Coupling strategies for coherent operation of quantum cascade ring laser arrays

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Abstract. We report the design, fabrication and operation of coherently coupled ring cavity surface emitting quantum cascade lasers, emitting at wavelength around 8 μm. Special emphasis is placed on the evaluation of optimal coupling approaches and corresponding parameters. Evanescent field coupling as well as direct coupling where both devices are physically connected is presented. Furthermore, exploiting the Vernier-effect was used to obtain enhanced mode selectivity and robust coherent coupling of two ring-type quantum cascade lasers. Investigations were performed at pulsed room-temperature operation.

Keywords: Evanescent field coupling, quantum cascade laser, coherent coupling.
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INTRODUCTION

Since quantum cascade lasers (QCLs) [1] represent compact reliable coherently emitting devices in the mid infrared (MIR) and terahertz (THz) spectral region, investigations with respect to their material system and especially their resonator design are highly appreciated. Several tasks call for high optical output power and selectable emission wavelength. This fact makes considerations of two dimensional QCL arrays become essential. Moreover, coherent coupling in such arrays plays an important role since it results in a significant enhancement of the spatial and spectral brightness. This application promises not only power enhancement under retention of coherence, coupled devices with different resonators can achieve increased mode selectivity by exploiting the Vernier effect.

Recently, our group presented an ideal elementary building block for such QCL arrays, the ring cavity surface emitting lasers (ring-CSELs) [2]. This resonator type provides the feasibility of producing symmetric low divergence optical beams combined with single-mode operation, reduced thresholds and enhanced radiation efficiency. It incorporates a ring shaped resonator, holding a second order distributed feedback (DFB) grating on top that acts as a Bragg reflector for surface light extraction.

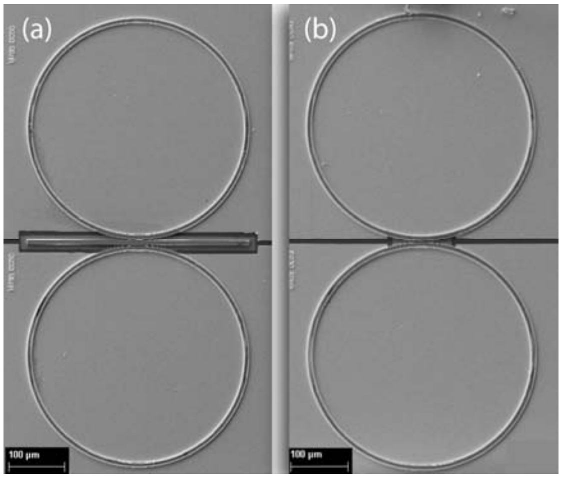

Figure 1 Scanning electron microscopy image of the realized coupling designs. (a) The ring-CSEL devices are directly coupled via a straight ridge waveguide. (b) Both light sources are separated by a narrow coupling gap (1 and 3 μm). The excited modes couple via their evanescent fields.

Here, we report investigations on coherent operation of a coupled pair of those ring-CSEL devices. Therefore, the direct coupling approach and the evanescent field coupling (EFC) method were realized (Fig. 1).

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REALIZATION

The experiments were performed using InGaAs/InAlAs superlattices grown on InP substrates by molecular beam epitaxy. The active region of this heterostructure is formed by a 4-well design with a double phonon resonance, emitting at a wavelength of $\lambda \approx 8.05$ µm. All presented coupling structures are based on ring-CSELs with 400 µm outer diameter and a ridge width of 10 µm, as recently published by our group [3 and references therein]. The second order DFB-grating on the top of the cavity serves for surface light emission in the spectral region of about 1240 to 1290 wavenumbers. The waveguiding structures were formed by means of reactive ion etching (RIE). For the top contact, a 300 nm gold layer was evaporated on a 330 nm passivation layer of SiN that ensures electrical insulation to the subjacent heterostructure. The direct coupled geometry was used to form a structure of coupled devices with enhanced mode selectivity along with a gain in mode stability. Therefore, two ring-CSELs were directly coupled via a Fabry-Perot (FP) waveguide with dimensions of 400 x 10 µm (Fig. 1 (a)). The involved elements are physically connected, what is represented by a coupling gap of 0 µm. The EFC approach was realized for two ring-CSELs, placed next to each other and separated by a gap (designs with 1 µm and 3 µm between the two outer sidewalls, see Fig. 1 (b)). The coupling region was designed to be free of any gold and silicon nitride deposition in a lateral distance of 50 µm around the closest point of the two cavities.

RESULTS

Figure 1 (a) shows the collected optical power and voltage versus current density characteristics of the direct coupled devices pair. Furthermore, this structure expresses a comparable large free spectral range (FSR) of about 6.9 cm^{-1} due to the fact that the lasing modes have to fulfill two resonance conditions given by the corresponding cavities. Each second mode of the FP ridge (FSR = 3.5 cm^{-1}) and every third resonance of the ring waveguide (FSR = 2.35 cm^{-1}) match to form the excited (lasing) modes. The peaky, structured far field is a result of a common coherent operation of both ring-CSELs (Fig. 2 (d)). For a non-coherent operation a continuous ring type shape similar to the far field of a single ring-CSEL (Fig. 2 (b)) would appear.

Characterization of the EFC-device pair showed that a coupling air gap of 1 µm exhibits the best performance in respect of robust coherence and, at the same time low intercavity losses (mode-leakage from one into the other cavity). Beside spectral investigations, coherence was proven by means of the recorded far field. Combined operation of the coupled light sources generates a “star”-shaped beam profile due to the interference of both beams (Fig. 2 (c)). This reveals coherent (phase-locked) operation. A coupling gap of 3 µm, however, causes an insufficient overlap of the evanescent fields, yielding independent (not coherent) operation of the coupled cavities. The gained results open up numerous future prospects for coupled QCLs, up to two dimensional QCL arrays for powerful, monochromatic emission at room temperature.

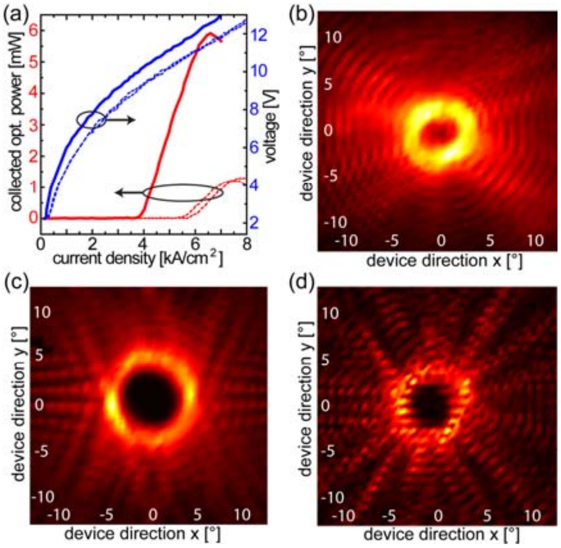

Figure 2 (a) The LIV characteristic of the direct coupled device-pair. Solid lines indicate combined operation, dashed lines single ring operation. While (b) shows the far field of one ring-CSEL, (c) and (d) depict the far field of the EFC and the direct coupled devices, respectively.

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