Optoelectronic Integration of a Resonant Tunneling Diode and a Laser Diode

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Abstract. *We report on a hybrid integration of a resonant tunneling diode laser diode driver configuration that operates as a self-oscillating circuit and can be described as a Liénard's oscillator. When externally perturbed it is capable of frequency division, chaos generation and synchronization with potential novel functions for optical communications systems.*

Introduction

Recent work on Opto Electronic Integrated Circuits (OEICs) has shown that it is possible to monolithically integrate a resonant tunnelling diode (RTD) with an optical waveguide electroabsorption modulator (RTD-EAM) [1] and a RTD with a laser diode (RTD-LD) [2]. Crucially the RTD introduces negative differential resistance (NDR) into the electrical characteristics of the RTD-EAM and the RTD-LD. RTDs have attracted much attention due to their strong nonlinear current-voltage (*I*-*V*) characteristic, wide-bandwidth NDR region, and high frequency operation [3].

This paper presents recent work on a hybrid optoelectronic integrated circuit (OEIC) consisting of a RTD driving a communication laser diode (LD) that produce various optical outputs including self-sustained oscillations, frequency division and chaos in electrical and optical domains [4]. The circuit preserves the nonlinear dynamical behavior of the RTD increasing laser diode functionality with several potential advantages, such as low modulating voltage, ultrahigh speed operation, and significant reduction in the complexity of chaotic optical carriers generators needed for optical communications [5]. The RTD-LD circuit operation can be described by Liénard's oscillator theory. Numerical simulations also show optical chaotic synchronization in two identical resonant tunneling diode – laser diode circuits operating as an unidirectional driven coupled system. We anticipate that this circuit will lead to new applications in optical communications including clock recovery, clock division and data encryption using synchronized chaos.

Circuit Description and Operating Principle

Figure 1(a) shows the schematic diagram of the RTD-LD hybrid OEIC. The shunt capacitor was used to decouple the DC from the AC circuit. The RTD detailed structure is described in [1]. The LD was an optical communications laser fabricated by Compound Semiconductor Technologies (Scotland); it has a threshold current of 6 mA, 20 GHz bandwidth, and operates at 1550 nm with average output power of 5 mW. The room temperature *I*-*V* characteristics of the RTD, LD, and the RTD-LD are shown in

Fig. 1(b). The circuit electrical output was taken across the RTD-LD series, Fig. 1(a); the laser optical output was coupled to a lensed optical fibre and detected by a 45 GHz IR New Focus Photo-detector.

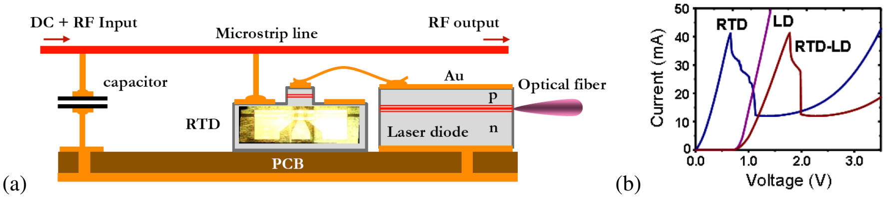


Fig. 1 (a) Schematic of the RTD-LD OEIC; (b) *I-V* characteristics of RTD, LD and RTD-LD.

When DC biased in the NDR region the experimental circuit represented by Fig. 1(a) produces self-sustained oscillations at frequency around 560 MHz, determined mainly by the wire bonding inductance and intrinsic RTD-LD capacitance. The LD optical output is modulated by the current oscillations induced by the RTD, producing an optical output with the same harmonic content of the electrical oscillations.

Theory and Numerical Model

The nonlinear dynamics behavior of the RTD-LD module can be analyzed using the lumped circuit shown in Fig. 2(a). The physics-based RTD $f(V)$ current-voltage description given in [6] was used, Fig. 2(b). When operated above the threshold, the laser can be modeled using an ideal diode in series with a voltage source V_{TH} and a current limiting resistor R_S. From Fig. 2(c) we obtain $V_{TH} = 0.84$ V and $R_S = 11\ \Omega$.

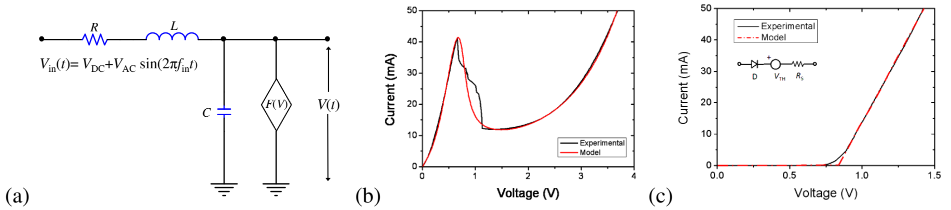


Fig. 2 (a) Equivalent lumped circuit of circuit shown in Fig. 1(a); (b) Experimental and fitting of RTD *I-V* curves; (c) Experimental *I-V* characteristics of the laser diode and model.

For a given DC bias voltage, V_{DC}, the voltage output across the RTD-LD series, $V(t)$, Fig. 1(a), can be described by a nonlinear system known as Liénard's oscillator:

$$V''(t) + H(V)V'(t) + G(V) = V_{AC}\sin(2\pi f_{in} t), \qquad (1)$$

where $G(V)$ is a nonlinear "force", $H(V)V'(t)$ and $V_{AC}\sin(2\pi f_{in} t)$ are the damping factor and the externally applied forcing signal, respectively. $H(V)$ and $G(V)$ are given by:

$$H(V) = \frac{R}{L} + \frac{1}{C}\frac{df(V)}{dV}; \quad G(V) = \frac{V(t)}{LC} + \frac{R}{LC}f(V) - \frac{V_{DC}}{LC}. \qquad (2)$$

The laser diode optical output was modeled using the laser diode single mode rate equations for the electron density $N(t)$ and the photon density $S(t)$:

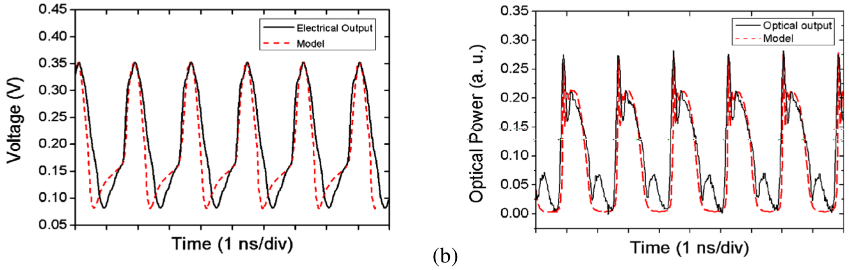
$$N'(t) = \frac{I(t)}{q\vartheta} - \frac{N(t)}{\tau} - g_0 \left(N(t) - N_0\right) \frac{S(t)}{1 + \varepsilon S(t)} \qquad (3)$$

$$S'(t) = g_0 \left(N(t) - N_0\right) \frac{S(t)}{1 + \varepsilon S(t)} - \frac{S(t)}{\tau_p} + \frac{\beta N(t)}{\tau}, \qquad (4)$$

where $I(t)$ is the current through the laser diode given by Liénard's model (1), q is the electron charge, ϑ is the active region volume, τ and τ_p are the spontaneous electron and photon lifetime, respectively; β is the spontaneous emission factor; g_0 is the gain coefficient, N_0 is the minimum electron density required to obtain a positive gain and ε is the value for the nonlinear gain compression factor.

Self-sustained oscillations

In Fig. 3(a) we show the electrical output of the RTD-LD in the self-oscillating mode (V_{AC}=0 V); also represented is numerical output given by the Liénard's model [equation (1)]. In Fig. 3(b) we show the laser optical output experimental data fitted with the calculated light intensity as a function of the injection current $I(t)$ using the rate equations [equations (3) and (4)] with typical parameters of communication laser diode.



(a) (b)

Fig. 3 (a) Experimental and modeled electrical signals at voltage of 1.8 V, both with fundamental frequency oscillation around 560 MHz. The circuit parameters used in the model are L=8.0 nH, C=5.0 pF, R=6.2 Ω and V_{DC}=1.8 V, V_{AC}=0.0 V; (b) The corresponding photo-detected signal and the model output.

The comparison between the experimental results with the numerical simulation shows that the theory of the Liénard's nonlinear differential equation can be used to model the RTD based driver circuit of an optical communications laser diode.

Frequency Division, Chaotic Behavior and Synchronization

Frequency division in a hybrid optoelectronic integrated RTD-LD circuit has been investigated numerical and experimentally when an external sinusoidal voltage signal is applied. Figure 4 shows experimental and numerical results of frequency division by 2 and 5 in the laser optical output induced by low driving AC voltages. The bifurcation diagram representing the amplitude peaks heights of RTD-LD output voltage oscillations, $V(t)$, as a function of the excitation frequency f_{in}, obtained numerically shows period-adding bifurcation in a sequence of quasi-periodic (unlocked) and periodic (locked) oscillations [4]. In the quasi-periodic regions, depending on parameters conditions, route to chaos behavior is expected [3][4].

We have also analyzed the electrical and optical synchronization of two identical coupled chaotic RTD-LD oscillators using the Liénard's oscillator and the synchronization diagrams of the evolution of output signals of the transmitter vs. receiver show chaos synchronization between the RTD-LD coupled circuits.

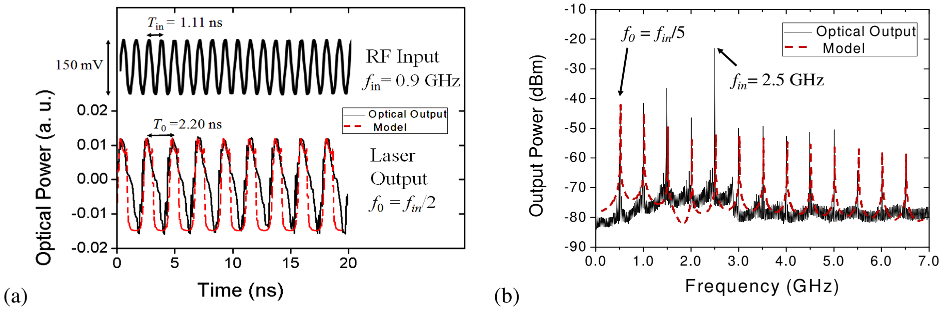


Fig. 4 (a) Laser output showing frequency division by 2 when V_{AC}=150 mV at 0.9 GHz and model; (b) Spectrum of the laser output showing frequency division by 5 when V_{AC}=150 mV at 2.5 GHz and model.

Conclusions

A RTD-LD circuit acting as an oscillator producing self-sustained oscillation and frequency division both in the electrical and optical outputs was demonstrated. The self-sustained behavior can be a simple way to convert fast, short electrical pulses into fast sharp optical pulses. The sub-harmonic locking can be used for dynamic frequency division with a selectable dividing ratio. We also have shown that the electrical and optical operation of the circuit can be described by Liénard's oscillator theory.

Although the hybrid RTD-LD circuit presented here operates at relatively low frequencies compared to modern optical communication systems, recent work by the authors has shown that with reduced RTD-LD bond wire inductance, voltage controlled oscillation frequencies in the range of 1.9 GHz to 2.1 GHz can be achieved. With fully integrated versions we anticipate much higher operating frequencies in the region of 10 Gbits or higher - data rates more appropriate for present day and future optical communication systems.

Acknowledgments

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