505. Dominik Schock, Michael Jaidl, Dominik Theiner, Florian Pilat, Aaron Maxwell Andrews, Rahul Yadav, Gottfried Strasser, Benedikt Schwarz, Sascha Preu, Marie Ertl, Anna Invernici, Lucas Grandits, Elias Plankenbichler[1 2], Daniel Saleh[1 2], Juraj Darmo[1 2], Karl Unterrainer "Phaser – An Integrated Photon Source and Phase Shifter in the Terahertz Range", Talk: ITQW2025, St.Malo, France, 01.09.2025 – 05.09.2025

Phaser - An Integrated Photon Source and Phase Modulator

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Abstract—**Phase modulation is an essential technique in optics for sensing and communication applications. We demonstrate a monolithic integration of a light source and phase modulator unified within a single on-chip device called a phaser. By injecting high-frequency power into a ring QCL, we induce phase modulation, generating spectral sidebands with modulation indices up to 0.6π at modulation frequencies up to 14.5 GHz. The resulting laser emission forms a high-quality, phase-locked frequency comb.**

1. Introduction

Phase modulators are essential for photonic switching and are thus essential for all types of photonic systems, including interferometers, integrated circuits, and quantum computing [1]. While various phase modulation techniques for moderate switching speeds exist, fast and efficient modulators remain limited. The main technique suitable for photonic integrated circuits (PIC) is based on semiconductor p-n junctions, providing switching rates of tens of GHz [2] but is prone to suffer from considerable parasitic absorption modulation.

Because of the highly asymmetric gain profile of quantum cascade lasers (QCLs), phase modulation can be achieved by modulating the gain of the laser medium instead of using an external device. This results in the generation of sidebands around the carrier frequency, spaced by multiples of the modulation frequency, which, by definition, form a frequency comb [2,3,4].

The real part of the intersubband susceptibility in QCLs is highly asymmetric due to Bloch gain [5,6] and the resulting linewidth enhancement factor [7], both crucial for frequency comb formation. Therefore, the modulation of the gain strongly affects the real part of the susceptibility, which should lead to significant phase modulation. Additionally, the fast gain dynamics of QCL allow for very high modulation bandwidths [8,9]. To enhance the phase modulation, a ring geometry is used, allowing the electromagnetic wave to undergo multiple roundtrips within the cavity before exiting, thereby extending the path length inside the structure.

2. Results

We show that harmonic RF driving of the phaser generates sidebands around the single-mode center frequency (Fig. 2b), following the RF frequency (1.5–14.5 GHz) and forming frequency-equidistant modes (Fig. 2a). These modes are not constrained by the cavity modes and can be continuously detuned across the entire RF range. Optical beat note measurements (Fig. 2c) confirm comb formation, with a linewidth of 3.5 Hz, demonstrating the superior quality of the comb itself. Unlike the classical phase modulation picture, where the carrier power gets redistributed to its newly generated sidebands, in the phaser system we show that the central mode remains at a constant power while sidebands grow. This leads to an increase of total emitted photons and QCL driving current due to enhanced photon-assisted transport [10]. Furthermore, at full modulation, a significant enhancement in extraction efficiency (nearly double) of the energy stored in the upper laser levels of the QCL was observed. To confirm that the phaser output is indeed a frequency comb generated by phase modulation, SWIFTS measurements [11] are performed, which show a linear phase difference. This suggests that phase modulation dominates over amplitude modulation in our system. By adjusting the QCL's driving current, a transition from single-mode to multimode operation is possible, forming a free-running frequency comb. Adding an RF signal generates sidebands on multiple modes, creating distinct mode groups: the inherent free-running mode spacing of 13 GHz and the grid imposed by the applied phase modulation. By comparing the measured spectral shape with the classical phase modulation model, an effective modulation of >0.6π can be estimated.

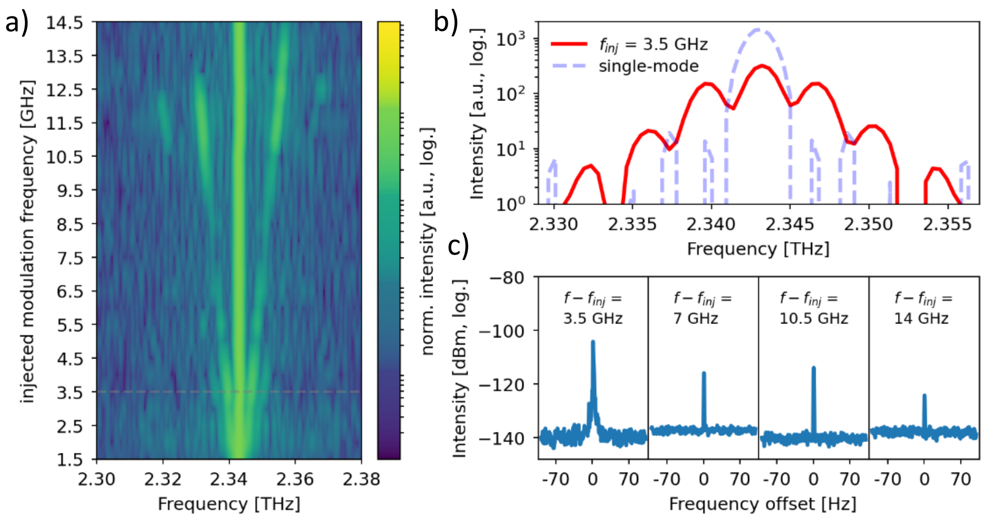

Figure 1: Phase modulation of the ring QCL in the single-mode regime. a) Spectral intensity map in dependence of the injected RF with a nominal power of 18.9 dBm from 1.5 to 14.5 GHz. b) Comparison of single-mode and phase-modulated spectra at 3.5 GHz modulation frequency. c) Optical beat note spectrum.

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