Photonic crystals used as resonators for terahertz quantum-cascade lasers

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***Abstract*— The authors present the integration of photonic crystals (PC) with a complete bandgap for TM-modes into the active region of terahertz quantum-cascade lasers. The PC are used as frequency selective mirrors to provide the positive feedback. The active region of the laser and the PC are embedded directly into the double-metal waveguide, which has a mode confinement near unity.**

***Index Terms*— Complete bandgap, photonic crystal, terahertz quantum-cascade laser**

I. Introduction

The integration of photonic crystals (PC) and quantum-cascade lasers (QCL) can lead to a powerful set of new devices for various applications, such as multi-wavelength laser, detector arrays, on-chip integration and spectroscopy. The PCs are artificial crystals that have allowed and forbidden bands for the propagation of light. Typically PCs are built up by a regular pattern of air holes inside the active region of a QCL. Such structures have a complete bandgap for TE-modes only but not for TM-modes, which is the polarization of the inter-subband transitions in QCLs [1].

II. Device Design and Fabrication

Here we present the design and fabrication of a PC with a full bandgap for TM-modes to provide positive feedback for the active region. The PC is built up by a triangular lattice of rods surrounded by air. The ration r/a is 0.3 for all periods, where r is the radius of the rods and a the period of the crystal. The period has been varied from 22.18 µm to 35.49 µm. This structure has the first bandgap for TM-modes from 0.2 to 0.28 and the second one from 0.37 to 0.48 in terms of the normalized frequency $f{\cdot}a/c$, where f is the frequency and c the speed of light. For the calculation of the bandstructure a 2D model has been used [2]. A calculated bandstructure is shown in Fig. 1.

The devices are built up by a core, which generates the necessary optical gain, and two or four unit cells of the photonic crystal, which surround the core. The core and the PC are defined by reactive ion etching (RIE) using a SiN_x etch-mask. The devices are fabricated into a high-confinement double-metal waveguide using an Au-Au thermo-compression bonding [3]. A SEM-picture of the processed device is shown in Fig. 2, the inset in Fig. 2 shows the core and the surrounding PC before the wafer bonding. The double-metal waveguide forces the mode to propagate inside the PC and prevents mode-spreading into the substrate or leakage through the surface.

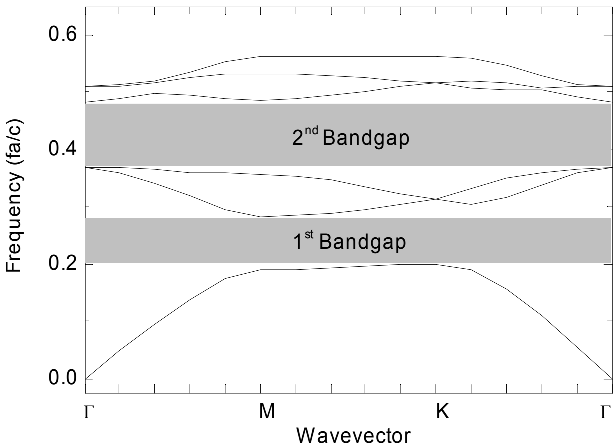

Fig. 1. Calculated bandstructure of the PC. The first two bandgaps for TM-modes are shown.

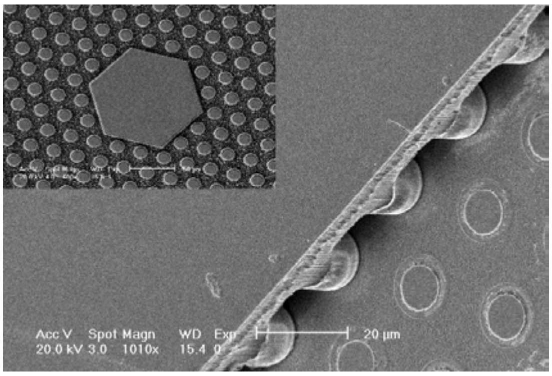

Fig. 2. Phctonic crystal resonator after the wafer bonding. The thickness of the waveguide is 15 µm. The inset shows the core and the surrounding PC before the wafer bonding.

III. Measurement Results

To be able to isolate the effect of the PC, reference cavities, which are made up by the hexagonally shaped core without the surrounding PC, have been processed as well. Two

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different samples have been used for the active region. Sample (a) emits between 2.8 and 2.9 THz, sample (b) between 2.45 and 2.7 THz [4]. Spectra of sample (a) with and without PCs are shown in Fig. 3. There is hardly any change in the spectrum between the cavities with a PC and the reference cavities, if the bandgap of the PC is in the region of the maximum gain of the QCL. If the gain maximum and the bandgap don't overlap, then the emission is shifted into the bandgap. This shows clearly that the PC acts as a mirror, which is capable of changing the emission frequency, as long as the active region provides the necessary gain. The simulation is in good agreement with the measurements as the vertical confinement of the mode is strong and only the first order mode in vertical direction can propagate, both effects are due to the double-metal waveguide.

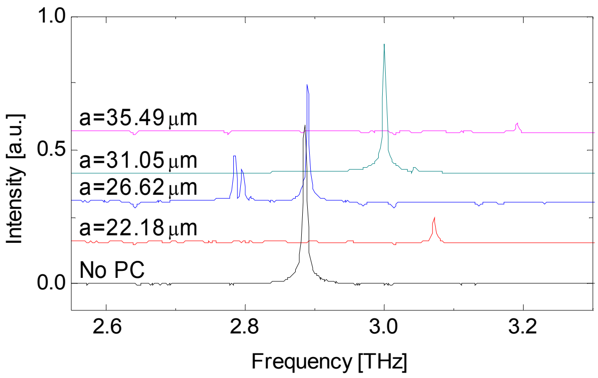

Fig. 3. Spectra of sample (a) with and without PC. The period of the PC has been varied from 22.18 to 35.49 μm. The emission is shifted from the gain maximum of the active region into the bandgap.

IV. Conclusion

We presented the use of PC with a complete bandgap for TM-modes as mirrors for THz QCLs. The emission of the QCLs was tuned through the gain region away from the gain maximum of the active region into the bandgap of the PC. Due to the high reflectivity of the mirror it was enough to use only one period of the PC to achieve the desired effect.

References

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