

An Optoelectronic Oscillator based on a Resonant Tunneling Diode Photo-Detector Integrated Chip

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Abstract—We present a low-phase noise microwave oscillator based on a version of an optical fiber optoelectronic oscillator that employs self-injection of a resonant tunneling diode oscillator, integrated with a photo-detector, that drives a laser diode.

I. INTRODUCTION

MICROWAVE oscillators capable of generating pure high-frequency RF signals using low-phase noise and low cost optoelectronic oscillators (OEO) have been proposed for communication links and precise test and measurement equipment [1]. There has been a great deal of research on OEO configurations capable of generating pure RF carriers in both electrical and optical domains including direct modulated semiconductor lasers and optical and optoelectronic injection schemes [1,2], or using photonic oscillators based on InP HBT monolithic oscillators [3]. The disadvantages of the OEO oscillators are their complexity, usually requiring a number of optical, optoelectronic and electrical components including optical modulators, RF amplifiers and filters, photo-detectors and lasers. Moreover, synchronizing and stabilizing RF signals usually requires low-noise and high-stable RF sources.

Here we report on a novel optoelectronic oscillator design that considerably simplifies the typical OEOs and is based on resonant tunneling diode (RTD) optoelectronic integrated chips (RTD-OEICs) [4]. Our version of the OEO relies on the integration of RTD-OEICs oscillators with detectors and optical sources. RTD-based optoelectronic oscillators (RTD-OEOs) are simple circuit configurations and take advantage of RTD negative differential resistance (NDR) current-voltage (I - V) characteristic - the NDR provides wide bandwidth electronic gain to the circuit. In the work presented here the oscillation frequency is around 1.4 GHz but with an appropriate resonant circuit RTDs can produce self-sustained oscillations at much higher frequency (up to 831 GHz [5]).

In previous work we have demonstrated the principles of operation of an optoelectronic voltage controlled oscillator (VCO) at GHz frequencies consisting of a resonant tunneling diode oscillator integrated with a laser diode [4]. More recently, we have investigated the photo-detection and optical injection locking capabilities of a unipolar semiconductor optical waveguide photo-detector incorporating an RTD (RTD-PD) [6]. We then integrated the RTD-PD with a laser diode realizing a simple OEO circuit configuration, the RTD-PD-LD, that can be phase-locked to reference RF sources by either optical or electrical injection locking techniques allowing remote synchronization and providing electrical-optical (E/O) and optical-electrical (O/E) conversions [4,6].

In this paper we demonstrate a low-phase noise microwave oscillator that employs self-injection of a resonant tunneling diode OEO configuration using a long optical delay for phase-

noise reduction. Injecting into the RTD-PD a delayed replica of the RTD-PD-LD optical output the oscillator frequency fluctuations are substantially reduced due to the high- Q of the optical delay line. The RTD-OEO configuration avoids the need of low-noise and high stable RF sources usually required for OEO synchronization and stabilization [1-3]. Moreover, it can produce optical signals modulated by the resulting RTD-PD low phase-noise RF signals, with interest for photonic applications such as radio-over-fiber systems [7].

II. RTD-OEO SELF-INJECTION LOCKED SETUP

The self-injection locking is realized in a compact and simple OEO configuration consisting of an RTD monolithic waveguide photo-detector oscillator (0.5x0.4 mm² chip size) that provides O/E conversion, direct modulation of a laser diode for the E/O conversion and an optical feedback loop comprising a long optical fiber and an erbium doped fiber amplifier (EDFA).

Figure 1 shows the RTD-OEO self-injection locked schematic setup where the RTD-PD-LD modulated optical output is injected after passing through a long optical delay for phase-noise reduction. Because the circuit is an optoelectronic VCO, the free-running frequency and quality factor of the RTD oscillator can be controlled by adjusting the DC bias voltage. (For a detailed description of RTD-optoelectronic integrated circuits and their principle of operation see [4].)

The circuit used in the experiment oscillates with a natural frequency ranging from 1.05-GHz to 1.41-GHz, depending on DC bias voltage. In this investigation, the bias was set close to the valley region of the RTD-PD-LD I - V curve, Fig. 1, to oscillate ~1.4 GHz. This experimental condition takes advantage of the RTD-PD responsivity in the NDR region close to valley point region [6]. The measured external responsivity of the RTD-PD in this region at 1550 nm was ~0.28 A/W. In what follows, we present and discuss the optical self-injection locking results showing stable frequency and low-phase noise signals.

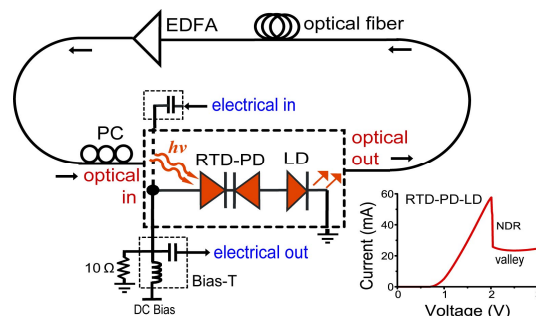


Fig. 1. Schematic of the RTD-OEO self-injection locked setup. Inset is the I - V curve showing the NDR region of the RTD-PD device in series with LD.

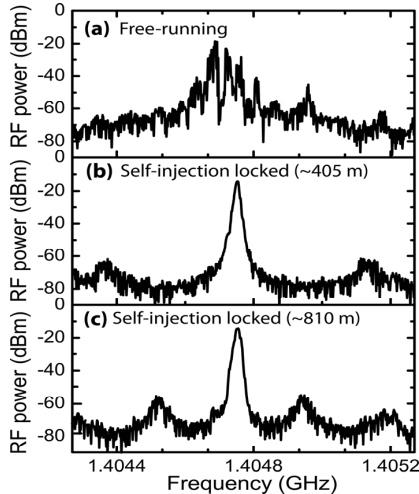


Fig. 2. RF power spectra of the RTD-OEO electrical output. (a) Free-running without optical injection, (b) $P \sim 7$ dBm and 405 m fiber length, and (c) $P \sim 7$ dBm and 810 m fiber length. The frequency span and resolution bandwidth settings of figures (a)-(c) were 1 MHz and 10 kHz, respectively.

III. RESULTS AND DISCUSSION

When the RTD-PD-LD is DC biased close to the valley region (~ 2.4 V), and without optical injection, free-running oscillations take place around 1.4047 GHz. Figure 2(a) presents the free-running oscillation, showing a broad spectrum caused by the frequency oscillation instability.

In the optical self-injection experiment the communications laser optical output, modulated by the RTD RF current oscillations, was sent through an optical fiber then amplified using an EDFA that provided an optical power $P \sim 7$ dBm, and injected into the RTD waveguide photo-detector using a lensed single mode fiber. We used two fiber lengths of 405 m and 810 m. In Figs. 2(b) and 2(c) we present the self-injection locked free-running oscillations using 405 m and 810 m optical fiber lengths, respectively. The results clearly show the self-injection enhances the signal quality improving considerably the frequency stability with a substantially phase noise reduction, which can be improved by increasing the optical loop length. Higher injected optical power level also leads to an improvement of signal quality. 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 ~ 0.2 . A redesign of the RTD-PD would also yield higher responsivities allowing, for example, the elimination of the EDFA amplifier.

The side modes shown in Figs. 2(b) and 2(c) are separated from the center frequency by about 380 kHz and 183 kHz, respectively. These are the mode spacing of the free spectral range (FSR) of the oscillator system which in our case is expressed in terms of the electrical delay and fiber optical delay. It is evident that the coupled RTD-OEO fiber loop configuration effectively suppresses the other modes of the fiber loop and only leaves one mode to oscillate. The mode-suppression ratio is more than 40 dB.

We have also analyzed single-sideband (SSB) phase noise of free-running and self-injection locked signals which are shown in Fig. 3. SSB phase noise is reduced with increasing

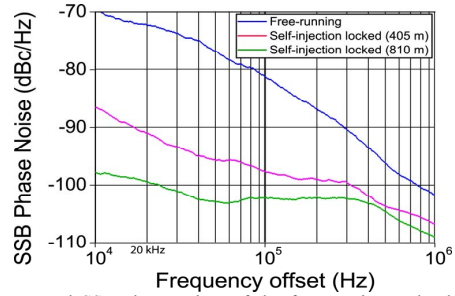


Fig. 3. Measured SSB phase noises of the free-running and self-injection locked RTD-OEO output signals with 405 m and 810 m of fiber loop.

fiber delay and also the injection power. The measured phase-noise value at 20-kHz frequency offset of free-running oscillation is -72.4 dBc/Hz. For an injected power of 7 dBm and optical fiber lengths of 405 m and 810 m, the corresponding self-injection locked phase noise values are -91.27 dBc/Hz and -99.4 dBc/Hz, respectively. From the results, a clear phase noise reduction is achieved with an improvement of output signal of more than 25-dB at 20-kHz offset. As shown in Fig. 3, phase noise reduction below -100 dBc/Hz is achieved at 100-kHz offset for the longer fiber loop.

IV. CONCLUSION

We have proposed and demonstrated a new simple optoelectronic self-injection-locked microwave oscillator that is based on a resonant tunneling diode photo-detector optoelectronic oscillator (RTD-PD-OEO) for O/E injection, and using a laser diode for E/O conversion. The RTD-OEO optical-modulated signal was optically self-injected after passing through a long optical delay line. With this new configuration, we achieved stable free-running self-locked oscillations with more than 25-dB phase-noise reduction at 20-kHz frequency offset from the center frequency using a 810 m fiber loop. Because of simplicity and flexibility the RTD-OEO is expected to find applications over a wide range of RF photonic systems such as high-precision radar and distribution of low-phase noise signals, and high-stable RF carriers in communication links. Moreover, it is expected an increase of RTD-OEO frequency operation by realizing both microwave and optical functions in a single integrated chip.

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