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Study of Electrically Excited Photon-Photon Resonances in Self-Injection-Locked Coupled-Cavity VCSELs

M. Lindemann[1], N.C. Gerhardt[1], M.R. Hofmann[1], N. Ledentsov Jr.[2], V.A. Shchukin[2], N.N. Ledentsov[2], O.Y. Makarov[2], V. Zerova[2], M. D'Alessandro[3], A. Tibaldi[3] and J.P. Turkiewicz[4]
[1] Photonics and Terahertz Technology, Ruhr-Universität Bochum, Bochum, Germany
[2] VI Systems GmbH, Hardenbergstr. 7, Berlin 10623, Germany
[3] Dipartimento di Elettronica e Telecomunicazioni, Politecnico di Torino, 10129 Torino, Italy
[4] Warsaw University of Technology, Warsaw 00–665, Poland
Markus.Lindemann@rub.de

***Abstract*—We investigate photon-photon resonances in laterally coupled mini-arrays of vertical-cavity surface-emitting lasers under electrical excitation. We observe resonance peaks in the frequency response of the optical signal, which we investigate for each array element and spectral modes. Furthermore, we show self-injection locking with modulation bandwidth enhancement.**

Keywords— vertical-cavity surface-emitting laser, photon-photon resonance, injection-locking, coupled cavity laser

I. INTRODUCTION

While the demand for high modulation speeds of vertical-cavity surface-emitting lasers (VCSELs), typically used for short-haul interconnects, is increasing continuously, the modulation bandwidth of conventional VCSEL devices remains limited. The limiting factor is the relaxation oscillation frequency (ROF) caused by the intrinsic photon-carrier resonance of each device. The ROF increases as the square root of the current density, thus high ROF is associated with high current densities and strong overheating, limiting ROF and reliability. Thus, alternative concepts to increase the modulation speed of VCSELs are needed. Proposed approaches include using polarization instead of intensity dynamics, to enable modulation frequencies above 200 GHz [1], integrating an electro-optical modulator [2], including resonances in the modulation bandwidth curve [3], or adding built-in injection-locking [4-6]. In this work we investigate 2x1 mini-array VCSELs with laterally coupled cavities, which exhibit additional features in their modulation bandwidth curve due to photon-photon resonance (PPR) and self-injection locking (SIL), depending on the bias current. The devices are electrically modulated up to 70 GHz and the output is analyzed with a streak camera. In contrast to our previous work [7, 8], which used optical pulse injection [7], here we use electrical modulation.

II. EXPERIMENT

A. Experimental Setup

We use a 2x1 mini-array device which is connected to a Keysight E8257D PSG Analog Signal Generator. The maximum modulation frequency of this configuration is 70 GHz. Small-signal modulation is used. The VCSEL light is either coupled into a spectrometer and then into a Hamamatsu streak camera, or directly into the streak camera, enabling both spectrally and spatially resolved analysis. The streak camera configuration used for these measurements ensures temporal resolution of approximately 9.3 ps and is therefore suitable for measuring the frequencies expected from the modulation input.

The laser emission spectrum has two distinct states: (a) below 8 mA – the first mode group consists of two modes and (b) above 8mA – where injection locking between these modes occurs and only one "master" mode lases. Figure 1 shows the spectra measured with and without self-injection mode locking demonstrating this effect.

B. Two Mode Photon-Photon Resonance

In the first state (a), a narrow PPR peak feature can be observed in the frequency response, and the resonance frequency is equal to the frequency difference between the optical modes, similar to results reported previously under optical excitation [7].

We find that the phase of the modulation intensity emitted by the two modes depends on the relation of electrical modulation frequency and PPR frequency, the latter being defined by the frequency difference of the fundamental supermodes. When electrical modulation frequency corresponds to the PPR frequency, the two intensities oscillate anti-phase (see traces in Fig. 2 for 49.528 GHz), otherwise in-phase (see traces in Fig. 2 for 49.377 GHz). The frequency difference between the supermodes is controlled by the bias current (see [7]), so the frequency at which anti-phase behavior occurs, is controlled by the bias current as well.

In the injection locked case (b), a broader PPR resonance is observed in the frequency response.

C. Self-Injection Mode Locking

We have shown that for bias currents below 8mA, two separate supermodes are observed and their frequency difference defines the PPR frequency [7]. For bias currents

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above 8 mA emission from only one of the supermodes can be observed, as a result of the SIL. This can be seen in Fig. 1: The spectrum for 7 mA bears two close peaks (marked by the black arrows), while the spectrum for 8 mA has only one peak, corresponding to the frequency expected for the lower supermode.

D. Modulation Responses

Modulation responses have been measured for the PPR and SIL cases and are depicted in Fig. 3. The case for PPR shows the PPR frequency peak marked with a red arrow, and at a frequency corresponding to the supermode frequency difference. The 8 mA response shows the SIL case. A broader peak around 42 GHz can be observed. The position of the resonance peaks is the same if measured under electrical modulation or optical excitation for both two-mode PPR and SIL. The spectrum is not corrected for the RF signal reflection (S21) related to the electrical impedance of the MA VCSEL mesa. Consequently, the shape of the modulation response at high frequencies is not intrinsic but limited by the electric parasitic bandwidth.

III. CONCLUSION

We have investigated coupled-cavity 2x1 mini-array VCSELs exposed to high frequency electric signal. Under resonance frequency excitation matching the photon-photon resonance frequency an anticorrelated intensity modulation of the light intensity in the coupled apertures is observed. We have shown that the intensities of the light emitted from the apertures of the device oscillate anti-phase with electrical modulation at frequencies close to the PPR frequency. The narrow photon-photon resonance peak can be excited by pulsed and sinusoidal modulation and might be of interest for applications requiring high-frequency optical beat notes, such as, e.g., radio-over-fiber. At higher currents self-injection mode locking is revealed and a broad modulation intensity resonance restricted by electrical impedance is found. With further optimization of the design both narrow resonance and broad frequency resonance applications can be optimized. We note that the novel effect of antiphase intensity modulation under single-phase high-frequency external electrical excitation may enable new applications in sensing and coherent data transmission.

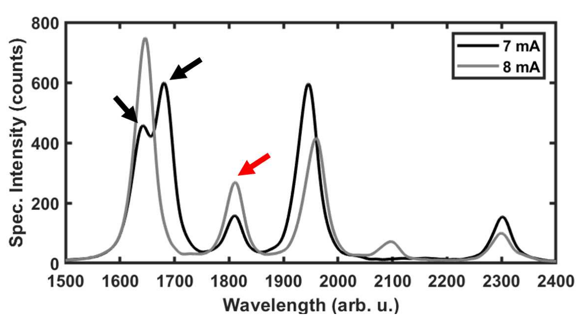

Fig. 1. Spectra for PPR case (7 mA) and SIL case (8 mA). To identify whether the single remaining mode in state (b) at 8mA corresponds either to the high or low wavelength mode in state (a) at 7mA, we compensated the current induced red shift by shifting the the 8 mA spectrum along the wavelength axis to align to the 7 mA spectrum at the peak marked with the red arrow.

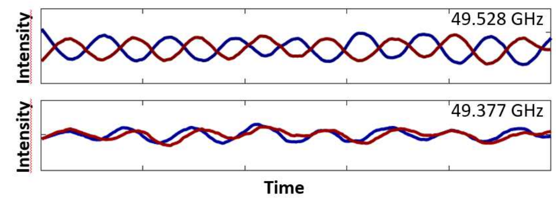

Fig. 2. Intensity emitted by the two apertures (red and blue trace each correspond to one aperture) of the mini-array with modulation at the PPR frequency.

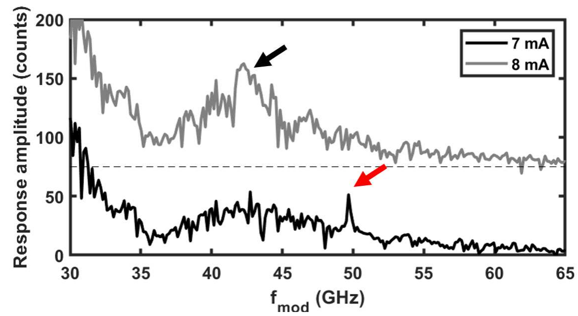

Fig. 3. Modulation Response for PPR case (7 mA) and SIL case (8 mA). The red arrow marks the PPR frequency peak. The black arrow marks the broader response induced in the SIL case, while no PPR peak is visible in the SIL case. The 8 mA response is vertically shifted 50 counts up.

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