Optoelectronic resonant tunneling diodes for high purity oscillations and excitable pulse generation

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***Abstract*—We investigate the dynamics of optoelectronic oscillators (OEOs) employing high-speed resonant tunneling diodes (RTDs) integrated with a laser diode. This RTD-OEO excitable system is analyzed in the context of two applications: ultra high spectral purity microwave generation for sensing and telecommunication networks and high-speed excitable pulse generation for biologically inspired information processing.**

I. Introduction

Dynamics with both time delay and external perturbations play a vital role in understanding complex behavior in the fields of science and technology, such as electronic engineering, chaos control, laser physics or neuroscience. In biology, time delays control cellular transport processes, and they appear in various areas including neural networks. Neurons are excitable units that can produce spikes or bursts of electrical signals: while the system rests in a stable state, it produces a pulse of fixed shape and amplitude [1] whenever it is excited beyond a certain threshold. In the context of optics and optoelectronics, generation of neuron-like excitable pulses (0.73 ns) at a low repetition rate of 4 MHz was demonstrated from an optically injected monolithic vertical cavity laser with intracavity saturable absorber [2]. A neuron-like semiconductor microstructure was also explored although it operates at a speed of the order of 20 kHz and do not possess an optical output [3]. Following these recent developments, there has been a quest on high-speed controllable optoelectronic excitable systems capable of such behaviors.

In this work we investigate the dynamics in optoelectronic oscillators (OEOs) employing high-speed resonant tunneling diode (RTD) devices [4] in two different regimes. Depending of the operating conditions, this hybrid excitable optoelectronic oscillator system generates either low-phase-noise single tone microwave oscillations or nanosecond excitable spikes with interest for information processing applications.

II. The RTD excitable optoelectronic oscillator

Our excitable OEO, Fig. 1(a), incorporates a double barrier quantum well (DBQW) resonant tunneling diode monolithic integrated with a semiconductor photo-detection region, a laser diode (LD), and an optical fiber delay line, operating in either open- or closed-loop configurations. The RTD provides a non-monotonic current-voltage (I-V) characteristic with a region of negative differential resistance (NDR), Fig. 1(b), allowing to operate our system in either a pulsing regime, region I and III, or a self-oscillatory regime, region II. The dynamics of our system can be fully explained with a model consisting of single mode laser rate equations describing LD's photon and carrier number (S, N) dynamics coupled to a Liénard equation that considers the current and voltage of the RTD (I, V):

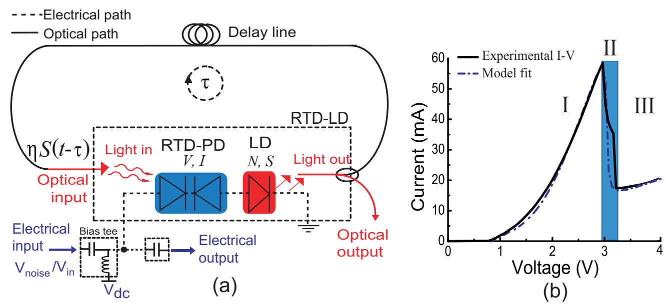

Fig. 1. (a) RTD excitable optoelectronic oscillator. (b) Experimental and model I-V characteristics function $f(V)$.

$$\dot{V} = \frac{1}{\mu}\left[I - f(V) - \chi\xi(t) - \eta S\left(t - \tau\right)\right] \quad (1)$$

$$\dot{I} = \mu\left[V_{dc} + V_{in} - \gamma I - V\right] \quad (2)$$

$$\dot{N} = \frac{1}{\tau_n}\left[\frac{I_m}{I_{th}} - N - \frac{N-\delta}{1-\delta}\{1-\epsilon S\}S\right] \quad (3)$$

$$\dot{S} = \frac{1}{\tau_p}\left[\frac{N-\delta}{1-\delta}\{1-\epsilon S\}S - S + \beta N\right] \quad (4)$$

The source of the RTD oscillations is given by the NDR region of the I-V function, $f(V)$ [4], see Fig. 1(b). The optoelectronic feedback is modeled by the term $\eta S\left(t-\tau\right)$. We model the stochastic effects as an effective delta-correlated Gaussian white noise of zero mean $\chi\xi(t)$ where χ stands for the dimensionless variance of the distribution. A comprehensive description of the dimensionless parameters employed in the model, Eqs. (1)-(4), can be found in [4].

In spite of the conceptual simplicity of our model, we achieve a very good agreement with the experimental prototype devices implemented in hybrid optoelectronic integrated circuits [4]. This is partly due to robustness of the generic behaviors based on the paradigms of non linear dynamics. The RTDs employed consisted of 10 nm wide AlAs/InGaAs/AlAs DBQW structures grown on semi-conducting InP substrates.

The DBQW structure is embedded in a InGaAlAs layers forming the core of a unipolar ridge optical waveguide, allowing the device to operate as a photo-detector around $\lambda = 1550$ nm [4]. The LD (CST Global Ltd.) operates at $\lambda \sim 1550$ nm with 6 mA threshold current.

III. Results

When operated in the NDR, region II of Fig. 1(b), the RTD exhibits self-sustained current oscillations which can be tuned from kHz to several GHz driving the laser diode output. As such the RTD-LD works as an optoelectronic voltage controlled oscillator since its free-running frequency adjustable using the DC bias voltage. We were able to operate a circuit to oscillate with natural frequency ranging from 0.944 GHz to 1.129 GHz, with typical RF widths of $\sim$ 100 kHz. In order to improve the RF width in the kHz and sub-kHz range we implemented a long feedback fiber loop that reinject a portion of the optical output into the RTD-PD in a closed loop configuration, Fig. 1(a). When the time delayed feedback is included diverse dynamical effects are observed, namely close-to-carrier noise reduction and the appearance of side modes due to the delay line contribution corresponding to the free spectral range (FSR) of our OEO.

Figure 2 presents the experimental (a) and simulated (b) power spectra around the fundamental free-running oscillation with and without delayed feedback. When the fiber-loop is included the results show phase noise and linewidth reductions at offsets below 250 kHz of the carrier frequency, and side-modes separated by about 425 kHz with a single mode suppression ratio (SMSR) of -43 dBc. The SMSR can be further reduced employing multi optical fiber-loops [4]. Note that the linewidth of the self-synchronized output could not be resolved by the 3 kHz resolution limit set by the instrument.

When the RTD operates in the stationary regime, regions I and III, it responds to weak external perturbations by emitting pulses in both electrical and optical domains when the perturbation exceeds a given threshold. We have observed spiking behavior with identical shape and intensity triggered by either a square or a pulse shape signal, V_{in}, or a stochastic voltage signal generated by a Gaussian noise source, V_{noise}. We verified the existence of a critical threshold below which there is no response and estimated the critical value of the perturbation to be 9 V.ns when d.c. biased at 2.9 V, e.g. a 100 ns square whose plateau is 90 mV. Figure 2(c) presents the experimental time traces of induced neuron-like pulsing behavior when the RTD-LD is driven by a stochastic signal. We have analyzed the temporal traces, Fig. 2(d), using the same experimental conditions. The numerical dynamical regimes obtained are in a very good agreement with the behavior observed in the experimental results. Plots in (i) show upward and downward electrical spikes triggered randomly due to the stochastic nature of the driven signal with a time repetition determined by RTD-LD's refractory time, in this case around 500 ns. The upward electrical pulses have $\sim$ 13 ns FWHM with identical shape. The LD light output follows the electrical current switching induced by the RTD with a sequence of downward pulses of identical shape with FWHM of $\sim$ 200 ns. When operated in the region III, the direction of the pulses is reversed, (iii) and (iv), and bursts of several pulses appear due to the asymmetry of the $f(V)$ function.

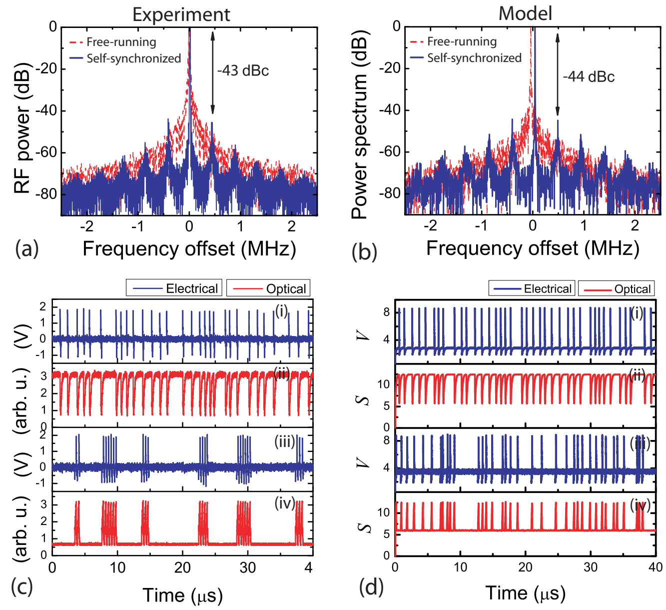

Fig. 2. (a) Experimental RF power spectra of free-running and self-synchronized electrical outputs biased in region II employing a 0.4 km fiber and 6 dBm re-injected optical power. (b) Simulated power spectra of V outputs with time delay of $\tau_d = 2.35$ μs, feedback strength of $\eta = 5 \times 10^{-4}$. In (a) and (b) the span was 5 MHz and the central frequency was 1.12207 GHz. (c) Experimental time traces of noise induced neuron-like pulsing behavior: (i)-(ii) RTD-LD is biased in region I (V_{dc}=2.9 V) and $V_{noise} = 175$ mV; (iii)-(iv) region III (V_{dc}=3.2 V) and $V_{noise} = 150$ mV. (d) Numerical simulations employing the noise strengths of (i)-(ii) $\chi = 0.158$, and (iii)-(iv) $\chi = 0.310$.

IV. Conclusion

We have demonstrated, experimentally and theoretically, high purity oscillations and excitable pulse generation in a simple resonant tunneling-laser diode optoelectronic system. In the oscillatory regime RF widths in the sub-kHz range can be achieved thanks to the delayed feedback fiber loop. Excitable pulsing is achieved with lethargic times and pulse widths in the nanosecond range. Since the I-V N-shape of RTD-LD is maintained almost from DC up to GHz frequencies, RTD excitable optoelectronic systems can be easily tuned for either low or fast speed excitable response depending of the desired application. Potential uses of our excitable system include ultra-fast data processing and neural emulation applications.

References

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