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Contrasting dynamical properties in laser and resonant tunneling diodes with optical feedback

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Abstract– We propose to study the dynamical behavior of a Resonant Tunnelling Diode (RTD) emitting in the THz domain subjected to delayed optical feedback and to compare it with what is reported in the case of semiconductor lasers. In laser systems, bifurcation mechanisms leading an initially stationary solution to chaos or high-frequency complex dynamics as the feedback strength is varied have been intensively reported and analyzed. We carry out an experimental analysis of the same nature in the context of a resonant tunneling diode. RTDs are used as compact sources of stable continuous wave THz radiation, in which the phenomenon of photon generation is based on quantum tunnel effect occurring in a resonant cavity. We show that RTDs with feedback can exhibit nonlinear dynamics comparable to their laser counterparts, in particular high-frequency pulsations governed by the feedback delay time. We propose a comparative confrontation of the properties of the dynamics seen in these two optical systems in terms of experimental conditions, fundamental mechanism and frequency range. Perspectives for all-optical signal generation, high-frequency applications and electro-optical conversion are discussed as well.

1. Introduction

Nonlinear dynamical effects in systems with delayed feedback are studied throughout all domains of physics as interdisciplinary mechanisms and dynamical behaviours can be identified and universally interpreted. In the field of optics, the best-known systems with optical feedback are semiconductor lasers in which part of the emitted light is sent back to the internal cavity, causing an elevation of the dimension of the system and allowing complex dynamics to occur in the corresponding temporal waveform. In such systems, bifurcation mechanisms leading an initially stationary solution to chaos or high-frequency complex dynamics can be observed as the feedback strength is varied [1, 2].

In particular, studies addressing the question of the behaviour of lasers with feedback either in free-space configurations [3, 4] or in integrated circuits [5, 6] have demonstrated a large variety of dynamical properties. Among the most relevant dynamical particularities identified in such systems, one can mention chaos generation and control, pulsing dynamics, linewidth or coherence improvement. These dynamical phenomena, resulting from interactions between an emitted beam and a feedback beam and often piloted by a modulation of phase, amplitude or delay time, are likely to show up in systems showing coherence. Hence, the great majority of the studies, although very numerous, are restricted to lasers. The high coherence specificities of laser emission allows for investigations in a wide range of laser systems and in consequence nonlinear dynamical phenomena have been reported in systems as various as gas or solid lasers, laser diodes and on-chip integrated lasers [7-9]. Applications have followed in domains of physics and engineering involving the frequency ranges covered by these laser devices, and especially in optical communications, signal cryptography, optical signal and random number generation [10, 11]. As a result, the spectral bandwidth on which the analysis of nonlinear dynamics in optics focuses approximately ranges between the visible light and the near infrared.

We propose to address the question of nonlinear dynamics in the THz domain, defined by the frequency region between the near infrared and microwaves, typically in the 0.1-100 THz frequency interval. The terahertz frequency range has been drawing pretty much attention in the last decades. Many applications involving THz emission, imaging and detection have been proposed in the domains of biology, sensing or wireless communications [12]. As for THz emitting techniques, several methods and devices are being used for either pulsing or continuous sources among which nonlinear interactions between laser beams, oscillations in quantum cascade laser or semiconductor components [13, 14]. A very interesting particularity of the THz domain is the fact that it defines a common border between optics and electronics. As such, these two domains of physics are strongly interconnected by THz devices for communication technologies, sensing or imaging.

In this study, we focus on a semiconductor diode termed Resonant Tunnelling Diode (RTD), designed for continuous wave THz emission [15]. Beyond its stable steady-state operating regime, for which a constant bias current causes the diode to emit constant THz optical power, we aim at studying what occurs when this kind of device is subjected to its own optical feedback and in particular what kind of nonlinear dynamics can be exhibited. This is done with the objective of establishing a confrontation of the dynamical scenarios with their laser counterparts. By contrast to lasers, resonant tunneling diodes are often considered as electronic devices rather than optical devices. RTDs are often modeled by equivalent electrical oscillators which fairly reproduce their linewidth properties and general behaviour when simply biased with an external DC voltage [16, 17]. However, they also show optical coherence properties, suggesting the possibility to make an emitted beam and a feedback beam interfere in order to yield nonlinear dynamics in the same way as what is done in the case of lasers.

Although nonlinear dynamics of semiconductor lasers with feedback have been intensively investigated under various experimental conditions, studies addressing the question of the dynamical phenomena observed in RTDs with optical feedback are still lacking. The purpose of this study is to tackle this topic. RTDs dedicated to THz generation are still relatively recent devices and have not yet fully spread into the common knowledge of electronics or photonics. Besides, most of them are still found as prototypes only.

2. Light emission in semiconductor lasers versus resonant tunneling diodes

In semiconductor lasers, the principle of photon emission relies on stimulated emission with electrical pumping. The frequency of the photons is determined by the energy bandgap of the semiconductor material constituting the active layer. In most studies reporting dynamical studies of semiconductor lasers, the wavelengths range from 850 to 1550 nm.

In resonant tunneling diodes, the photon emission is based on the quantum tunnel effect. Electrons are driven by a voltage that makes them pass through a tunnel resulting from the existence of a narrow p–n junction barrier. The electrons fill the states in the conduction band on the n-side and, when transiting to the p-side, emit photon which frequency is equivalent to the energy difference between each side of the tunnel. An antenna collects then the photons and guides them out of the device and, symmetrically, guides the incoming photons from the feedback beam into the active layer. Structural details and oscillation conditions are explained in references [13, 18].

A unique particularity of RTDs is the existence of a negative differential resistance (NDR). As the control voltage increases above a given value, the electron states become misaligned causing a drop in the current and in the consequent photon density. Then, as the voltage increases even further, the diode behaves like a normal diode, where the electrons simply travel by conduction across the junction. This region of negative differential resistance is very interesting from the point of view of nonlinear dynamics since the device shows the highest nonlinearity when operating under these conditions. In the following experimental report, the RTD operates in its negative differential region.

3 Experimental analysis

The experimental setup is presented in Fig. 1 and consists of a resonant tunneling diode emitting at 0.56 THz and controlled by DC voltage.

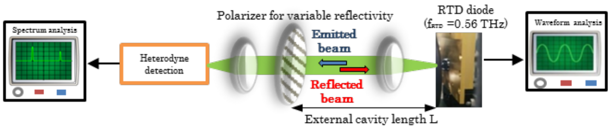

Figure 1: Experimental setup of the RTD with feedback

The light emitted by the diode is partially reflected by a wire-grid polarizer, acting in the THz domain as a partial reflector would in the optical domain, thus generating the feedback beam. Temporal and spectral data are acquired by a digital oscilloscope and a heterodyne detection system. The feedback strength is varied by rotating the polarizer.

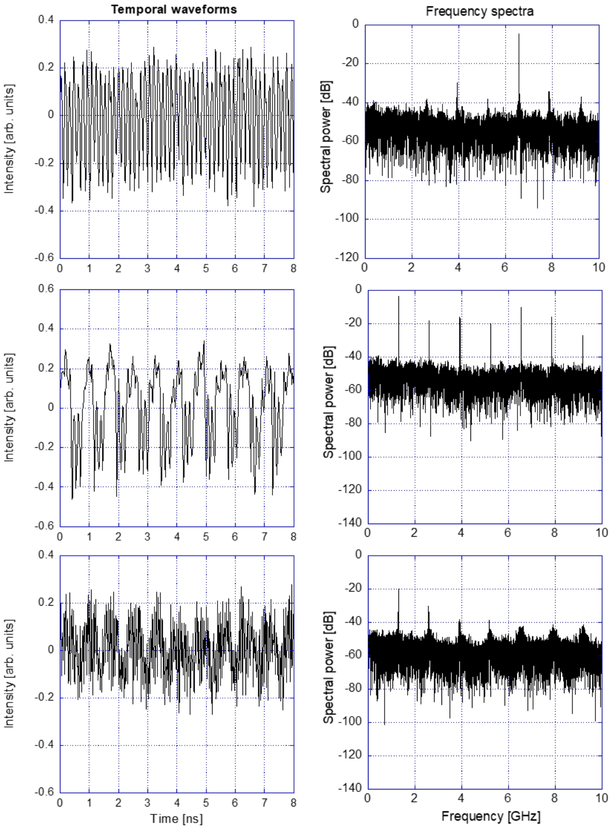

Figure 2: Example of dynamics observed for different values of the feedback strength

By changing the feedback strength, the initial continuous steady state of the non-feedback condition can give way to complex dynamics characterized by fluctuations in the time waveform and bunches of peaks rising on the spectrum. Fig. 2 illustrates the dynamical diversity observed. We can identify periodic oscillations (top) along with quasi-periodic dynamics (center) and more complex pulse packages still showing some periodicity (bottom). The timescale of these oscillations ranges in the GHz order. It is therefore very close to what is usually observed in semiconductor lasers with feedback.

Now, if one pays a closer attention to the pulsing dynamics, one can notice interesting phenomena, with both similar and contrasting properties compared to the case of lasers. We observed that the pulsing dynamics, such as the one in the top in Fig. 2, occur at frequencies perfectly determined by the feedback delay time. Similarly to the case of lasers with feedback, the feedback delay time defines an external cavity frequency, equal to the inverse of the round-trip time in the external cavity bounded by the RTD and the polarizer: $f=c/2L$, where c is the speed of light in vacuum and L the distance between the RTD output unit and the polarizer (see Fig.1). This frequency governs the periodic oscillations exhibited in the RTD. Fig. 3 illustrates this phenomenon by showing examples of self-pulsing dynamics in which the frequency of the oscillations changes as a consequence of a change of the feedback strength.

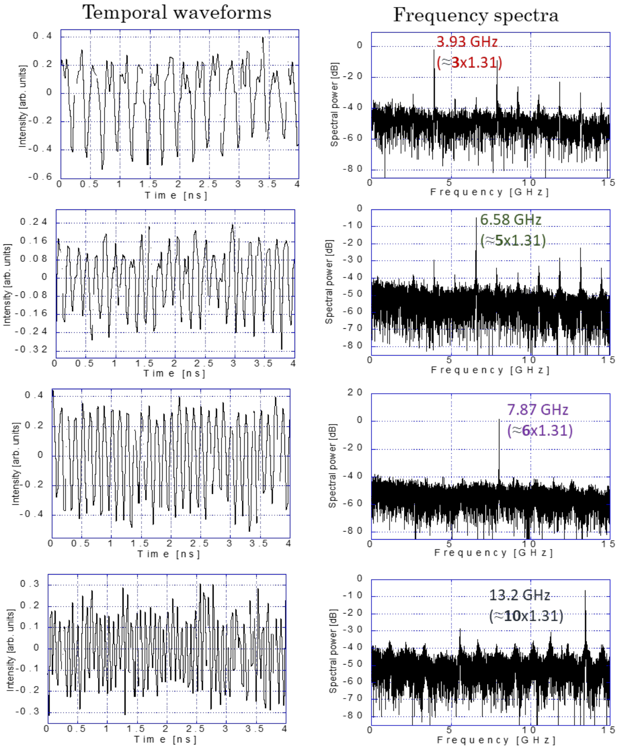

Figure 3: Evolution of the self-pulsing frequency as the feedback strength increases (from top to bottom)

In the curves presented in Fig. 3, the external cavity frequency equals 1.31 GHz. As the feedback strength increases, the frequency of the self-pulsing dynamics exhibited by the RTD increases by multiples of this external cavity frequency. In other words, apart from initial oscillations at the fundamental frequency of the external cavity (1.31 GHz), the RTD is capable to pulse at a large number of multiples of this fundamental one. We observed pulsations at 3 (3.93 GHz), 5 (6.58 GHz), 6 (7.87 GHz) and 10 times (13.2 GHz) the fundamental frequency of 1.31 GHz. We term this phenomenon super-harmonic self-pulsation, as the RTD needs no external modulation to yield oscillations at frequencies multiples of the fundamental external cavity frequency.

4. Dynamical laser/RTD confrontation and discussion

The self-pulsing dynamics presented in the previous section presents common particularities with the case of semiconductor laser with feedback. It has been reported that lasers with feedback can, under appropriate feedback configuration, exhibit pulsing dynamics of the same nature, at frequencies determined by the external cavity [19]. However, there is a major difference between the two cases. In laser systems, such kind of self-pulsing dynamics is only reported in very short feedback configurations (external cavity frequencies above 7-8 GHz) [9, 20] and on top of this, the pulsing frequency is always lower than the external cavity frequency. Indeed, it has been demonstrated that, under the effect of an increasing feedback, the pulsing frequency continuously increases from a value close to the relaxation oscillation frequency and up to the external cavity frequency, yet without reaching its value, as it acts like a horizontal asymptote [21, 22]. By contrast, the evolutions observed in the RTD case reported here is totally different since the pulsation frequency starts at the external cavity frequency and increases by "quantified steps" equal to this same external cavity frequency. The observation of pulsations up to ten times the external cavity frequency presented in Fig. 3 clearly illustrates this contrast with the laser case.

Theoretical studies addressing the question of nonlinear dynamics of RTDs with feedback are very scarce and there is to our knowledge no established explanation to the phenomenon described here. Apart from the intuitive understanding that oscillations at the time scale of the feedback delay time occur in the diode based on the laser dynamics background, the current state of the art lacks of fundamental interpretation of the mechanism at the origin of the observations reported here. In particular, it would be interesting to know if there is a limit to how high the pulsation frequency can rise (up to which harmonic of the external cavity frequency can the system pulse?). We will carry on further experimental investigations to address this question, along with the study of other potential dynamical phenomena that can show up when feedback is changed.

Nonetheless, we suspect that the discrepancy in the timescales governing RTDs and lasers may be a factor at the origin of this difference. In lasers with feedback, two relatively close timescales are involved: the relaxation oscillation frequency (typically 3-9 GHz) and the external cavity frequency (about 0.1-2 GHz in free-space optics with long external cavities and 3-20 GHz in integrated optics with short external cavities). In RTDs there are no relaxation oscillations. The electron tunneling transit time is estimated to be of the fs order, which is several orders faster than the timescale of the feedback delay (few GHz or lower). This large difference between the respective slow and fast dynamics in the two systems may be an origin to the difference in the frequency evolutions observed and discussed here. Generally speaking, the expected dynamics in RTDs could qualitatively differ from the laser case due to this timescale discrepancy.

5. Conclusion

Resonant tunneling diodes have not been a major center of attention in optics up to now. However, with the recent possibility to grow compact antennae on semiconductor structures and the spreading interest for THz technology, studies aiming at performing optical feedback or injection in RTDs can be expected to thrive in the coming years. These compact sources of THz emission are expected to reveal promising features and their technology is likely to play a major role in research oriented towards connecting electronics and optics. Applications in electro-optical conversion, modulation and detection out of the reach of the frequency domain covered by laser systems are already underway. In terms of nonlinear dynamical behaviors, there is for the moment no detailed report of how RTDs behave and bifurcate under feedback conditions. Research in this field is motivated by promising properties for high-frequency modulation, spectral and coherence enhancement, super-harmonic THz oscillations or exploitation of nonlinear THz dynamics.

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