Photonic Crystal Frequency Control in Terahertz Lasers

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We present the design and the fabrication of a photonic crystal with a complete bandgap for TM-modes. The photonic crystal is used as a resonator for terahertz quantum-cascade lasers. This allows us to control the emission frequency of the devices within the gain region precisely.

Introduction

Designing microresonators for semiconductor lasers is a challenging task. Aspects such as cavity quality factor, laser far-field, lasing threshold or output power have to be balanced. All of them are greatly influenced by the resonator. The widely used standard resonator geometries, such as Fabry-Perot or ring resonators, do not allow meeting all the requirements simultaneously. The full control over the dispersion relation is required.

Photonic crystals (PhCs) offer exactly this unique feature, the control of optical properties on a sub-wavelength scale [1]. All device characteristics such as quality factor [2] or lasing far-field [3] can be designed. For the realization of compact lasers, direct integration of an active gain medium into the PhC is the most promising solution. However, for conventional semiconductor lasers, this approach is limited by the greatly increased device surface which leads to strong increase in surface recombination and leakage currents. Any benefit gained by the improved resonator is destroyed by the increased threshold current. Therefore, it is necessary to separate both components spatially, leading to increased device size and complexity. Quantum-cascade lasers (QCLs), being unipolar devices, do not suffer from any of these parasitic effects, which make them the ideal choice for monolithic solutions. Since their realization in 1994 [4], QCLs have become the preferred source in the mid-infrared and terahertz (THz) spectral region, covering wavelengths from 3 to 300 µm.

Design of Photonic Crystals

The present work describes the design and fabrication of PhC-resonators for THz-QCLs. The PhC used consists of free standing pillars which are surrounded by air. A calculated band structure for the ideal PhC is presented in Fig. 1. This two-dimensional array is embedded in a double-metal waveguide for vertical confinement. The pillars have diameters between 12 and 21 µm which make them significantly smaller than the emission wavelength of typically 120 µm. The period of the PhC is in the range of 22 to 35 µm, resulting in a filling factor of only 33%. The sub-wavelength pillars are fabricated directly from the active THz quantum cascade layer structure. Thereby, we are able to realize all components monolithically.

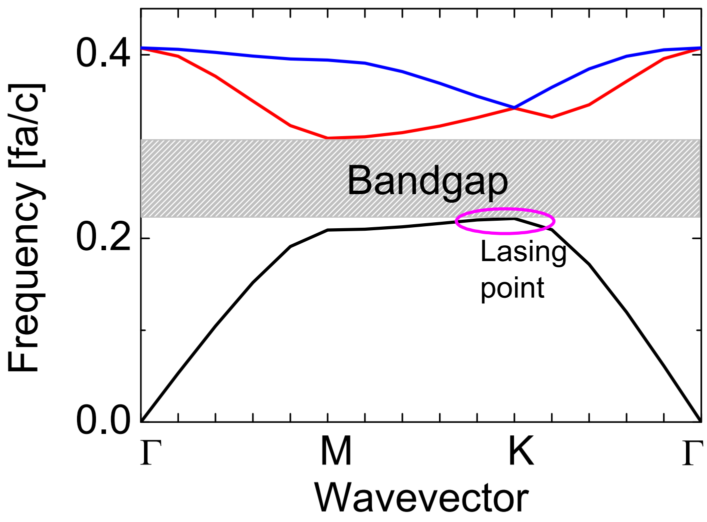

Fig. 1: A calculated band structure for the perfect, two-dimensional PhC. The first full bandgap for TM-modes is clearly visible.

Experimental Results

We start with devices based on a bulk gain region which is surrounded by a PhC-mirror. Both components are embedded in a double-metal waveguide which ensures strong interaction of the optical mode with the PhC and prevents any out-of-plane scattering. This approach achieves a reasonable frequency control while maintaining a simple processing based on standard planar processing technology. Spectra for PhCs with periods ranging from 22.18 to 35.49 µm are presented in Fig. 2.

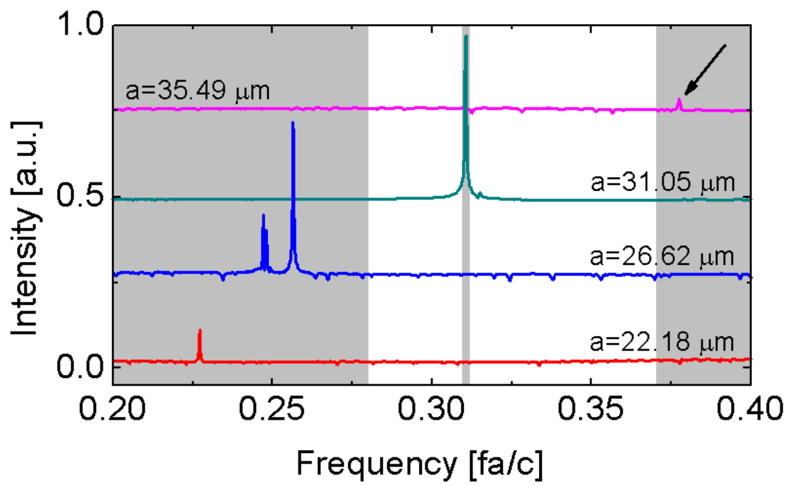

Fig. 2: Measured spectra for the PhC-resonator with different PhC-periods. The emission can be tuned from the gain maximum of the active region into the bandgap of the PhC-mirror.

The second type of devices omits the bulk gain region [5], [6]. Instead the pillars themselves provide the necessary optical gain as they are fabricated directly from the active region THz quantum-cascade layer structure; a SEM-image of the finished device is shown in the inset of Fig. 3. This resonator type requires a substantially more complicated processing. However, it offers some advantages compared to the first approach, such as small cavity volumes, stable single-mode emission or large tuning range. We are able to achieve resonators with diameters of 240 µm, comparable to twice the emission wavelength. It is important to stress that only 1/3 of the volume contains gain region. Nevertheless, the strong index contrast between the active region and the surrounding vacuum allow us to achieve a modal confinement of 95 %. The strong optical coupling of the lasing mode and the PhC results in stable-single mode emission for all driving currents, results for a PhC with a 26.62 µm period are shown in Fig. 3. Varying the PhC period allows us to tune the emission frequency over 400 GHz, this is significantly larger than the typical gain bandwidth of THz-QCLs of only 130 GHz [7].

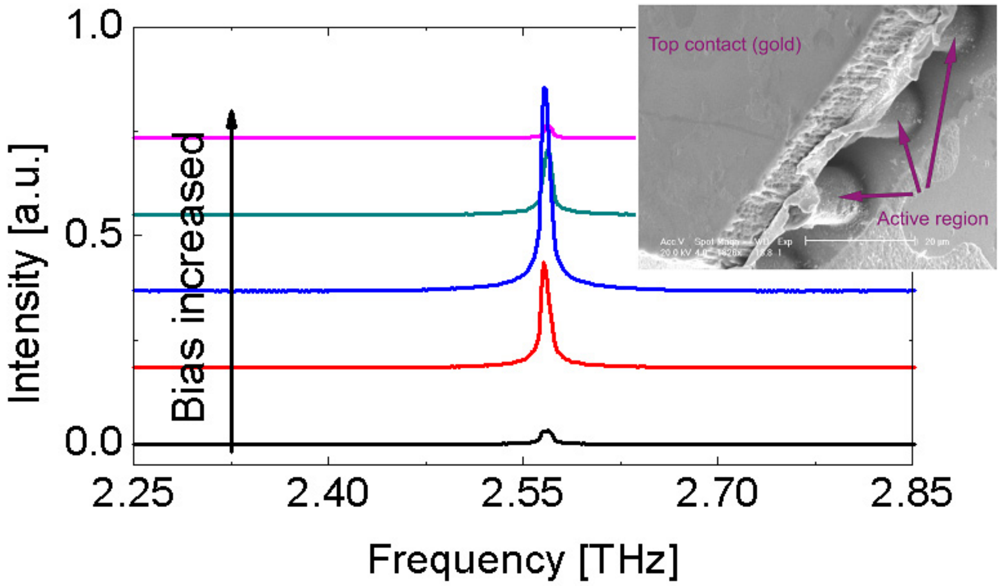

Fig. 3: Measured spectra for the active PhC-resonator with a period of 26.62 µm. The stable single-mode emission under all driving conditions is clearly visible. The inset is showing a SEM-picture of the facet.

Conclusion

We have presented different resonator concepts for THz-QCLs based on PhC. The designable dispersion of the PhCs allows us to tune the optical properties of the resonators on a sub-wavelength scale. The emission wavelength can be adjusted to almost any value within the gain bandwidth.

Acknowledgements

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References

[1] J. D. Joannopoulos, S. G. Johnson, J. N. Winn and R. D. Meade, “Photonic crystals – Molding the flow of light”, Princeton University Press, 2008

[2] Y. Tanaka et al., Nature Materials 6, 862 (2007)

[3] Y. Chassagneux et al., Nature (London) 457, 174 (2009)

[4] J. Faist et al., Science 264, 553 (1994)

[5] H. Zhang et al., Opt. Express 15, 16818 (2007)

[6] A. Benz et al., Opt. Express 17, 941 (2009)

[7] J. Kröll et al., Nature (London) 449, 698 (2007)