domain by means of direct bias voltage modulation of an LD. This method was demonstrated in [6] where an RTD-based oscillator was able to modulate an LD in a series configuration. The authors of [8] recommend direct laser modulation as the most cost-effective solution for picocellular transponder operation. The monolithic integration of an RTD and LD is currently under investigation [22] and would allow further circuit area reduction, as well as increased frequencies of operation of the wireless to optical signal converter.

![Experimental setup of Rx RTD-LD, PD, and analyzer used for modulation accuracy measurements.](image)

**Fig. 9.** Experimental setup of Rx RTD-LD, PD, and analyzer used for modulation accuracy measurements.

<table>
<thead>
<tr>
<th>Table IV</th>
<th>InGaAsP LD Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Cavity Type</td>
<td>Fabry-Perot</td>
</tr>
<tr>
<td>Center Wavelength</td>
<td>1550 nm</td>
</tr>
<tr>
<td>Modulation Bandwidth</td>
<td>12 GHz (I_{bias}=30 mA)</td>
</tr>
<tr>
<td>Relative Intensity Noise</td>
<td>-135 dB/Hz</td>
</tr>
<tr>
<td>Slope Efficiency</td>
<td>0.25 mW/mA</td>
</tr>
<tr>
<td>Saturation Power Level</td>
<td>~20 mW</td>
</tr>
</tbody>
</table>

A modulation accuracy report was generated for GMSK signal bursts measured after wireless reception with the setup shown in Fig. 9. The received signal injection locks the RTD oscillator connected to the circulator, which at the same time modulates the LD. EVM, magnitude error, and phase error results are presented in Section VI for carrier frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz.

**C. Transceiver Operation**

The experimental setups for the RTD-PD and RTD-LD circuits in Figs. 8 and 10 were assembled on a laboratory bench and separated by a distance of 75 cm. An illustration of the communications link is shown in Fig. 11 where the optical subcarrier locking the RTD-based oscillator at the Tx is also used to wirelessly lock the RTD oscillator at the Rx. Locking experiments took place at the frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz when the path losses are 29, 32, and 40 dB, respectively. A power amplifier was inserted between the RTD-PD of the Tx and the broadcast antenna in order to compensate for the cases when the path loss reduced the received power level more than 30 dB below the RTD-LD oscillator power.

Simultaneous locking of the RTD-based oscillators in the Tx/Rx was achieved for the case of the three carrier frequencies investigated. The locking was optically controlled from the Tx using the technique explained earlier in this section. An improvement of the phase noise of the oscillators under locking conditions was observed for each case as inferred from the
Fig. 10. Photograph of Rx setup showing: (a) coupling of light from LD using lens fiber, (b) fiber guide micropositioner, (c) LD module, (d) oscillator module, (e) microwave circulator, and (f) Rx antenna (3.2 GHz).

Fig. 11. Experimental setup for simultaneous locking of: (a) Tx and (b) Rx oscillators.

Phase modulation experiments with Tx- and Rx-locked oscillators were performed at frequencies of 940 MHz and 3.2 GHz. However, in order to obtain reliable performance metrics, a set of digital modulation tests were performed in Section V for the Tx and Rx parts of the link.

The transceiver setup illustrated in Fig. 11 does not need a low-noise amplifier stage or a power amplifier stage to operate. Its operating distance $d$ is given by the amount of power required to injection lock the Rx oscillator within a frequency range given by the chosen channel bandwidth. A narrow channel bandwidth requires less locking power, which implies longer transmission distance. A first-order estimation of the maximum $d$ under these conditions can be calculated from Adler’s equation after consideration of the free-space path loss

$$d_{\text{max}} = \frac{c}{4\pi\Delta f Q_{\text{ext}}}$$

where $\Delta f$ is the required locking range, $Q_{\text{ext}}$ is the external quality factor of the Rx oscillator, and $c$ is the speed of light. The assumption was made that the power of the Tx and Rx oscillators is the same, the interconnections between the hybrid circuits are lossless, and the antennas have a gain of 0 dB. A required channel bandwidth of $\Delta f = 500$ kHz with $Q_{\text{ext}} = 20$ gives a calculated maximum distance $d_{\text{max}} = 2.4$ m.

V. MODULATION ACCURACY RESULTS

The RTD-PD (Tx) and RTD-LD (Rx) circuits illustrated in Figs. 7 and 9 were tested independently to generate a modulation accuracy report after converting signals between the optical and wireless domains. For the case of the RTD-PD, the GMSK signal described in Section II was used to optically control the device while the signal was broadcast and monitored by a VSA. An antenna placed 75 cm away from the circuit was used to receive the signal and couple its power to the VSA. A plot of the transmitted locked signal spectrum is shown in Fig. 13 for the three different cases of RTD-PD circuits working at the frequencies of 940 MHz, 1.3 GHz, and 3.2 GHz. It is possible to observe in the GMSK spectrum that a higher level of noise is present for the RTD-PD oscillator working at 1.3 GHz. A noisier oscillator with a lower external $Q$ factor could explain degradation of the modulation accuracy performance seen earlier in Fig. 5(b) at this frequency. The spectral plots in Fig. 13 are averages of 200 traces measured by the VSA.
Fig. 13. Measured spectrum of GMSK signal after conversion from RTD-PD Tx.

Fig. 14. GMSK constellation diagrams measured for Tx circuits at frequencies of: (a) 940 MHz, (b) 1.3 GHz, and (c) 3.2 GHz.

Fig. 15. Measured spectrum of GMSK signal after conversion from RTD-LD Rx.

Fig. 16. GMSK constellation diagrams measured for Rx circuits at frequencies of: (a) 940 MHz, (b) 1.3 GHz, and (c) 3.2 GHz.

TABLE V

<table>
<thead>
<tr>
<th>Link Frequency</th>
<th>940 MHz</th>
<th>1.3 GHz</th>
<th>3.2 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>Tx</td>
<td>Rx*</td>
<td>Tx</td>
</tr>
<tr>
<td>EVM (%)</td>
<td>7.8</td>
<td>1.9</td>
<td>8.1</td>
</tr>
<tr>
<td>Magnitude error (%)</td>
<td>0.5</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Phase error (°)</td>
<td>4.5</td>
<td>0.9</td>
<td>4.6</td>
</tr>
</tbody>
</table>

* Tx stands for RTD-PD circuit. Rx stands for RTD-LD circuit
* Measured at the output of gain amplifier stage after photo-detection

Constellation diagrams obtained after signal demodulation are shown in Fig. 14 and the calculated modulation accuracy metrics are shown in Table V. The RTD-PD (Tx) circuits show EVM values below 10% and phase errors below 5° for the three measured carrier frequencies. These results are consistent with the parameters reported earlier in Fig. 5.

A vector signal generator (VSG) and an antenna were used to broadcast GMSK bursts 75 cm away from the RTD-LD (Rx) circuit shown in Fig. 9. The power level of the transmission was set to replicate the power level generated by the RTD-PD circuit while locking the Rx RTD-LD oscillator. Under these conditions, the modulated LD output in Fig. 9 was photo-detected for vector signal analysis.

Fig. 15 shows the measured GMSK spectrum of the photo-detected locked signal output from the RTD-LD (Rx) circuit. The higher noise level observed at carrier frequencies of 940 MHz and 3.2 GHz is a direct consequence of including an additional amplifier stage after photo-detection. The amplifier was used to increase the SNR and facilitate demodulation by the VSA. The gain of the amplifier stage was 30 dB at 940 MHz, and 15 dB at 3.2 GHz.

The use of the amplifier stage for the cases illustrated in Table V can be justified as compensation for impedance mismatch at the input of the LD module at frequencies of 940 MHz and 3.2 GHz. The mismatch reduces the modulation depth of the LD optical output and the SNR of the received signal. The amplifier also compensates for variations on the coupling losses between the LD and the lens fiber used in the Rx system.

Measured constellation diagrams of the RTD-LD (Rx) circuits are shown in Fig. 16 and modulation accuracy results are shown in Table V. EVM values below 10.5% and phase error values below 6° were reported for the three different frequencies investigated in this work with the measurement conditions described in this section.

VI. RTD MILLIMETER-WAVE RELAXATION OSCILLATORS

An example of RTD-based V-band relaxation oscillator design has been demonstrated in [23] where the authors presented a monolithic version of a circuit operating at a frequency of 50 GHz. Their results did not include measurements on the effect of bias voltage over the fundamental oscillation frequency and the tuning range. However, based on the observed experimental tuning ranges of the microwave oscillators shown in Fig. 3(b) (19%) and Fig. 3(c) (15%), it is possible to argue that a modified, scaled, and monolithic design with adjusted global
parameters $I$ and $C$ can be optimized to cover the full frequency range required for V-band applications. The work in [24] demonstrated that it is possible to increase tunability of an RTD-based $K$-band voltage controlled oscillator up to 10% of the carrier frequency using varactors within the circuit topology.

In this section, the electrical model proposed in [6] is used to calculate the tuning frequency range of an RTD relaxation oscillator whose dimensions have been scaled down by a ratio of 20 according to the dimensions of a circuit operating at V-band. Fig. 1 showed the $I$–$V$ characteristics of the RTDs used in this study, as well as the fitted physics-based model used in [6]. A device consistent with the current density (500 kA/cm$^2$) of the work in [23] was used to obtain the numerical solution of the model in [6]. The adjusted global parameters used in the calculations were $I_c = 0.4$ nA, $C = 15$ fF, and $R = 10$ Ω, which resulted in the oscillator frequency tuning ranges and relative peak-valley power variation shown in Fig. 17.

The numerical results show that it is possible to cover the whole 56.5–62-GHz license-free industrial, scientific, and medical band for RTD oscillator biasing conditions within the NDR region. The electrical model at present can only give a relative measure of the fundamental oscillation power variations obtained from different bias points within the NDR region, with absolute power levels expected from $-20$ to $-30$ dBm. A solution to the problem of low power levels at millimeter-wave frequencies would be the implementation of power-combining arrays and structures as those previously reported in [25] and [26].

VII. CONCLUSIONS

In this study, the feasibility of an RoF communications link based on RTD optoelectronic circuits has been demonstrated for three different carrier frequencies. The link works under the principle of injection locking to photo-detected signals in the Tx (RTD-PD) and injection locking to wireless signals in the Rx (RTD-LD). A single GSM channel was used to test modulation accuracy of the transmitted signal in each part of the link. The results showed that it is possible to obtain phase error values that are below the $5^\circ$ rms limit required by a stringent standard such as E-GSM900 [27]. The RTD-PD and RTD-LD circuits provide gain and convert the injected signals between optical and wireless domains while reducing circuit cost and complexity. Monolithic integration of RTDs and lasers is under way [22] and implementation of RTD-based oscillators and PDs at $V$-band frequencies would allow fabrication of single package transceivers designed for deployment of radio access points within femto and picocellular networks.

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