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THz frequency combs form dispersion-compensated antenna-coupled ring quantum cascade lasers

Paolo Micheletti[1,*], *Urban* Senica[1], *Andres* Forrer[1], *Sara* Cibella[2], *Giudo* Torrioli[2], *Mattias* Beck[1], *Jerome* Faist[1], and *Giacomo* Scalari[1]

[1]Institute of Quantum Electronics, Physics Department, ETH Zurich, Zurich, Switzerland
[2]CNR-Istituto di Fotonica e Nanotecnologie, Rome, Italy

Abstract. We report comb operation of RF injected ring Quantum Cascade Lasers. A coupled waveguide approach is implemented for dispersion compensation while passive bullseye antenna improves the device power extraction and far field. Phase sensitive measurements are presented which hints at the presence of soliton state.

1 Introduction

Quantum cascade ring lasers are a promising alternative to the commonly used Fabry-Perot cavities to obtain soliton states. Whispering gallery modes exhibiting a distinct direction of rotation were observed in defect-free circular cavities in mid-IR[2]. In this case the absence of spatial hole burning, in combination with an anomalous dispersion, leaded to the demonstration of solitons. Here we report frequency combs formation in THz QCL ring cavities. The double metal waveguide laser is encapsulated in benzocyclobutene (BCB) on which the top contact is deposited. This allows to explore alternative designs such as ultrathin ring cavities and coupled double ring waveguides for dispersion compensation avoiding issues with the electrical connection of the device and the introduction of unwanted sources of back-scattering. Furthermore, passive metallic structures can be deposited onto the polymer for light extraction and far field engineering.

2 Experimental Results

We report the frequency comb operation in coupled waveguides ring lasers. The two waveguides are designed such that the propagation vectors of the modes in each waveguide are equal for a resonant frequency. These modes then couple forming a symmetric and anti-symmetric supermode where the global GVD is respectively enhanced or depressed [1] (Fig. 2 a). Thanks to the different overlap factor of the supermodes the laser naturally selects the anti-symmetric one which exhibits negative GVD (Fig. 2 b-c).

With this design spectra featuring sech2-shaped envelopes are obtained in free running and RF injected devices (Fig 1 d,e,f), hinting at the existence of soliton regimes in the QCLs. Nevertheless, the absence of any

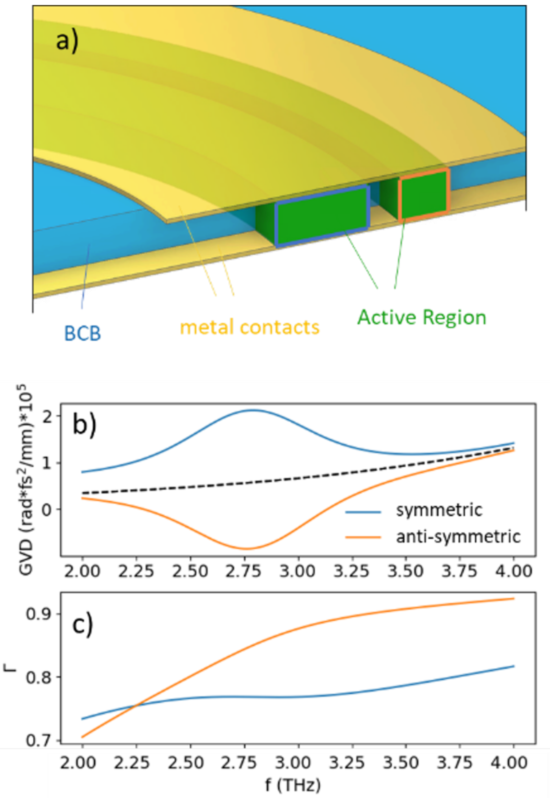

Figure 1. a) Schematic representation of a coupled waveguide ring laser. b) Group velocity dispersion of the symmetric (blue trace) and anti-symmetric (orange trace) super-modes of a coupled waveguide ring laser. The black dotted line represents the GVD of the bare GaAs. c) Overlap factor (Γ) of the symmetric (blue trace) and anti-symmetric (orange trace) supermode. Both GVD and Γ are computed with 2D axisymmetric simulations performed with Comsol Multiphysics.

[*]e-mail: pmicheletti@phys.ethz.ch

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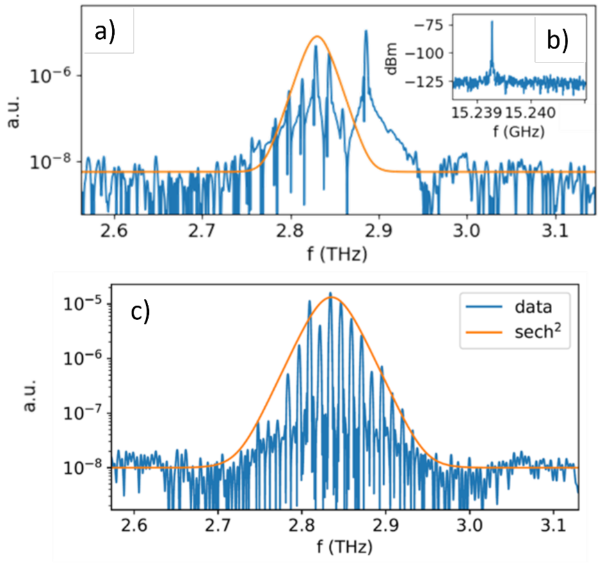

Figure 2. a) Free running Spectrum of a coupled waveguide ring laser with 800 µm radius driven in CW at 1.045A and kept at 37K with its electrically measured beatnote (b). c) Spectrum of a 1 mm radius double waveguide ring laser driven at 700mA in CW and kept at 35K. The device is strongly injected (~ 35 dBm) at the repetition frequency (12.45 GHz).

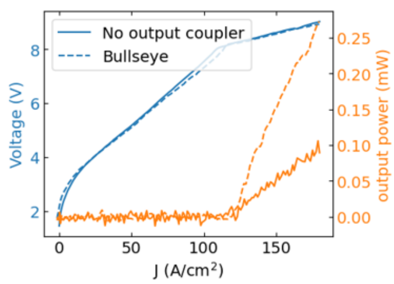

Figure 3. a) Voltage and output power as a function of current density of two devices with (solid lines) and without (dashed lines) bullseye antenna.

source of scattering inevitably, fundamental to obtain soliton states, also leads to low output power. It is therefore difficult to fully characterize the comb state performing phase sensitive measurements such as Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS)[3] as they rely on fast detectors which typically lack in responsivity in the THz domain. To face this challenge a bullseye passive antenna is integrated on top of the double ring laser. Thanks to the strictly axi-symmetric geometry no additional source of backscattering is introduced, while the output power and the far-field of the device are sensitively improved (Fig. 4 a). On these devices SWIFTS can be finally performed under moderate RF injection. Here we report a comb state featuring almost flat phases and a reconstructed waveform consisting of ~5 ps pulses (Fig. 4 b-c).

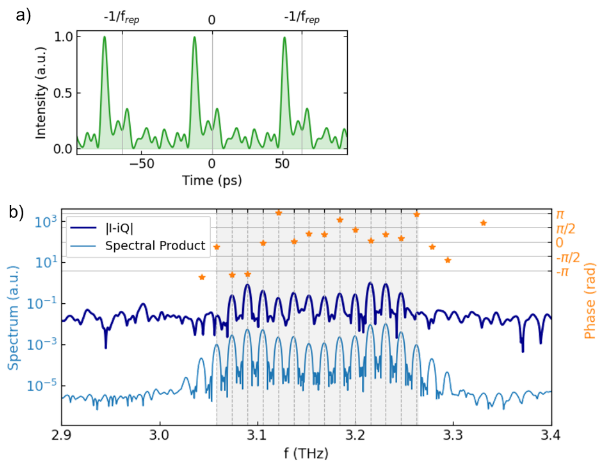

Figure 4. a) Reconstructed intensity profile of an 800 μm radius double ring laser with bullseye antenna. The relative Spectral product (i.e. $I(\omega)I(\omega + f_{rep})$ (light blue), SWIFT spectrum (dark blue) and the modes phases (orange stars) are reported in b).

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