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A new scheme for phase matching in quantum cascade lasers for terahertz-range frequency generation

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We propose a design of a dual-frequency quantum cascade laser that ensures phase matching during generation of difference-frequency in the terahertz range. The novelty of the proposed design lies in a new approach to achieving phase matching wherein the difference-harmonic waveguide is the substrate of the quantum cascade laser.

Keywords: terahertz radiation, difference-frequency generation, quantum-cascade lasers, phase matching.

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Electromagnetic radiation of the terahertz (THz) frequency range attracts attention of researchers due to the breadth of its application caused by its high penetrating ability and low ionizing activity compared to X-ray radiation. THz radiation is used in analytical chemistry, diagnostic medicine and pharmaceutics, quality control systems, monitoring and security systems, wireless communications, astronomy, and atmospheric research. A detailed review of currently available THz radiation sources and their applications was made in recent paper [1].

Among semiconductor sources of THz radiation, quantum cascade lasers (QCLs) are of greatest interest. The main problem with QCLs emitting in the THz range is their low operating temperatures. Even although in recent years there have arisen new ways to bring the operating temperatures of such lasers closer to room temperature, an increase only to 260 K [2] has been gained. Another challenge is difficulties in generating, controlling and detecting THz radiation from QCLs, which stem from low photon energy [3].

Another approach to obtaining THz radiation, which was for the first time proposed in [4], is to use difference-frequency generation in a circuit based on a mid-IR dual-frequency QCL. Such devices, along with Gunn diodes, are today the only all-semiconductor sources of room-temperature THz radiation with electrical pumping [5]. In this case, the main difficulty is the need for phase matching currently being realized in the Cherenkovś geometry [5], which reduces efficiency of the difference-frequency generation and, at the same time, complicates the radiation outcoupling because of its propagation at such an angle to the laser waveguide that exceeds the total internal reflection angle.

This paper proposes a design for a simple all-semiconductor THz radiation source based on a new approach to phase matching in generating the difference-frequency in a mid-IR dual-frequency QCL. Fig. 1 presents the cross-sectional view of the laser structure.

Active region of the QCL structure under study [6] provides lasing at the wavelengths of 7.46 and 8.15 μm simultaneously. The difference-frequency of these waves appears to be 3.4 THz. Unlike the Cherenkovś phase matching scheme, this scheme does not imply the difference harmonic outcoupling at an angle to the direction of the pump waves propagation.

To ensure efficient nonlinear light conversion, two fundamental conditions are to be met in addition to high pump wave intensity: high values of nonlinear susceptibility of the used materials and phase matching. The QCL waveguide structure is based on the InP and $In_{0.53}Ga_{0.47}As$ layers. Such structures possess a quadratic susceptibility several orders of magnitude higher than that of homogeneous materials [4]; thus, the problem gets reduced to increasing the coherence length of the pump waves and difference-frequency, whose decrease causes a dramatic decrease in the conversion efficiency. The condition of phase matching for waves in vacuum can be represented as follows [7]:

$$k_1 - k_2 = k_3, \qquad (1)$$

where $k_i = 2\pi/\lambda_i$, $\lambda_1 = 7.46\,\mu$m, $\lambda_2 = 8.15\,\mu$m, $\lambda_3 = 88.2\,\mu$m.

In the process of wave propagation in a medium, the situation gets complicated by the material dispersion of refractive index n, i.e. its dependence on wavelength λ. In this case,

$$k(\lambda) = \frac{2\pi}{\lambda} n(\lambda).$$

In this situation, fulfilling condition (1) requires more effort. In the scheme under consideration, it is proposed to provide phase matching via the waveguide dispersion; if it is taken into account, relation (1) transforms to

$$\beta_1 - \beta_2 = \beta_3. \qquad (2)$$

Here β_i is the propagation constant of the i-th wave quite easily calculable by solving the wave equation.

The QCL active region is located on a semi-insulating InP-based substrate having thickness w_s that is significantly

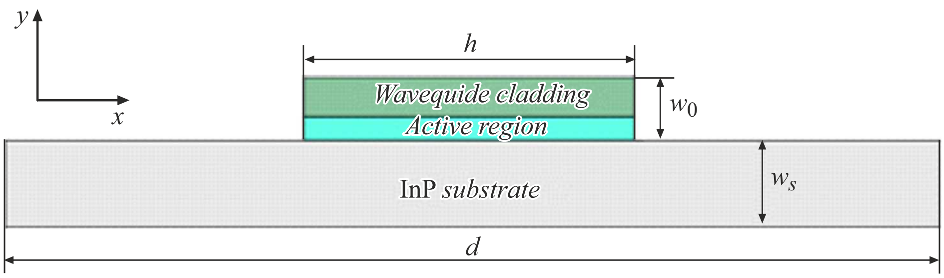

Figure 1. Schematic structure of the THz radiation source.

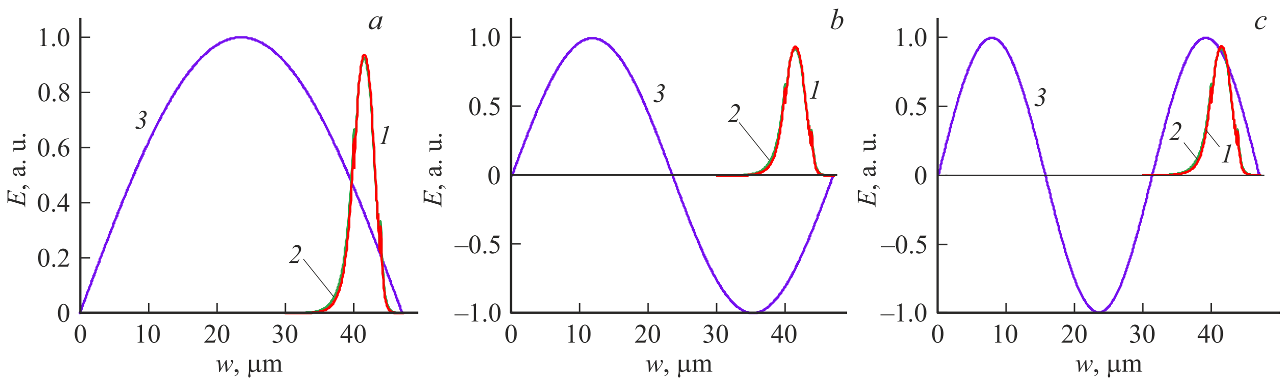

Figure 2. Distribution of the field magnitudes of fundamental zero-order modes ($\lambda_1 = 7.46\,\mu$m — red line *1*, $\lambda_2 = 8.15\,\mu$m — green line *2*) and of the difference-harmonic ($\lambda_3 = 88.2$,μm — blue line *3*) at $m = 1$ (*a*), 2 (*b*) and 3 (*c*).

greater than the laser structure thickness w_0. Metal contacts are deposited on both the top plate and bottom side of the substrate. The main distinctive feature of the proposed structure is that the substrate is used as a difference-frequency waveguide. In this case, fundamental IR modes propagate through the QCL waveguide w_0 thick without leaking into the substrate, while the difference-harmonic having an order of magnitude longer wavelength propagates through the substrate as through the waveguide. It may be assumed that the substrate thickness has a significant effect on the character of the difference-harmonic propagation and does not in any way affect the fundamental waves propagating over the w_0 region.

Substrate width d significantly exceeds both the QCL width h and thickness w. Thus, in direction x for the difference-harmonic there exists a simple three-layer planar waveguide approximately $400\,\mu$m wide, the wave propagation constant in which is easily calculable; waveguide dispersion at such a width is almost fully suppressed. For the entire structure, it coincides with the wave vector component x which may be designed as κ_{3x}.

Profile of the difference-frequency mode in the y direction has the following form:

$$E(y) = E_0 \sin\frac{\pi m y}{w}, \tag{3}$$

where w is the waveguide thickness that is a sum of the substrate thickness w_s and total QCL structure thickness w_0; m is an integer. Expressions (2) and (3) imply the condition for the substrate thickness which ensures complete phase matching:

$$\frac{\pi m}{w} = \sqrt{(k_3 n_s)^2 - \kappa_{3x}^2 - \beta_3^2}, \tag{4}$$

where n_s is the difference-harmonic refractive index of the substrate and epitaxial layer.

It is important to take into account that efficient conversion needs overlapping of the pump and difference-frequency waves. Fig. 2 presents the distributions of magnitudes of the fundamental modes and difference-frequency mode.

The greatest overlap between the pump and difference-frequency waves is observed at $m = 1$. The relevant waveguide thickness calculated via (4) appears to be $43.17\,\mu$m. The procedure for fabricating the scheme in question implies obtaining the required substrate thickness by grinding and/or chemical etching. In this case, it is difficult to accurately provide the design values; therefore, it is important to analyze the structure sensitivity to variations in the substrate thickness, which is governed by coherence length $L_c = \pi/|\beta_1 - \beta_2 - \beta_3|$ [7,8]. When the phase matching is ideal, i.e. when the substrate thickness coincides with the calculated value $43.17\,\mu$m, the coherence length becomes infinite and decreases with deviating from the target value (provided absorption is neglected).

The coherence length dependence on the substrate thickness is shown in Fig. 3. The figure demonstrates that

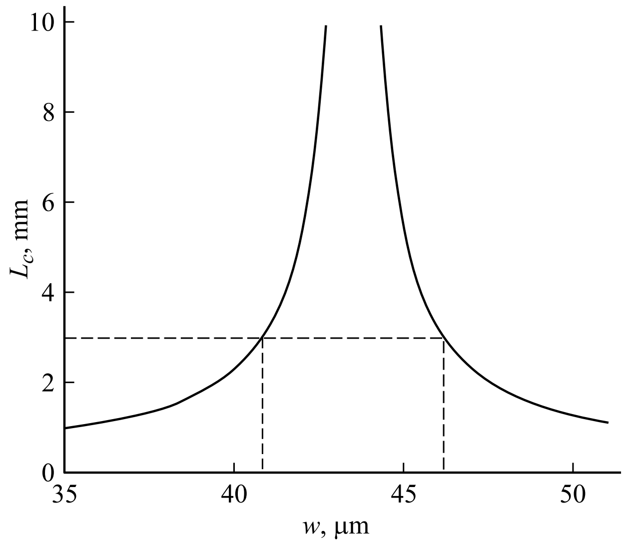

Figure 3. Coherence width versus the InP-substrate thickness.

the proposed scheme is weakly sensitive to variations in the substrate thickness: when the thickness deviates from the calculated value within $\pm 3\,\mu$m, the coherence length does not fall below 3 mm which is the typical laser crystal length.

Thus, by using a QCL structure substrate as a difference-frequency waveguide it is possible to ensure an acceptable level of phase matching and efficient lasing at the THz difference-frequency.

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Conflict of interests

The authors declare that they have no conflict of interests.

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