Optical Injection Locking of a Resonant Tunneling Diode-Optical Waveguide Photo-Detector

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***Abstract*—We report photo-detection and optical injection locking of a resonant tunneling diode - optical waveguide (RTD-OW) voltage controlled oscillator (VCO). When incorporated in a resonant tank the RTD-OW photo-detector is capable of locking to optical radio-frequency sub-carriers, with considerable reduction of VCO phase noise and locking ranges above 15 MHz.**

Keywords-Optical injection locking; optoelectronic devices; optical waveguides; photo-detectors; resonant tunneling diodes

I. INTRODUCTION

Photonic radio-frequency (RF) receivers extract RF signals from optical carriers with a wide range of applications in RF-over-fiber communication systems. Efficient and low noise receivers are being currently object of intense developments towards low cost photonic-microwave communication systems. An interesting approach is the capability of the optical RF sub-carrier to control the receiver circuitry [1]. Also of interest is the capability of transferring phase shift keyed (PSK) digitally encoded signals from the optical to the wireless domain [2]. Among the photo-detection devices, waveguide photo-detectors promise both the high-speed and high internal quantum efficiency.

In this paper we present a photo-detection device based on a resonant tunneling diode (RTD) embedded in an optical waveguide (OW), the RTD-OW. The RTD-OW can work both as electro-absorption modulator and as photo-detector at optical communication wavelengths [2] [3]. Here we show RTD-OW operation as a voltage controlled oscillator (VCO) capable of locking to optical injected RF carriers.

RTDs have attracted much interest due to their nonlinear N-shape current–voltage (*I-V*) characteristic, exhibiting negative differential conductance (NDC). The NDC provides wide bandwidth electronic gain that can give rise to high frequency self-sustained oscillations (up to 831 GHz [4]). RTD-based photo-detectors have been proposed for low noise optical injection and optical-to-RF conversion taking advantage of the nonlinear NDC [2] [5]. In what follows we describe the recent developments on monolithic RTD-OW photo-detectors operating as microwave-photonic receivers capable of low noise optical injection locking with exceptional frequency-locking range.

II. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

The RTD-OW consists of an AlAs/InGaAs/AlAs double barrier quantum well (DBQW) resonant tunneling diode integrated with a InAlAs/InGaAlAs/InP optical waveguide (more details can be found in [3]). The InGaAlAs waveguide core was made 1 μm thick with a ridge waveguide 3 μm wide providing light confinement along the double barrier quantum well plane.

Figure 1 shows the schematic diagram of the typical RTD-OW band structure when DC biased in the valley region (see inset the *I-V* characteristic). A light pulse with photon energy close to the waveguide core band gap energy produces photo-charges which under the presence of an electric field give rise to a photocurrent. The current flow depends on bias voltage and the incident optical power.

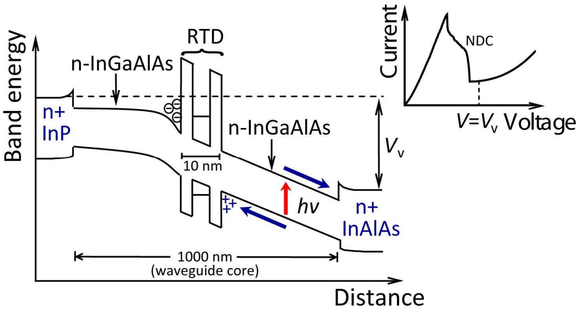

Figure 1. Diagram of the RTD-OW band structure when DC biased in the valley region. Inset is shown the schematic *I-V* characteristic.

Figure 2 shows the experimental arrangement used to characterize RTD-OW photo-detection and optical injection locking operations. Continuous light-wave from a tunable single mode laser was modulated up to 10 dB extinction ratio

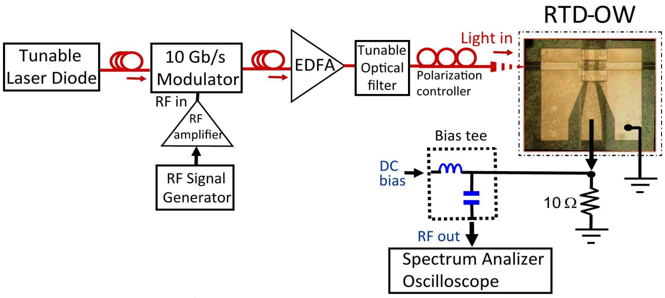

Figure 2. Diagram of the experimental arrangement used to characterize RTD-OW photo-detection and optical injection locking operations.

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(ER), using an electro-optical 10 Gb/s external modulator driven by a RF signal generator. The modulated light signal was amplified by an Erbium Doped Fiber Amplifier (EDFA), passing through a tunable optical filter and then coupled to the RTD waveguide using a standard lensed fiber.

The RTD-OW circuitry includes a 10 ohm resistor shunting the RTD-OW coplanar waveguide (CPW) transmission line, which decouples the DC bias circuit from the resonant tank formed by the CPW inductance and bonding wires and the RTD-OW intrinsic capacitance [2]. This arrangement provides the appropriate resonant conditions for operation as a self-sustained microwave VCO with fundamental frequency ranging from 0.98 GHz to 1.25 GHz.

III. RESULTS AND DISCUSSION

The RTD-OW photo-detector works as follows. Light at wavelengths around 1550 nm coupled to the DC biased RTD-OW is progressive absorbed as it propagates along the waveguide. The light absorption generates charge carriers resulting in a photocurrent that adds to the current flowing through the device. Such current increase can be interpreted as a device series resistance reduction, which leads to an overall shift to lower voltage of the *I-V* characteristic. Figure 3(a) shows RTD-OW illuminated and dark *I-V* characteristics.

Figure 3(b) presents device responses for biasing at peak and valley regions as a function of incident optical power. The light was modulated at 1.2 GHz with 10 dB ER. If the coupling loss is estimated at 8 dB, then the responsivity in the valley is 1.5 A/W. As shown in Fig. 3, the peak-to-valley transition gives rise to 14 dB increase on the photo-detection response in the range of optical powers used. The improvement on the response in this region occurs because the holes photo-generated in the depletion region accumulate around the collector barrier (see Fig. 1), causing a local enhancement field which leads to higher current, Fig. 3(a).

When DC biased in the NDC region, the RTD-OW self-sustained oscillations lock to the photo-detected signal, i.e., the oscillator synchronizes to the optical sub-carrier. Figure 4(a) shows electrical spectra of free-running and synchronized oscillations, of a RTD-OW DC biased in the NDC region, near the valley, where it produces free-running oscillation at around 1.2 GHz. The 4 mW injected power was modulated at 1.2 GHz with 10 dB extinction ratio. The results show single side band (SSB) phase noise of -104 dBc/Hz at 20 kHz (the reference source was < -110 dBc/Hz), a ~36 dB phase noise reduction compared to free running oscillation (-68 dBc/Hz). The free-running oscillator's phase noise was < -70 dBc/Hz at 100 kHz offset and compares with previous reported RTD-based photo-detectors [5]. Figure 4(b) presents the corresponding frequency-locking capture range as a function of power level, for extinction ratios of 5 dB and 10 dB. Optical powers around 10 mW with 10 dB extinction ratio leads to locking capture ranges up to 15.9 MHz, almost four times the maximum reported in [5] for comparable incident optical power levels. This is a promising performance considering the fiber to waveguide light low coupling efficiency, mainly due to the thin absorption layer.

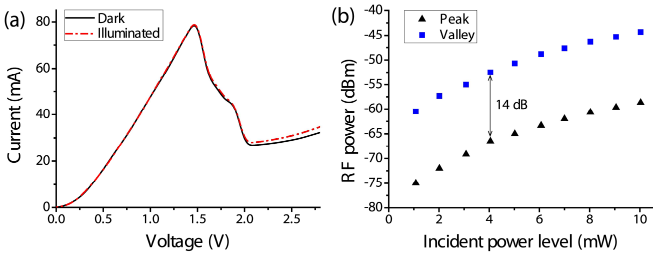

Figure 3. (a) RTD-OW illuminated and dark *I-V* curves for an incident optical signal λ=1550 nm and 4 mW power modulated at 1.2 GHz. (b) Photo-detection in the peak and valley regions as a function of power level.

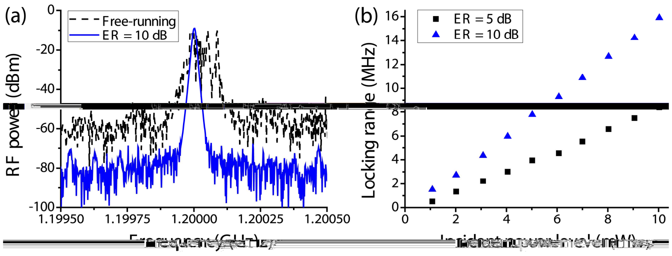

Figure 4. (a) Free-running RTD-OW VCO oscillation at around 1.2 GHz and optical injection locking for a 4 mW optical signal at λ=1550 nm, modulated at 1.2 GHz. (b) Frequency locking range as a function of power level.

The frequency-locking range and spectral measurements reported here indicate clear advantages of using the RTD optical waveguide configuration design when compared to standard RTD photo-detection schemes to obtain higher optical-to-RF conversion efficiency, since the limitations imposed by the low optical coupling between the lensed fiber and the RTD optical waveguide can be substantially improved.

IV. CONCLUSION

In conclusion, we have employed a resonant tunneling diode-optical waveguide to perform photo-detection and optical injection locking to gigahertz RF sub-carriers at input power levels as low as 1 mW. The locking range went up to 15.9 MHz for incident power of 10 mW. The device can be the basis of a low cost optoelectronic receiver for error free timing extraction. This application is currently under investigation towards the implementation of new digital communication schemes. Because of the small physical dimensions and low noise optical injection locking, RTD-OW-based optical-to-RF interfaces have interesting applications as optoelectronic receivers for radio-over-fiber communications.

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