Mixed mode oscillations in a forced optoelectronic circuit for pattern and random bit generation

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***Abstract*—We investigate the generation of mixed mode oscillations in a periodic forced optoelectronic circuit comprising a high-speed resonant tunneling diode (RTD) and a laser diode (LD). The driven RTD-LD exhibits a two-state level operation, characterized by either periodic or aperiodic intermittent patterns with a high amplitude followed by small amplitudes, that can be used for applications in switching at very fast modulation speeds and encoding of binary data sequences into the corresponding electrical and optical states of the dynamical system.**

I. Introduction

Complex oscillatory patterns of small and large amplitude oscillations have been observed in a wide variety of physical, chemical, biological and engineering systems [1]–[3]. These are generally called mixed-mode oscillation (MMO) patterns. They were first noticed in the Belousov-Zhabotinsky chemical reaction [1], and have been used to analyze neuron population activity [2]. In the context of neural dynamics, large (L) oscillations correspond to the firing of action potentials while small (S) oscillations correspond to subthreshold oscillations.

The realization of experimental systems that could at the same time generate these rich dynamical patterns, operate at fast speeds, and employ typical semiconductor materials utilized in optoelectronic devices such as photo-detectors and lasers is still a great challenge. One of the few recent demonstrations show the existence of slow chaotic spiking sequences in the dynamics of a light-emitting diode with ac-coupled optoelectronic feedback [3]. More recently, we have proposed a novel optoelectronic oscillator with high-speed excitable response capabilities employing double barrier quantum well resonant tunneling diode (DBQW-RTD) photo-detectors and laser diodes (LDs) [4]. When perturbed either electrically or optically by an input signal above a certain threshold, the optoelectronic circuit have shown potential for the generation of rich variety of signal outputs that include short electrical and optical spikes, square pulses, and bursting phenomena mimicking the behavior of biological neurons.

In this work, we demonstrate theoretical and experimental evidence of periodic and aperiodic (quasi-periodic/chaotic) gigahertz-range MMO patterns in a forced optoelectronic circuit system comprising an externally perturbed resonant tunneling diode driving a laser diode operating at telecommunication wavelengths. We have observed two-state level MMO operation in these devices and demonstrate that this behavior can be used as a very efficient switching method to modulate the laser intensity output for applications in pattern and random bit generation. The configuration proposed here has many interesting advantages when compared with solitary laser systems including quadruple electronic and optical inputs/outputs, and an asymmetric nonlinearity arising from the non-monotonic RTD current-voltage (I-V) curve which is quite different from the one of Lorenz-like or FitzHugh-Nagumo systems [5].

II. The periodic forced optoelectronic circuit

The schematic of the forced optoelectronic circuit is shown in Fig. 1(a), and incorporates a DBQW resonant tunneling diode hybrid integrated in series with a laser diode. The RTDs employed consisted of 10 nm wide AlAs/InGaAs/AlAs DBQW structures grown on semi-conducting InP substrates, and the commercial LD device (CST Global Ltd.) operates at $\lambda \sim 1550$ nm with ~ 6 mA threshold current [4]. An external periodic force, V_{in}, is utilized to a.c. modulate the RTD-LD bias voltage. The RTD provides a non-monotonic I-V curve with a region of negative differential resistance (NDR), Fig. 1(b). The circuit operating quiescent point corresponds to the intersection of the I-V curve and a load line whose slope is defined by the inverse of the circuit equivalent resistance. In order to operate the system as a two-state level MMO pattern generator, the bias point is selected in either the first [Fig. 1(b)] or second positive differential resistance (PDR) region.

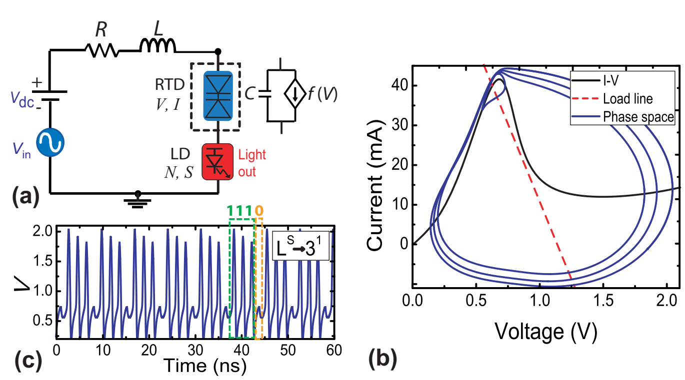

Fig. 1. (a) Equivalent circuit schematic. (b) Nonlinear I-V curve, $f(V)$, load line, and simulated limit cycle of a 3^1 MMO pattern. (c) A typical time series of a simulated 3^1 MMO periodic pattern.

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The dynamics of our system is described with a model consisting of a high-dimensional forced Liénard system that considers the external forcing, the current and voltage of the RTD (I, V), coupled with single mode laser rate equations describing LD's photon and carrier number (S, N) [4]:

$$\dot{V} = \frac{1}{\mu}[I - f(V)] \tag{1}$$

$$\dot{I} = \mu[v_0 + v_{ac}\sin(2\pi\Omega t) - \gamma I - V] \tag{2}$$

$$\dot{N} = \frac{1}{\tau_n}\left[\frac{I}{I_{th}} - N - \frac{N-\delta}{1-\delta}\{1-\epsilon S\}S\right] \tag{3}$$

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

where time has been scaled to by the LC resonance frequency $\omega_0 = (\sqrt{LC})^{-1}$, $f(V)$ [4] describes the I-V curve, v_0 describes the bias voltage, and $v_{ac}\sin(2\pi\Omega t)$ describes the periodic force, where $\Omega = f_{in}/\omega_0$; $\mu = V_0/I_0\sqrt{C/L}$ and $\gamma = R(I_0/V_0)$ describe the equivalent circuit parameters [inductance, L, capacitance C, and resistance R, Fig. 1(a)]. A description of laser parameters can be found in [4].

III. Results and discussion

In the following, we first analyze the conditions to achieve two-state level MMO operation. We employ in the model $\mu = 0.0247$, $\gamma = 12.8$, $v_0 = 1.13$, and $\Omega = 0.116$. For this set of parameters, a dynamical MMO sequence occurs about $v_{ac} = 0.192$. A typical time series for these parameter value choices can be seen in Fig. 1(c), showing a periodic $L^S \to 3^1$ MMO sequence of high amplitudes of V followed by small amplitude in the other state. Naturally, the two-state level operation can be associated with a binary encoding $\{0, 1\}$.

In order to understand the dynamics of the MMO pattern generation, we discuss the voltage-current phase space diagram displayed in Fig. 1(b). For the chosen parameters the load line intersects with the nonlinearity in the first PDR region (rest state), but sufficiently close to the NDR region where self-sustained relaxation oscillations can occur. For driving amplitudes below a given level of v_{ac} the dynamics only occurs around the fix point shown in the upper left corner of the phase-space diagram that corresponds to the small amplitude oscillations (binary '0'). There exist certain threshold values that have to be exceeded before a large oscillation corresponding to a large excursion in the limit cycle can occur. If we increase the driving amplitude up to the threshold value, oscillations of large amplitude (binary '1') can occur and patterns of large and small (L^S) amplitudes are achieved. The L^S electrical current patterns will then modulate the laser light, providing an intensity optical output following the same MMO dynamics occurring in the electrical domain.

Depending on the driving frequency and amplitude of the control signal, for fixed dc bias point and circuit parameters, either periodic or aperiodic intermittent MMO patterns may occur. In Fig. 2 we show experimental results of an implemented prototype circuit. We measured the response of the circuit to sinusoidal electrical signals in the range of 0.53

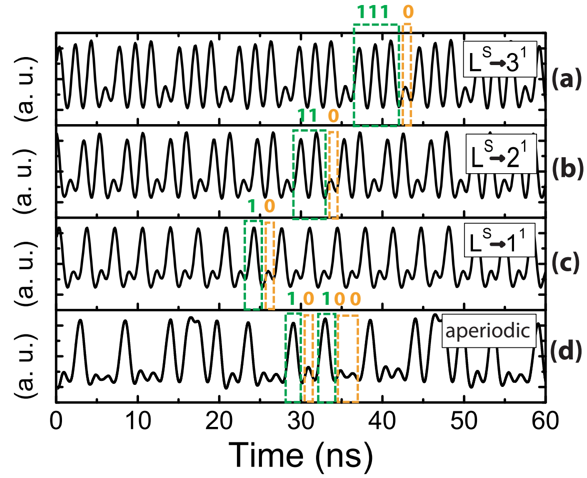

Fig. 2. (a) Experimental time traces of periodic and aperiodic MMOs for a periodic signal with an amplitude of 281 mV as a function of the injected frequency: (a) 0.544 GHz, (b) 0.564 GHz, (c) 0.586 GHz, and (d) 0.581 GHz.

GHz to 0.63 GHz, that is, close to the natural oscillation frequency of the circuit, and recorded the laser photo-detected output employing a 2 GHz oscilloscope. The results show that changing the periodic external signal will trigger an MMO sequence periodic of $L^S \to 3^1 \to 2^1 \to 1^1$, upon varying the frequency parameter. Between periodic MMOs, more complex patterns can be achieved including quasi-periodic and chaotic MMOs. In Fig. 2(d) we show an example of an aperiodic sequence displaying random MMOs with interest for novel random bit generator circuits. Considering that small perturbations of our circuit changes the dynamical behavior of the MMO patterns this can have a high interest to efficiently encode data sequences since our system it will only require small signals to ensure a successful encoding.

IV. Conclusion

We have demonstrated, theoretically and experimentally, the generation of gigahertz-range mixed mode oscillations in a periodic forced optoelectronic circuit that employees a resonant tunneling diode to modulate the intensity output of a laser diode. Potential uses of our system include ultra-fast signal processing namely switching at very fast modulation speeds which will be needed for high-speed data encoding.

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