Published in final edited form as:
IEEE Photonics Technol Lett. 2011 August 15; 23(16): 1148–1150. doi:10.1109/LPT.2011.2154320.

A Self-Synchronized Optoelectronic Oscillator based on an RTD Photo-Detector and a Laser Diode

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Abstract

We propose and demonstrate a simple and stable low-phase noise optoelectronic oscillator (OEO) that uses a laser diode, an optical fiber delay line and a resonant tunneling diode (RTD) free-running oscillator that is monolithic integrated with a waveguide photo-detector. The RTD-OEO exhibits single-side band phase noise power below −100 dBc/Hz with more than 30 dB noise suppression at 10 kHz from the center free-running frequency for fiber loop lengths around 1.2 km. The oscillator power consumption is below 0.55 W, and can be controlled either by the injected optical power or the fiber delay line. The RTD-OEO stability is achieved without using other high-speed optical/optoelectronic components and amplification.

Keywords

Delay line; laser diode; optoelectronic oscillator (OEO); photo-detector; resonant tunneling diodes

I. Introduction

Optoelectronic oscillators (OEO) combine electronic and photonic components to achieve high-purity microwave signals. They have interesting applications in optical communication links and precise test and measurement equipments [1]. Self-injection locking of OEOs generate low-phase noise microwave signals in both electrical and optical domains, without requiring highly-stable external RF sources, by injecting a part of the output signal into the oscillator through a high-quality (Q) or low loss energy storage element [1]-[4]. Several configurations have been reported to generate spectrally pure microwave signals using direct and external modulation of semiconductor lasers together with optical/optoelectronic injection schemes using an optical feedback route. Compact OEO realization has been recently reported using heterojunction phototransistors (HPT) as electrical free-running

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oscillators [2]. These implementations however require RF amplifiers and erbium doped fiber amplifiers (EDFA), which are usually the major noise contributing elements [1]-[4], increasing as well the OEO package size and power consumption.

In this work, we demonstrate the feasibility of using resonant tunneling diode (RTD) free-running oscillators for low powered optoelectronic oscillator systems that considerably simplifies the typical OEO configurations [1]-[4]. RTD-based oscillators are simple circuits that take advantage of RTD's negative differential resistance (NDR) current-voltage ($I - V$) characteristic. The NDR provides wide bandwidth electronic gain to the circuit and within an appropriate resonant circuit it can induce self-oscillations at very high-frequency [5]. Furthermore, RTD-based oscillators provide low noise levels [6], with single-side band (SSB) noise power density as low as −86 dBc/Hz at 100 kHz offset from the free-running frequency being reported [7], which compares with the lowest noise levels for other analogous electronic free-running oscillators reported recently in [2], [4]. In order to obtain further improvement in the phase-noise of free-running oscillations, external injection locking techniques are usually employed [8], [9].

In this letter, we demonstrate a stable and low-phase noise self-synchronized free-running OEO based on a RTD-photodetector (RTD-PD) driving a laser diode (LD) where a fraction of the modulated LD light output is re-injected into the oscillator through the RTD-PD waveguide optical input using a fiber optic delay line that further reduces the phase-noise of the oscillations. The RTD-OEO, Fig. 1, obviates the need for low-noise and stable external RF amplifiers and microwave filters usually required to compensate electrical-optical (E/O) and optical-electrical (O/E) conversion losses and frequency mode selection [1]-[4], respectively. By eliminating the RF and EDFA amplifiers from our OEO, we remove the major noise contributing elements of typical OEOs [1]-[4]. The RTD-OEO has a low power requirement compared to previous OEOs and no high-speed high-cost extra components such as photo-detectors or modulators are used in our configuration.

II. Self-Synchronized RTD-OEO Setup

The self-injection locking is realized in a closed loop OEO configuration consisting of a single mode optical fiber-roll that acts as a delay-line, a double barrier quantum well (DBQW) RTD monolithic waveguide photo-detector oscillator, and a commercial laser diode on a 10 Gb/s high-speed submount, with both RTD-PD and LD hybrid integrated on a printed circuit board-transmission line layout. The RTD-PD with 0.5×0.4 mm^2 chip size [9], Fig. 1(a), provided O/E conversion with ~0.28 A/W efficiency at 1.55 μm when DC biased around 2.4 V, close to the valley region, Fig. 1(b). The E/O conversion was achieved by direct modulation of the laser diode operating around 1.55 μm with ~0.25 W/A efficiency.

Figure 1(c) shows the RTD-OEO self-synchronization schematic setup. The RTD-OEO is an optoelectronic voltage controlled oscillator (OVCO), e.g., the free-running frequency of the RTD-PD-LD oscillator is controlled by adjusting the DC bias voltage. It works as follows: when the RTD-PD-LD is biased in the NDR region, Fig. 1(b), electrical free-running current oscillations build-up, directly modulatig the LD. The LD optical modulated output is then decoupled using a lensed single mode fiber (SMF), sent through an optical fiber delay line, and finally re-injected into the RTD-PD waveguide using a similar lensed SMF. The optical re-injection induces self-injection locking of RTD free-running oscillations. The operation frequency of the RTD-OEO is essentially determined by the RTD-PD parallel capacitance and the series equivalent inductance of the wire bonding used to connect the RTD-PD to the LD (the wire length was ~3-4 mm, giving an equivalent inductance around 3.6 nH), which for the circuit reported here gives an operation frequency up to ~1.4 GHz. Using an

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appropriate circuit configuration, we estimate the RTD-PD oscillators used in this experiment could operate up to ~14 GHz. Since the LD used has a cut-off frequency of 11 GHz, the LD is the device that can limit the upper frequency of our OEO circuit for layouts that significantly reduce the series inductance. Our arrangement is a simple configuration not requiring external amplification. For operation at frequencies above the maximum achievable laser operating frequencies (>30 GHz), one can replace the laser by an RTD electroabsorption modulator (EAM) [10], or other external modulator devices [11].

The utilization of fiber-rolls with different lengths provided an easy way of changing the optical feedback route of the RTD-OEO. With this simple feedback route configuration we obtained an RTD-OEO having both electrical and optical input and output ports, with the RTD-OEO frequency and phase-noise fluctuations substantially reduced after passing the high-Q optical delay line. In what follows, we present and discuss the self-synchronization results showing stable frequency and low-phase noise signals.

III. Experimental Results and Discussion

Without optical re-injection, the RTD-PD-LD circuit reported here oscillates with a free-running frequency tunable from 1.05 to 1.41 GHz, depending on DC bias voltage. When the RTD-PD-LD is DC biased close to the valley region, ~2.4 V, produces electrical and optical modulated free-running oscillations at around 1.4052 GHz [shown inset of Fig. 1(c)] with power consumption of 0.55 W. The power consumption can also be further reduced below 0.1 W inserting a capacitor in series with the shunt resistor shown in Fig. 1(c). Figure 2(a) presents the free-running oscillation spectrum trace, showing the typical broad spectrum caused by the frequency oscillation fluctuations. The electrical power produced is determined by RTD circuit and $I - V$ characteristic. Although the output power reported here was around −14 dBm, output powers more than 10 dB higher were already demonstrated using similar RTD-PD oscillators [8].

In Figs. 2(b), (c) and (d) we present the self-synchronized free-running oscillations produced for three fiber-roll lengths, L, of 0.814 km, 1.219 km, and 1.624 km, respectively. The average in-fiber optical power was $P \sim 5$ dBm. Also shown inset on top of each figure is the spectrum surveillance screening the plot density spectrum. The results clearly show the self-injection enhances the signal quality, improving considerable the frequency stability with a substantially phase noise reduction. The phase-noise can be enhanced by increasing either the optical loop length or the in-fiber optical power. It is worth mentioning that the results presented here are limited by the responsivity of the RTD-PD used in the experiment, and can be further improved using anti-reflection coating facets and maximizing waveguide light coupling efficiency, which for the devices employed is estimated to be around 0.2. The side modes presented in Figs. 2(b) to 2(d) are separated from the center frequency by about 215 kHz, 154 kHz, and 120 kHz, respectively. These are the mode spacing of the free spectral range (FSR) of the RTD-OEO and are related to the re-injected signal time delay τ_d, which in our case depends on the electrical time delay τ_e, introduced by the electrical components, and the optical time delay τ_{op}, mainly due to optical fiber length. For our feedback route the optical time delay τ_d is much larger than the electrical time delay τ_e:

$$FSR = \frac{1}{\tau_e + \tau_{op}} \simeq \frac{1}{\tau_{op}} \simeq \frac{c}{n_F L} \quad (1)$$

where $\tau_{op} = n_F L/c$, with n_F being the optical fiber effective refractive index and c the velocity of light: that is, the RTD-OEO mode spacing is determined by the fiber length. We estimate from Eq. (1) the following FSR values: L = 0.814 km, FSR = 251 kHz; L = 1.219 km, FSR = 167.6 kHz; L = 1.624 km, FSR = 125.8 kHz, which compares with the

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experimental values for lengths above 1-km presented in Figs. 2(c) and 2(d). The results of Figs. 2(b)-(d) demonstrate RTD-OEO single mode suppression ratio (SMSR) of 38 dB, 36 dB and 32 dB, respectively. Additional techniques can be implemented to completely suppress the unwanted side modes, using for example a multi-loop fiber configuration [12].

In order to verify phase-noise reduction performance, SSB phase noises of output signals were measured and shown in Fig. 3. In the self-synchronized mode the SSB phase noise at 10 kHz offset from the center frequency was substantially reduced with the increase of the injection power and also the fiber delay, as shown in Fig. 3(a). For an in-fiber optical power of $P \sim 8.6$ dBm and optical fiber lengths of 0.814 km and 1.219 km, the corresponding self-injection locked phase noise values were −100.1 dBc/Hz and −101.8 dBc/Hz, respectively, as shown in Fig. 3(b). A phase noise reduction more than 30 dB at 10 kHz offset was achieved when compared to the free-running oscillations without light re-injection, Fig. 3(b).

The results clearly show the self-synchronization enhances the phase quality of free-running output signals. Although in terms of phase noise the RTD-OEO is still below commercial available voltage-controlled modules, such as coaxial resonator based oscillators (CRO) operating at the same range of frequencies that typically show phase noise values around −120 dBc/Hz at 10 kHz offset, it is expected that further techniques including temperature an vibration control can have a great impact in the OEO performance. Furthermore, there is still considerable scope for optimization in many aspects of our OEO configuration including complete monolithic integration of the RTD-PD with LD, plus high-Q feedback route. A comparison of recently reported OEOs based in fiber-looped configurations is presented in Table I showing the most relevant characteristics of an OEO. The system presented here is simpler, providing an OEO configuration without the need of extra RF or optical amplification.

IV. Conclusion

We have demonstrated a simple optoelectronic self-synchronized oscillator that is based on the integration of a resonant tunneling diode photo-detector for O/E conversion, a laser diode for E/O conversion, and an optical fiber delay line to achieve phase noise reduction. With this configuration we achieved stable free-running self-locked oscillations with a phase-noise reduction more than 30 dB at 10 kHz frequency offset from the center free-running frequency for optical fiber lengths around 1.2 km, without the need of RF or optical amplification. The RTD-OEO is a simple and low powered OEO with applications in RF photonic systems such as distribution of highly-stable RF carriers in communication links [11].

Acknowledgments

This work was supported in part by the Fundação para a Ciência e Tecnologia (FCT), Portugal, project grant PTDC/EEA-TEL/100755/2008. B. Romeira was supported by FCT PhD grant SFRH/BD/43433/2008 and by Fundação Calouste Gulbenkian, Programa Estímulo à Criatividade e à Qualidade na Actividade de Investigação, 2009.

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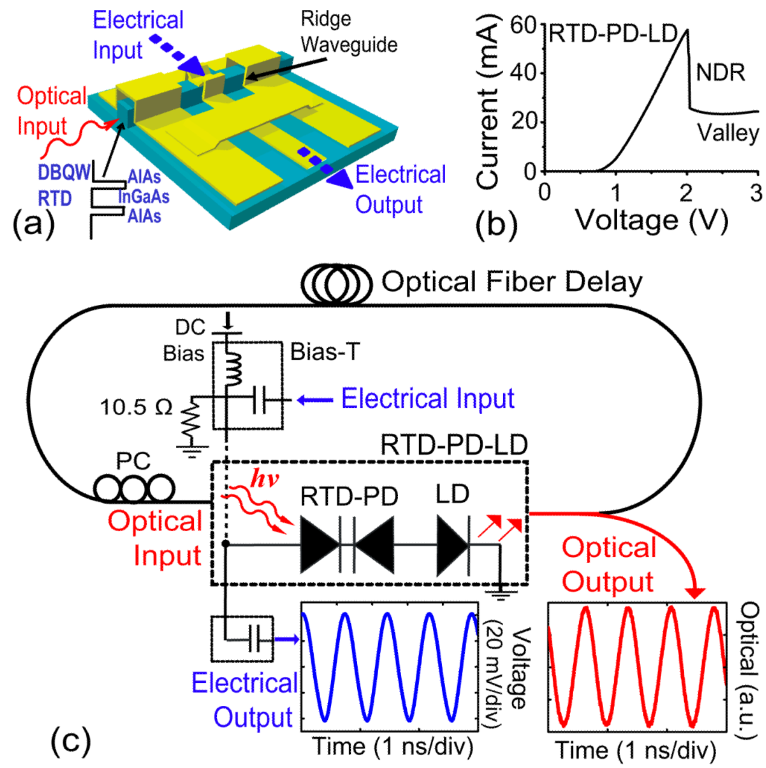

Fig. 1.

(a) RTD-PD monolithic integrated chip. (b) $I-V$ characteristic of the RTD-PD device in series with the LD showing the NDR region. (c) Schematic of the self-synchronized RTD-OEO setup.

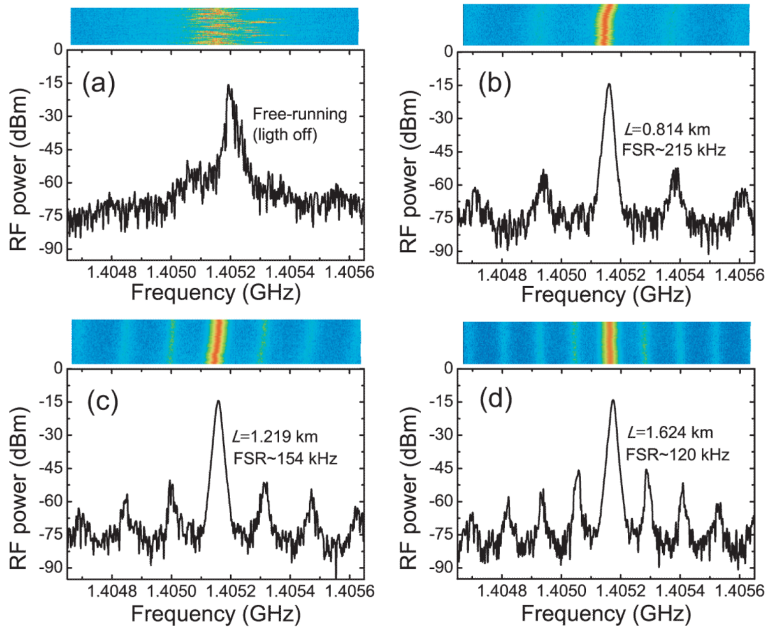

Fig. 2.

RF power spectrum traces of the RTD-OEO output. (a) Free-running. Self-synchronization at $P \sim 5$ dBm using fiber loops of (b) $L = 0.814$ km (c) $L = 1.219$ km (d) $L = 1.624$ km. The frequency span and resolution bandwidth settings of all figures were 1 MHz and 10 kHz, respectively. The top part of each figure shows a spectrogram that represents the evolution of spectral density recorded over ~30 s.

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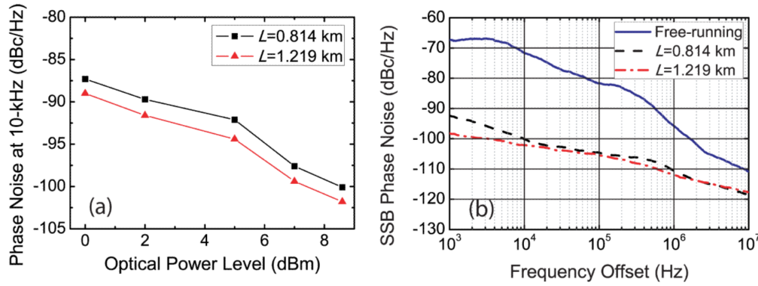

Fig. 3.

(a) RTD-OEO SSB phase noise at 10 kHz as a function of in-fiber optical power for L = 0.814 km and L = 1.219 km. (b) Measured SSB phase noises for $P \sim$ 8.6 dBm and free-running oscillation.

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TABLE I

A COMPARISON OF RECENTLY REPORTED OEOS.

Parameter	RTD	VCSEL [3]	HPT [2]	HPT [4]
Frequency (GHz)	1.40515	2.49	10.79	9.6
Power output (dBm)	−14	18	−11	−2
Fiber-loop length (km)	1.219	1.0	2.4	3
Phase noise @ 10 kHz (dBc/Hz)	−101.8	−107.57	−100	−114
FSR (kHz)	154	180	84	68
SMSR (dB)	36	53	35	43
RF/EDFA amplifier	No	Yes	Yes	Yes
Optical/RF filter	No	Yes	Yes	Yes