Photonic Engineering of Intersubband Devices

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Photonic cavities play a crucial role when engineering laser as well as detector elements. In the particular case of intersubband optoelectronic devices they are essential for light in- and out-coupling. We discuss three novel realizations of optical cavities that are used for a quantum well infrared photodetector (QWIP) and quantum cascade lasers (QCLs). Photonic crystals are employed for QWIPs in order to investigate their feasibility as a resonant detection scheme. A new waveguide design was developed that increases the coupling efficiency of a distributed-feedback (DFB) grating and hence allows fabricating ultra-short surface emitting DFB QCLs. Finally we have realized ring shaped DFB lasers that naturally exhibit a circularly shaped far field. Moreover, single-mode surface emitting ring QCLs have a reduced divergence of only 3° in either direction.

Introduction

Intersubband (ISB) transitions in the conduction band of III-V semiconductors are used to realize optoelectronic devices in the mid-IR (3 – 25 µm) as well as in the THz region (60 – 200µm). Quantum cascade lasers (QCLs) being intersubband based lasers have undergone tremendous progress since their invention in 1994 and are nowadays close to their exploitation in real world applications like trace gas sensing, spectroscopy or free-space communication. The level of output power is already in the Watt regime with wall plug efficiencies above 10% at room temperature and under continuous wave (cw) operation. Their detector counterparts – quantum well infrared photodetectors (QWIPs) – are also well developed, having several advantages over band gap based detectors like a ultra fast response time enabling transfer rates up to 30 GHz and are mature in growth and processing methods, which makes them interesting applications in the field of thermal imaging.

As a special property of ISB transitions they have a polarization selection: the electric field of the generated/absorbed light has to be polarized normal to the epitaxial layers. In order to realize surface emitters or detectors being sensitive to surface incident light a diffractive element like a grating or a photonic crystal (PhC) is required, which places an additional demand on photonic engineering of intersubband devices.

Photonic Crystal Defect States in Intersubband Detectors

As mentioned above, QWIPs have potential applications in thermal imaging. In order to make a single pixel sensitive to surface incident light such multi-pixel arrays usually carry gratings that diffract the light. Using (deep etched) photonic crystals instead of (shallow) gratings would have the advantage of providing a resonant detection. The light is not just redirected and passes the detecting layers one time but it is coupled resonantly into the cavity and the absorption probability can be enhanced. In this way the drawback of QWIPs, namely the inferior signal-to-noise behavior, can be improved.

We therefore started to investigate the properties and technical feasibility of PhC QWIPs. We were able to obtain information about coupling efficiency and its correlation to PhC symmetry, polarization dependence [1] as well as linewidth and the behavior of defect modes [2].

Figure 1 shows a comparison between the measured frequency shift of defect modes and results from a 2D finite-element simulation. The defect states were induced by removing a single hole, and by changing the diameter of the six defect surrounding holes (defect holes) a shift of the resonant frequencies was realized. This frequency shift is negligibly small for small defect holes ($r_D < 0.5r$) whereas for larger defect holes an almost linear increase is observed. The results enable us to shift the defect mode to a distinct frequency. And probably even more important is the fact that the region with small defect holes is stable over small inaccuracies in the fabrication process. The geometric dependence was also used to identify the peaks with calculated mode profiles.

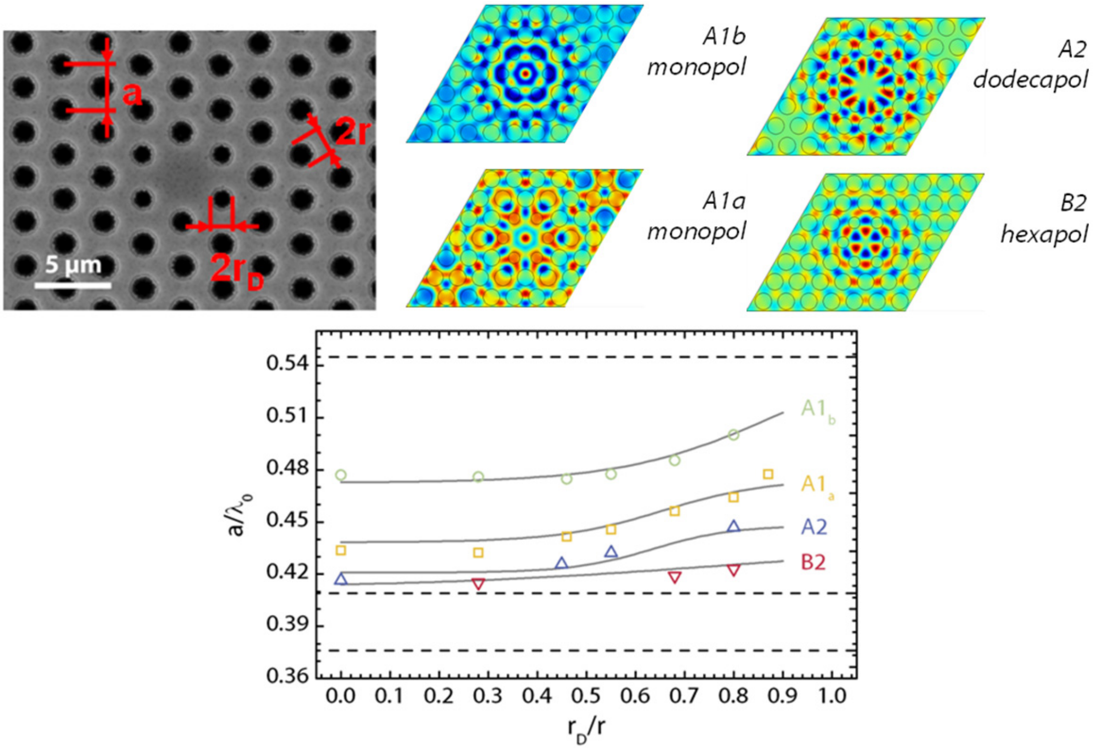

Fig. 1: A scanning electron microscope (SEM) picture with the relevant dimensions of the PhC is shown together with a graph that compares simulated with measured defect modes. The shift was achieved by changing the size of the six defect surrounding holes. Also the mode patterns of the defect modes are shown.

Ultra-Short Distributed-Feedback Lasers

In order to obtain single-mode surface emitting QCLs usually 2nd order distributed-feedback gratings are etched into the surface of ridge lasers. The coupling strength introduced by the grating is determined by the overlap of the waveguide mode with the grating and limits the laser length. Since the overlap is small (~0.2 % → coupling strength ~7 cm^{-1}) lasers have a typical minimum length of around 1 mm. In order to achieve further device minimization we have developed a new type of waveguide that increases the modal overlap.

The small overlap is due to the fact that the grating region is diluted by air and has a low refractive index. This pushes the waveguide mode away from the grating region. In order to overcome this we place a continuous metal layer on top of the grating and an air cladding on the opposite side. In this way the negative effect of the grating is partly compensated since the TM polarized mode is attracted by the metal. In addition the large step in refractive index from the waveguide core to air further improves this effect [3]. Finally we were able to increase the modal overlap with the grating region by roughly one order of magnitude.

The structure was realized by wafer-bonding the pre-structured laser chip grating-down on a gold covered, doped GaAs template. The grating is therefore sandwiched between the laser's active region and the continuous gold layer. The air cladding on the opposite side was fabricated by removing the substrate on the laser chip by selectively wet-etching and subsequent standard laser processing that includes lateral contact stripes leaving out an air window. The light out-coupling takes place via this air window.

The fabricated devices operate in single-mode down to a length of 180 µm being significantly smaller then 1 mm as for standard DFB QCLs. Lasing threshold as well as slope efficiency are comparable to standard DFB lasers and the waveguide design still leaves room for the reduction of loss without sacrificing coupling strength.

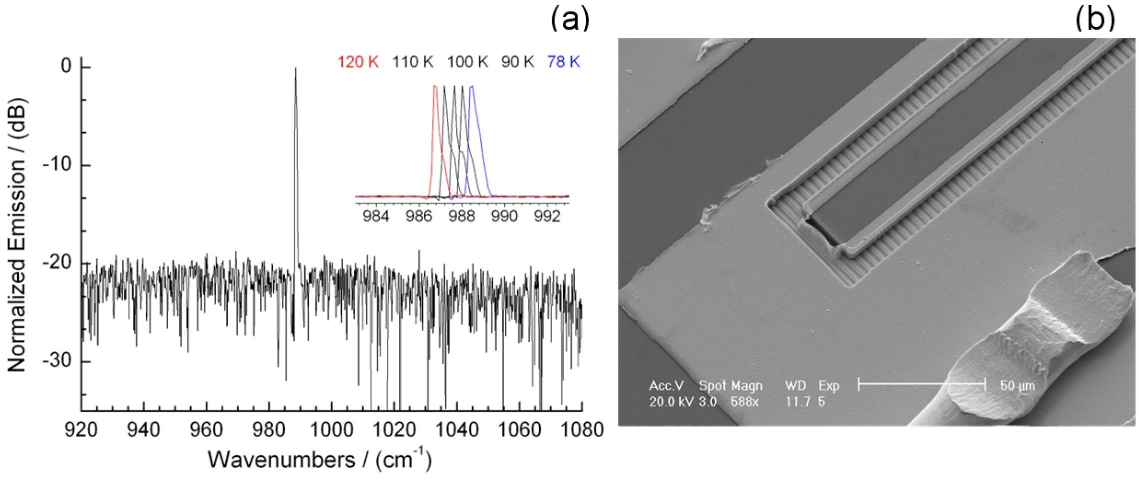

Fig. 2: (a) A single-mode spectrum and the temperature tuning of a 176 µm short DFB QCL fabricated with a combined metal-air waveguide is shown. (b) SEM picture of a finished device. The grating is on the bottom side and can only be seen in the trenches.

Surface Emitting Ring Lasers

A promising concept to address divergence of the output beam is a ring shaped resonator with a radial, light out-coupling grating on top (Fig. 3 (b)). The ring-type emitting area naturally forms a circularly shaped far field and the overall large emission area narrows the beam. The grating is crucial for light extraction via the surface as QCLs are intersubband devices and are therefore restricted to TM polarization. Light propagating normal to the epi-layers – and hence normal to the surface – cannot directly be generated and one needs a diffractive element to realize surface emission. Second order distribute-feedback (DFB) gratings are a perfect choice as they additionally allow for mode selection yielding single-mode surface emitting lasers.

Our group was the first to realize grating coupled, surface emitting ring QCLs in multi-mode [4] as well as in single-mode. [5] Multi-mode devices have a shallow grating that introduces only a small coupling not enough for single mode operation. The emitted far-fields are ring to point shaped, depending on the detuning of the lattice period. If the grating period matches the center of the emission spectrum, the far field forms a single spot with a full-width-at-half-maximum (FWHM) of around 10°. This value is limited by the broadness of the emission spectrum as a slight detuning causes angled emission. Lasing threshold is similar to those of Fabry-Perot type cavities, which is expected as the waveguide loss is unchanged and mirror loss for standard cavity lengths is comparable to out-coupling loss introduced by the grating.

The far fields emitted from single-mode devices show a clearly reduced FWHM below 3° (Fig. 3 (a)). This is due to the spectral narrowing induced by the DFB grating which has a higher coupling coefficient. Along with the increased coupling that leads to single-mode operation also the out-coupling is increased. This influences lasing threshold in a negative way but benefits slope efficiency so that at typical operating currents efficiency is identical to multi-mode devices.

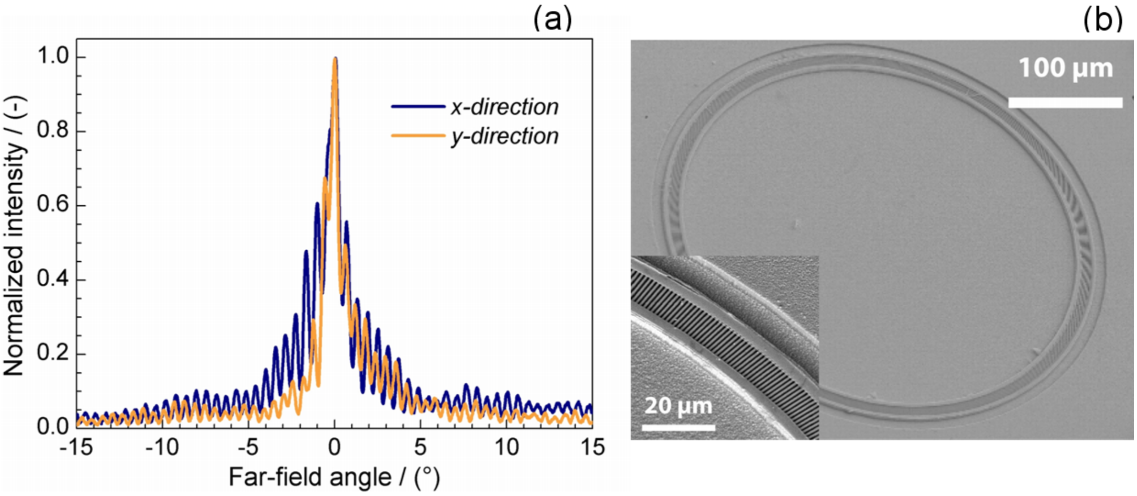

Fig. 3: (a) The far-field of single-mode surface emitting ring QCL has a FWHM of 3° (b) Top view SEM of a fully processed device.

Acknowledgements

Appart from the GMe we acknowledge partial support by the following projects and agencies: IRON, ADLIS, PLATON, and MNA.

References

[1] S. Schartner et al., *Appl. Phys. Lett.* **89**, 151107 (2006)

[2] S. Schartner et al., *Opt. Express* **16**, 4797 (2008).

[3] S. Schartner et al., *Opt. Express* **16**, 11920 (2008)

[4] E. Mujagić et al., *Appl. Phys. Lett.* **93**, 011108 (2008)

[5] E. Mujagić et al., *Appl. Phys. Lett.* **93**, 161101 (2008)