Monolithic photonic crystal quantum-cascade laser

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Abstract. We present the design and realization of active photonic crystal (PhC) terahertz quantum-cascade lasers. The devices consist of sub-wavelength isolated pillars which are embedded in a double-metal waveguide. The lasing is observed at flat-band regions not in the bandgap itself. A stable single-mode emission under all driving conditions is achieved.

1. Introduction
With the development of terahertz (THz) quantum-cascade lasers (QCLs), monolithic and coherent sources for the THz spectral region have become available [1]. The main applications are real-time imaging [2], heterodyne detection [3] or spectroscopy [4]. Due to the inhomogeneous gain broadening typically a multi-mode emission is observable [5]. For precise frequency control, the optical properties of the resonator have to be designed. The direct integration of photonic crystals (PhC) into the laser resonator allows to combine the full control over the dispersion relation with small modal volumes [6, 7].

Here, we will show the design and realization of two-dimensional PhC which are embedded in a high-confinement double-metal waveguide. The PhC consists of isolated, sub-wavelength pillars which are fabricated directly from the active region of the THz-QCLs. This allows their use as the gain region making any bulk gain region redundant [8, 9].

2. Active photonic crystal lasers
These lasers operate in the slow light regime next to the bandgaps, there are no states inside the bandgap as there are no defects incorporated. The calculated PhC bandstructure is illustrated in the inset of Fig. 1. This allows for a very precise frequency selection for the lasing mode as the slow-light regime works only for a narrow frequency range. Therefore it is easy to greatly reduce the number of emission modes [6, 7]. The optical gain in these structures is spatially separated, every single pillar is used to provide gain. It has to be pointed out that the pillars are of sub-wavelength dimension.

For the finite-difference time-domain (FDTD) simulations we use the MIT Electromagnetic Equation Propagation-package [10]. We arrange 37 infinitely high pillars in a two-dimensional (2D) array. The simulations predict two closely spaced modes, shown in Fig. 1. One corresponds
to the K-point, with a Q-factor of 1000, the other to the M-point, with a Q-factor of 60, in the bandstructure. For frequencies above 0.3 [fa/c] additional modes appear corresponding to higher bands of the PhC. In between, the full bandgap is clearly visible.

The active PhC lasers realized consist of 15 µm high, free-standing pillars which are embedded in a double-metal waveguide. All pillars are fabricated from the active region of a THz-QCL. The electric field distribution and the energy density for such a structure can be calculated very easily. The structure achieves a modal energy confinement of 95 %. The challenging task for the processing is the formation of the waveguide and the pumping of all the pillars as they are not interconnected. Details on the realization of these devices are given in Ref. [7]. The reason to attack this highly challenging processing is, apart from the beautiful physics, the theoretically predicted improvement in device performance. These 2D-PhC are predicted to give strong gain enhancement [11, 12, 13]. It is proportional to the overlap of the mode with the gain region multiplied by the time the mode spends inside the PhC. The group velocity and the modal overlap are both design parameters of the PhC, allowing to optimize both values at the same time.

The experimental data shows an excellent agreement with the theoretically predicted results. There is only one lasing mode visible corresponding to the K-point with the higher Q-factor. Measured spectra are showing the stable single-mode emission under all driving currents, an example for a device with a 26.6 µm period is shown in Fig. 2. The small discrepancy between the simulation and measurement is attributed to the uncertainty of the refractive index and the effects of the metallic waveguide. The predicted lasing mode is at 0.215 [fa/c] or 2.45 THz for this device.

These devices do not show any dependence of the emission frequency on the device size. This is not surprising as the lasing mode is defined by the photonic crystal itself and not by the position of any mirrors or facets. This concept shows already its high potential for the resonator tuning. It is easily possible to define the emission frequency of the device simply by changing the

**Figure 1.** Calculated spectrum for the active PhC. The two modes correspond to the M- and K-point. The inset is showing a calculated bandstructure for the ideal PhC.
Figure 2. Measured spectrum for the active PhC with a period of 26.6 µm. The stable single-mode emission independently of the applied bias is clearly visible. The dotted, gray line represents the predicted lasing frequency.

period of the PhC without any need for a regrowth of the active region itself. The experimentally observed tuning range is on the order of 400 GHz or 15 % of the central wavelength [6, 7], which is much larger than the typical gain bandwidth in THz-QCLs of 150 GHz [5]. This is a strong evidence for the theoretically predicted gain enhancement.

3. Conclusion
In conclusion, we have designed and realized active PhC lasers based on a THz-QCL active region. The devices are lasing at the band edge of the PhC band structure. The group velocity is extremely low for these regions, resulting in strong optical feedback. Together with the excellent modal confinement in this type of resonators, we are able to achieve a tuning range of 400 GHz by varying the period of the PhC lithographically. These experimental results are a strong evidence for the predicted gain enhancement. In addition, the realized resonators have very small modal volumes. The typical diameter is the order of 240 µm with a filling factor of 33 %.

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