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# Optoelectronic Oscillators for Communication Systems

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**Abstract.** We introduce and report recent developments on a novel five port optoelectronic voltage controlled oscillator consisting of a resonant tunneling diode (RTD) optical-waveguide integrated with a laser diode. The RTD-based optoelectronic oscillator (OEO) has both optical and electrical input and output ports, with the fifth port allowing voltage control. The RTD-OEO locks to reference radio-frequency (RF) sources by either optical or electrical injection locking techniques allowing remote synchronization, eliminating the need of impedance matching between traditional RF oscillators. RTD-OEO functions include generation, amplification and distribution of RF carriers, clock recovery, carrier recovery, modulation and demodulation and frequency synthesis. Self-injection locking operation modes, where small portions of the output electrical/optical signals are fed back into the electrical/optical input ports, are also proposed. The self-phase locked loop configuration can give rise to low-noise high-stable oscillations, not limited by the RF source performance and with no need of external optoelectronic conversion.

**Keywords:** optoelectronic oscillators, resonant tunneling diodes, laser diodes, optical waveguides.

## 1 Introduction

Photonic radio-frequency (RF) systems use optical waves as carriers to transport RF signals through optical fibers to remote locations, taking the advantages of optical fibers low loss, light weight, high capacity, high security and immunity to electromagnetic interference [1]. This technology is beginning to be used in local access networks to provide private users ultra-wideband digital communications. Since optoelectronic oscillators (OEOs) can significantly simplify and augment the capacity of photonic RF systems they have attracted great attention in recent years. Their high-frequency and ultra-pure microwave signal generation capabilities allow the development of high-capacity photonic RF communication systems such as radio-over-fiber networks [2].

Here we introduce and discuss the operation modes of an innovative OEO circuit based on the integration of a resonant tunnelling diode (RTD) embedded within a semiconductor optical waveguide (RTD-OW), containing a photo-detecting region, with a laser diode (LD). The RTD-OEO is capable to produce both RF and optical signals modulated at microwave frequencies, and opto-electronic/electro-optic

conversion with potential applications on signal processing and communication systems such as radio-over-fiber networks [3]. The combination of a RTD-OW and a LD [4,5] gives rise to a new kind of five port OEO configuration that incorporates both electrical and optical input and output ports, and whose dynamics can be controlled by either electrical or optical injected signals.

This paper is organized as follows. Section 2 summarizes the contribution of this paper to the technology innovation by presenting the state of the art in optoelectronic oscillators for communication systems and introducing the RTD-OEO concept, by discussing its operation principle, configuration schemes and potential applications in photonic radio-frequency systems. Section 3 reports on recent progresses in the RTD-based transmitter and RTD-based receiver circuits. The conclusions and future work are presented in section 4.

## 2 Contribution to Technology Innovation

Generating pure high-frequency RF signals using simple, efficient, low-phase noise and low cost oscillators are being considered as the major requirements for next generation photonic RF communication systems. Since RF resonator-based oscillator technology can not match all advantages of photonic systems, there has been a great search of OEO configurations capable to generate ultra-pure RF carriers in both electrical and optical domains. Several OEO systems have been proposed over the last few years, including photonic oscillators based on InP monolithic oscillators [8], or using direct modulated semiconductor lasers and optical/optoelectronic injection schemes [9]. However, these configurations either are too complex or do not meet all the photonic RF systems OEO requirements.

An ideal OEO should involve the generation of ultra-pure RF signals in both electrical and optical domains with its operation being controlled by both electrical and optical injected signals. An OEO configuration that close match these requirements, capable to produce ultra-pure microwave signals, was proposed by Yao et al. [10]. However, such configuration is quite complex, containing an optical fiber delay line several kilometers long, a wide-band Mach-Zehnder (MZ) modulator to modulate non-linearly a semiconductor laser continuous-wave coherent light beam, a pre-amplified photodiode, a narrow microwave RF filter and a microwave amplifier.

The main contribution of this paper to the technology innovation is the proposal of a novel five ports OEO based on the integration of RTDs with optical waveguides and laser diodes. Since monolithic integration of an RTD with a laser diode was already demonstrated [4], we foresee the monolithic integration of the RTD-OW with a laser diode will lead to a major breakthrough, increasing the potential of the hybrid RTD-OEO as a reliable monolithic integrated optoelectronic oscillator. Our work points towards the demonstration of a full monolithic RTD-OEO by the end of the associated PhD program. Next, we present RTD-OEO concept, describing its operation principle and analyzing two self-phase locking configurations.

2.1 Novel Optoelectronic Oscillators for Photonic RF Systems

Resonant tunnelling diodes (RTDs) are nanoelectronic semiconductor structures with wide bandwidth negative differential conductance (NDC) region capable of producing electrical oscillations up to 831 GHz [6], which make them the fastest purely electronic devices operating at room temperature. When integrated within optoelectronic devices, such as optical waveguides and laser diodes, they can enhance the devices optoelectronic characteristics by reducing power consumption and offering significant improvements in the modulation/detection performance and functionality since they can operate as optical modulators and photo-detectors with built-in electrical amplifiers [4,5,7]. With especially interest are the recently demonstrated optoelectronic voltage controlled oscillators and optical controlled RF oscillators based on the hybrid integration of an RTD with a laser diode (RTD-LD) and an RTD with a semiconductor photo-conductive region, respectively [3].

The RTD-OEO proposed here combines the RTD-LD emission and RTD-OW photo-detection functionalities, see [3], in a single circuit leading to a five port circuit with both optical and electrical input and output ports, where the fifth port allows the voltage control of the electro-optical oscillations. Since the RTD-OEO emulates the RTD wideband NDC region, high frequency oscillations and generation of stable low-phase noise electrical and optical signals are expected, with both being controllable by electrical or optical injection signals. Figure 1 shows a typical RTD-OEO configuration.

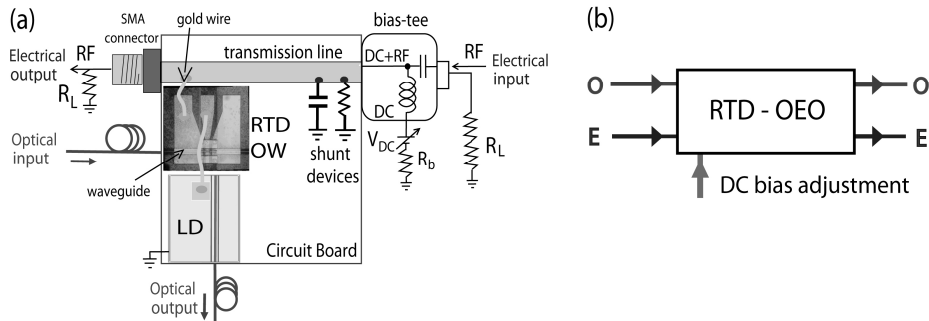


Fig. 1. RTD-OEO circuit schematics (not scaled). (a) RTD-OW connected in series with a laser diode with both electrical (E) and optical (O) output- and input-ports. (b) RTD-OEO diagram showing electrical and optical input and output ports plus the DC bias control port.

The schematic of Fig. 1(a) includes a shunt capacitor-resistor placed physically close and in parallel with RTD-OW and LD series connection to provide the appropriate resonant conditions for RTD operation as a microwave relaxation oscillator, with the relaxation frequency controlled by DC voltage. The RTD-OW photo-detection capability provides the circuit optical input port, allowing optical-to-electrical conversion. The laser diode acts as the circuit optical output port, which in combination with electrical input port allows electrical-to-optical conversion, Fig. 1(a). The diagram of Fig. 1(b) summarizes the five port functions. The electrical and

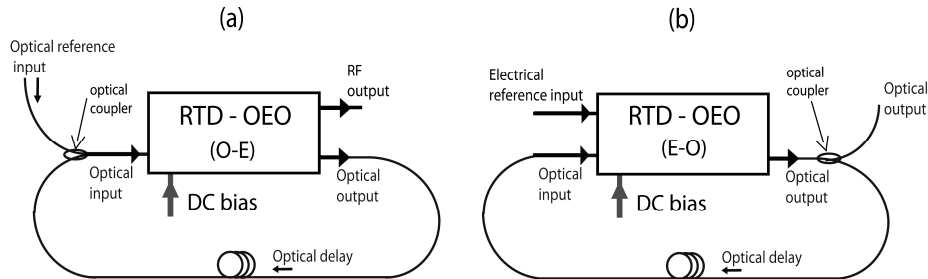
optical input ports act as injection ports to lock, optically or electrically, the OEO to reference sources. For detailed information on the RTD and LD, see [3] and [7].

This five port RTD based OEO circuit eliminates the need of discrete components such as RF amplifiers, RF couplers and filters, and corresponds to a significant simplification when compared to previously reported optoelectronic oscillators [8,9,12]. The RTD-OEO circuit proposed here aims to fulfill the needs of photonic RF systems and is much simpler and flexible due to RTD-OW optoelectronic nonlinearities and the RTD wide bandwidth negative differential conductance (NDC) characteristic. Since the wide-bandwidth NDC provides wide bandwidth electronic gain the RTD-OEO incorporates an intrinsically built-in RF amplification, which combined with the waveguide modulation/photo-detection and the laser diode emission capabilities, allows the implementation of low power consumption, high-frequency electrical and optical signal generators whose operation is controllable by both RF and optical injected signals. Moreover, its oscillation frequency can be tunable by a DC bias voltage.

## 2.2 RTD-OEO Self-Phase Locking Operation

The RTD-OEO operates as follows. Without external perturbation, biasing the RTD-OEO in the RTD-OW negative differential conductance region generates current relaxation oscillations that drive the laser diode connected in series to the RTD-OW, which modulates the laser optical carrier. As mentioned, the oscillation frequency is controllable by the RTD-OW dc bias voltage, making the circuit to act as an optoelectronic voltage controlled oscillator (OVCO) [3,5]. This operation mode can be used to frequency synthesis and clock generation in both electrical and optical domains. When working in the OVCO mode, injecting a modulated optical signal in the photoconductive region of the RTD-OW the RTD-OEO current relaxation oscillations lock to the optical RF sub-carrier leading to simultaneously to optical-to-electrical conversion and to optical-to-optical modulation. In the presence of an external RF signal the relaxation oscillations can lock to the injected RF signal giving rise to electrical-to-optical conversion and to electrical-to-electrical modulation.

Optical and electrical injection locking provides a simple way of synchronizing and stabilizing optoelectronic oscillators but requires low-noise and high-stable RF sources. To overcome this limitation we propose an OEO self-phase locked loop configuration using the optical waveguide input port of the RTD-OEO, Fig. 2. The schemes include optical-to-electrical conversion, Fig. 2(a), and electrical-to-optical conversion, Fig. 2(b), based on a self-injection locking loop implemented with either an optical fiber or an optical waveguide loop. The optical self-injection forces the oscillator to be locked with its past, since a delayed replica of the RTD-OEO optical output is injected back to the oscillator reducing substantially fluctuations and eliminating the need of high-stable RF sources. The frequency stability is expected to be proportional to the length of the delay line. Also, a larger optical power injection will produce more phase noise reduction.



**Fig. 2.** Self-phase locking in (a) optical-to-electrical (O-E) and (b) electrical-to-optical (E-O) schemes. In both cases the optical delay also controls the RTD-OEO providing low-noise E/O conversions.

Because of configuration simplicity and flexibility the RTD-OEO is expected to find applications over a wide range of photonic and RF systems such as for time-frequency metrology, for the next generation of high-precision radar/sensors where extreme purity for reference microwave is crucial, to produce ultra-low jitter optical pulses at high bit rates (>10 GHz), to generate multi-wavelength and synchronized optical pulses, and to perform clock recovery, carrier recovery, signal modulation and demodulation, photonic signal up/down conversion, and distribute low-phase noise and high-stable RF carriers in communication links [13].

Next we present and discuss the recent results on the two main blocks of the RTD-OEO, specifically the electro-optical and the opto-electrical conversions.

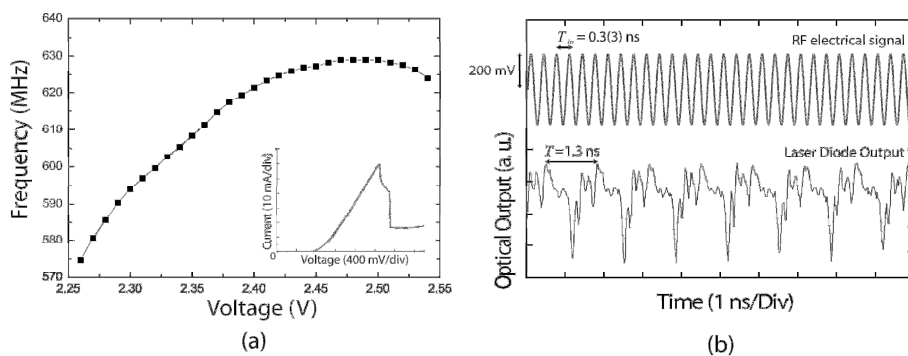
### 3 RTD-OEO Modes of Operation Results and Discussion

In this section we describe the main results on RTD-OEO operation as optoelectronic voltage controlled oscillator, photo-detector, electrical/optical converter, and chaotic generator.

#### 3.1 RTD-OEO Electro-Optical Conversion

When operated in the negative differential conductance region the RTD-OEO produces current relaxation oscillations that modulate the laser diode optical output, providing a simple way of producing optical sub-carriers with the relaxation oscillation frequency. Typical performance of implemented RTD-OEO biased in the RTD negative differential conductance region is shown in Fig. 3. Figure 3(a) shows RTD-OEO functioning as an optoelectronic voltage controlled oscillator (OVCO), with the oscillation frequency being tuned by the dc bias voltage. The photo-detected optical output power level remains practically unchanged over the entire tuning range. This mode of operation provides a simple way to tune optoelectronic oscillation frequency with high sensitivity when compared with other proposed voltage controlled oscillators [10].

The RTD-OEO can be locked by either optical or electrical signals. Injection locking due to an RF reference signal feed into the electrical port are presented in Fig. 3(b) [3,11]. In the presence of the RF injected carrier the RTD oscillator synchronizes either to the fundamental or harmonic frequencies modulating the laser diode. Figure 3(b) shows electrical-to-optical injection locking when the oscillator is locked to the 4<sup>th</sup> harmonic of RTD self-oscillations. The laser diode output is frequency modulated at  $\frac{1}{4}$  of the injected signal (3 GHz frequency), corresponding to frequency division operation by 4 [5]. The frequency locking is controlled by tuning both the bias voltage and power of the injected signal.



**Fig. 3.** (a) Optoelectronic voltage controlled oscillator. (b) Electro-optical conversion: injection locking at around 0.75 GHz measured in the laser output when a 3 GHz RF signal is injected in the RTD-OEO electrical input port.

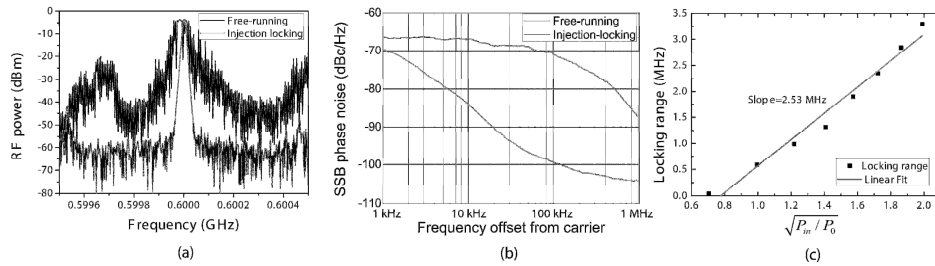
Under appropriate operating conditions, the strong nonlinearity of the RTD-OEO can produce aperiodic or chaotic signals as a result of frequency mixing between free-running relaxation oscillations and external RF signal [3,14]. In this regime the oscillator is not locked to the injected RF input (the injected frequency is outside the locking range). This behavior has interesting applications in optical chaos communications (see [14] and references therein).

### 3.2 RTD-OEO Opto-Electrical Conversion

The RTD optical waveguide contains a photo-conductive region that is used to extract the RF-subcarrier from a modulated optical signal. When the RTD-OEO is DC biased in the NDC region, the presence of a modulated optical signal reduces the device's series resistance due to inter-band absorption and gives rise to current oscillations that emulates the RF signal that was used to modulate the incident optical beam. In this mode of operation we measured responsivity-gain up to 10 dB at 1550 nm [3,11].

Taking advantage of the photo-detection capabilities, the RTD-OEO can be remotely synchronized with an injected optical signal. Typical optical injection locking is presented in Fig. 4. Figure 4(a) shows the spectra corresponding to free running oscillation and optical injection locking. When the reference optical subcarrier signal is injected with a maximum single-side-band (SSB) noise of -120

dBc/Hz, the SSB measurements show a phase noise reduction of ~30 dB at 100 kHz carrier offset, Fig. 4(b). The phase noise reduction value approaches the phase noise of the reference source by increasing either the optical power or the modulation amplitude. The locking range as a function of injection power is shown in Fig. 4(c). The results shows that as the injection power decreases the locking range also decreases and the phase noise increases. Because the RF power of the free-running oscillator remains the same, this means the gain is effectively increased.



**Fig. 4.** (a) RTD-OEO free-running oscillation and locking to an 8 mW continuous wave optical signal modulated by an RF signal with 0.6 GHz and 500 mV amplitude. (b) Single Side Band phase noise measurements as function of the frequency offset. (c) Locking range as a function of the square root of the injection RF power  $P_{in}$ .

#### 4 Conclusions and Future Work

In conclusion, we have proposed an innovative optoelectronic oscillator circuit based on the integration of a resonant tunnelling diode optical waveguide (RTD-OW) with a laser diode, the RTD-OEO. The RTD-OEO is a versatile and simple optoelectronic oscillator for microwave-photonic system applications because can be used for injection-locking, up-conversion, and down-conversion of both electrical and optical reference signals, and to produce RF and chaotic signals. Future work includes the monolithic integration of an RTD oscillator and a photo-conductive region with a laser diode, instead of using separated laser and RTD chips. This configuration could have applications in single chip OEO solutions for high-speed fiber-optic communication systems.

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