Self-oscillation and period adding from resonant tunnelling diode–laser diode circuit

J.M.L. Figueiredo, B. Romeira, T.J. Slight, L. Wang, E. Wasige and C.N. Ironside

A hybrid optoelectronic integrated circuit comprising a laser diode driven by a resonant tunnelling diode can output various optical and electrical signal patterns that include self-sustained oscillations, subharmonic and harmonic locking and unlocked signals, with potential applications in optical communication systems.

Introduction: Negative resistance elements are important components in oscillator circuits and form the basis of many other nonlinear circuits. Resonant tunnelling diodes (RTDs) have attracted much attention owing to their wide-bandwidth negative differential resistance (NDR), up to hundreds of GHz [1]. Because RTDs can be easily integrated in electronic and optoelectronic circuits, the applications span from high frequency signal generation and high speed signal processing to millimetre-wave frequency optoelectronics [2]. In this Letter we report self-oscillations, subharmonic and harmonic locking and unlocked oscillations in a laser diode hybrid optoelectronic integrated circut (OEIC) driver employing a RTD. The circuit operation is similar to the functioning of the resonant tunnelling chaos generator reviewed in [3]. However, the novel aspect here is the optical output. In optical communication systems these operation modes have promising applications including clock recovery, clock division and data encryption.

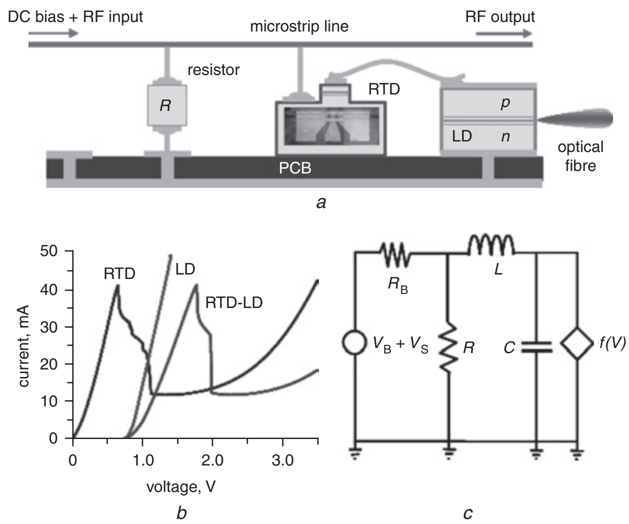

Fig. 1 *RTD-LD hybrid optoelectronic integrated circuit*

a Schematic of RTD-LD OEIC
b I-V characteristics of RTD, LD and RTD-LD
c Lumped circuit of schematic shown in Fig. 1*a*

Circuit description and operation: The resonant tunnelling diode-laser diode (RTD-LD) hybrid OEIC module is shown schematically in Fig. 1*a*. The RTD and the LD connected in series were embedded in a microstrip transmission line (TL), with the shunt resistor *R* used to decouple the DC from the AC circuit by 'short-circuiting' the AC loop that consists of the microstrip section between the shunt resistor and the RTD-LD module. The RTD detailed structure is described in [4]. The LD was an optical communications laser fabricated by Compound Semiconductor Technologies Global Ltd; it has a threshold current of 6 mA, 20 GHz bandwidth and operates at 1550 nm. The room temperature current-voltage (*I-V*) characteristics of the RTD, LD, and the RTD-LD module are shown in Fig. 1*b*. The RTD-LD module peak and valley currents were 41 and 12 mA, at voltages of 1.78 and 2.27 V, respectively. Fig. 1*c* shows the lumped circuit of Fig. 1*a*, where *C* and $f(V)$ represent the equivalent capacitance and the current-voltage of the RTD-LD series association; *L* represents the overall inductance owing to the microstrip and the bond wires. The biasing circuit is represented by the DC and AC voltage V_B and V_S, and the resistance R_B. The circuit electrical output was taken across the RTD-LD module; the circuit optical output, the laser optical output, was coupled to a lensed optical fibre and detected by a 45 GHz IR New Focus photodetector.

Circuit self-sustained oscillations are induced DC biasing the RTD-LD in the NDR region. When an AC signal $V_S(t) = V_0 \sin(2\pi f_S t)$ was added, the circuit produced subharmonic and harmonic and unlocked oscillations. The oscillations drive the laser diode, modulating its light output. The circuit free-running frequency is determined primarily by the AC loop equivalent inductance *L* (from the transmission line and the inductance from the wire bonding) and the equivalent capacitance *C*, which is approximately equal to the RTD capacitance.

Results and discussion: Fig. 2*a* shows typical self-sustained oscillation around 500 MHz produced by the circuit configuration of Fig. 1. The circuit electrical and optical outputs are represented by the upper and the lower traces. A similar circuit with the shunt resistor located slightly further away from the RTD-LD module and therefore giving a larger inductance value showed self-sustained oscillations at around 400 MHz. Excluding the fundamental frequency, the waveforms obtained were identical to Fig. 2*a*. Fig. 2*b* shows the RF spectra of both signals that confirms their high harmonic content (up to 12th harmonic). The RTD successive switching events drive the laser diode, producing sharp changes in its optical output at the RTD switching frequency. The full width at half maximum (FWHM) of the detected optical output pulses is approximately 200 ps but this measurement may be limited by the temporal resolution of the Philips PM3340 2 GHz digitising oscilloscope used to observed the optical and electrical outputs. The light modulation induced by the RTD free-running switching was higher than 20 dB (the laser average output power was 5 mW).

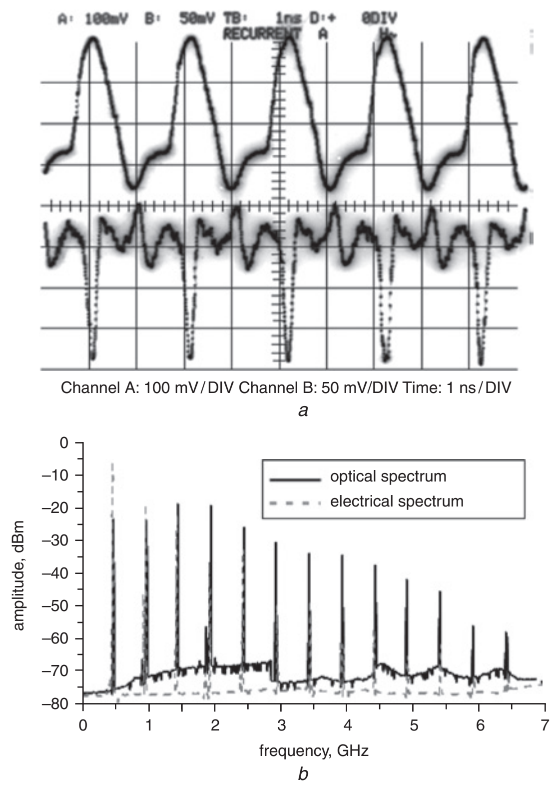

Fig. 2 *RTD-LD self-sustained responses at 500 MHz*

a Upper trace: electrical output; lower trace: optical output
b Optical (solid curve) and electrical (dotted curve) output signal spectra

The oscillation frequency was controlled by the bias voltage in the range $V_B = 1.78$ V to 2.00 V. The central frequency and tuning ranges observed in both circuits were, respectively, 490 and 40 MHz, and 385 and 30 MHz. This frequency tuning aspect of RTD-LD behaviour could be useful in voltage controlled oscillator (VCO) applications. From the transmission line and bond wire lengths an estimate of the two circuit's equivalent inductances are 9 and 13 nH, respectively. Assuming a capacitance around 2.5 pF, the SPICE model of the circuit represented in Fig. 1*c* produces identical voltage waveforms across the RTD-LD. A detailed numerical analysis of the circuit based on the Liénard's equation is under way.

A more complex circuit behaviour known as period-adding bifurcation can be induced by the injection of an AC signal $V_S(t) = V_0 \sin(2\pi f_S t)$. In this mode of operation, when the frequency of the driving signal $f_S(=1/T_S)$ was continuously increased from 0.1 to 2 GHz, frequency bands corresponding to period doubling, period tripling, and period quadrupling and so forth were found. The period of the voltage across the RTD-LD module and hence of the signal driving the laser, and therefore the corresponding period of the laser optical output observed were T_S, $2T_S$, $3T_S$, $4T_S$, $5T_S$, and $6T_S$. The frequency bands corresponding to period adding were separated by regions where the circuit generates other locked and unlocked signals (quasi-periodic and what seems to be a chaotic behaviour).

Fig. 3 shows frequency division by 2 and by 3 in the optical and electrical outputs when the injected signal frequencies were 0.5 and 1 GHz, respectively, and $V_0 = 1$ V. In both oscilloscope displays, the upper trace is the laser optical output and the lower trace is the RTD-LD module voltage output. The injected signal is schematically represented in both displays. Frequency division was also observed changing the AC amplitude or, alternatively, changing the DC bias voltage, keeping in both cases the input AC signal frequency fixed.

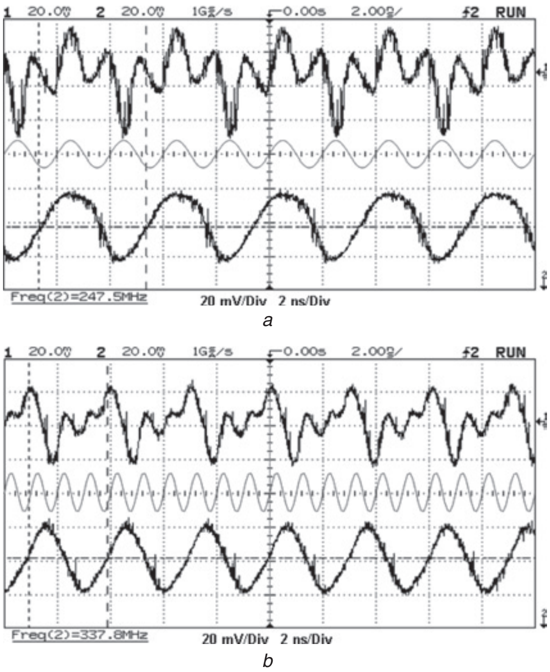

Fig. 3 *Frequency division induced by 1 V amplitude AC signals*

a Division by 2: AC signal with frequency 0.5 GHz
b Division by 3: AC signal with frequency 1.0 GHz

Conclusion: We have presented different modes of operation of a hybrid OEIC comprising a RTD in series with a laser diode and demonstrated a simple means of modulating optical carriers at frequencies around 0.5 GHz. Tunable self-sustained oscillation and frequency division behaviour were shown both in the electrical and in the optical outputs. The optoelectronic voltage controlled oscillator presented here can be a simple way to convert fast, short electrical pulses with low timing jitter and phase noise [5], into fast, sharp optical pulses. The subharmonic locking can be used for dynamic frequency division with a selectable dividing ratio. We anticipate that an optimised RTD-LD monolithic integrated version [6] will operate at much higher frequencies (tens of Gbits) within the data rates of present and future optical communication systems owing to reduced parasitics, in particular unnecessary inductances.

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