

## Collimating optical system of polymethylpentene for quantum cascade terahertz laser

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The results of an experimental study of a collimating optical system for a quantum cascade laser (QCL) with a frequency of  $\sim 4.1$  THz is presented. This system consists of a hyper-spherical lens, which is a semi-spherical lens glued to a spacer plate on the end of the QCL. The lens and spacer were made from polymethylpentene (TPX) — a material with low dispersion over a wide range of wavelengths and transparent in both the visible and THz ranges. The optimal thickness of the spacer was calculated and experimentally determined. An increase in the collected power of the QCL radiation using the hyper-sphere was found to be 14 times.

**Keywords:** quantum cascade laser, THz radiation, collimator.

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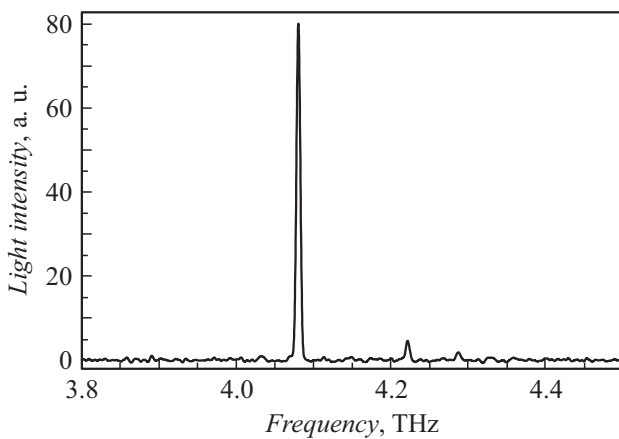
Terahertz (THz) technologies are developing rapidly and find numerous practical applications in the field of contactless non-destructive inspection of various media and materials [1], environmental monitoring and disease diagnostics [2–4], security threat detection [5,6], and broadband communications [7].

Advances in the design of compact THz laser sources have placed increased demands on optical systems that are used to collect, collimate, and focus THz radiation. With subwavelength dimensions of the active region, such lasers output a highly divergent beam [8–11]. Microstrips and their arrays, antennas based on carbon nanotubes, metasurfaces, horn antennas, and dipole microresonator antennas [12] may be used for sub-THz radiation within the 0.3–1 THz range. At higher frequencies ( $> 1$  THz), optical elements made of high-resistance silicon (HR-FZSi), germanium, sapphire, polymethylpentene (TPX brand), polypropylene, or high-density polyethylene (HDPE) [13] are preferable due to a reduction in wavelength. The refraction index of silicon is close to that of GaAs, which forms the basis of quantum cascade lasers (QCLs). Therefore, HR-FZSi lenses were used in a number of studies [14] to collect radiation from QCLs within the 1–5 THz range, although it is hard to position a lens–QCL pair precisely, since silicon is opaque in the visible range. However, the use of silicon lenses and prisms allows one to increase significantly the efficiency of THz radiation outcoupling from QCLs during Cherenkov generation [15]. Sapphire is also used to fabricate optical elements of the THz range. However, despite the high stability of optical and mechanical properties and transparency in the visible range, sapphire has a rather low transmittance (less than 0.3 at a wavelength of  $100\ \mu\text{m}$

with a thickness of 1 mm [13]) and strong dispersion (the refraction index is  $\sim 1.77$  and  $\sim 1.59$  at wavelengths of 0.6 and  $100\ \mu\text{m}$ , respectively). Polymethylpentene has a number of advantages over HR-FZSi: it is transparent within the visible range and has a higher transmittance within the range of  $\sim 4$  THz ( $\sim 0.52$  and  $\sim 0.8$  for 2-mm-thick HR-FZSi and TPX wafers, respectively [13]). The low dispersion of TPX (the refraction index is  $\sim 1.45$  within both visible and THz ranges) allows one to tune the optical system against a visible laser source.

The aim of the present study is to demonstrate experimentally the possibility of forming a beam of THz QCL radiation and its efficient collection by optical elements made of TPX plastic. A QCL (internal number 4111) with a double metal Ti/Au waveguide  $875\ \mu\text{m}$  in length,  $50\ \mu\text{m}$  in width, and  $10\ \mu\text{m}$  in thickness with a fundamental emission line frequency of 4.08 THz (Fig. 1) was used for experiments. The QCL radiation power measured by a calibrated THZ5I-BL-BNC (Gentec Electro-Optics, Inc.) pyroelectric detector was  $\sim 2\ \mu\text{W}$ .

The structure with a double metal waveguide is an efficient heat sink for the laser chip [16] and has low threshold currents [14]. The heat sink with the QCL was positioned on the stage of a closed-cycle helium cryostat. Lenses were fabricated by hot pressing a TPX plastic blank into an aluminum matrix at a temperature of  $220\ ^\circ\text{C}$ . QCL radiation was collimated by a hyper-spherical lens with a diameter of 6 mm, which consists of a hemispherical lens glued to a spacer plate pressed against the end of the QCL active region in such a way that the latter was in the focus of the hyper-spherical lens. Being a structural element used to position and secure the lens at a certain



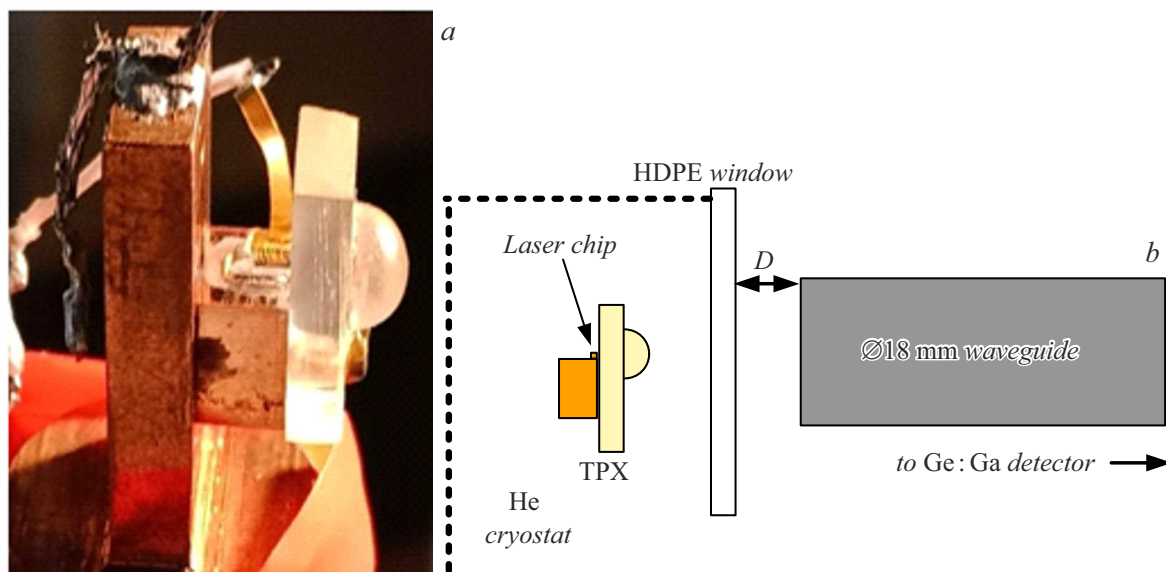
**Figure 1.** QCL radiation spectrum at  $T = 12$  K and  $I = 1.2$  A.

distance from the end of the QCL, the spacer allows one to adjust the optical characteristics of the hyper-spherical lens. The thickness of the spacer with a refraction index of 1.46 at a focal length of the hemispherical lens in a vacuum of 4.5 mm from a flat surface is  $\sim 3$  mm. The other end of the structure was cleaved and uncoated. The adjustment of lens positioning relative to the end of the QCL was carried out by monitoring it visually through the lens, which was then glued to the spacer. The heat sink with the QCL was mounted on the stage of the closed-cycle helium cryostat with a minimum temperature of 12 K. To maximize the amount of collected radiation, the spacer and the lens made of TPX were positioned as close as possible to the QCL (Fig. 2, *a*). For comparison, the radiation intensities were also measured without the lens: QCL radiation was fed into an intermediate cylindrical waveguide made of

polished stainless steel with a diameter of 8 mm and an HDPE window positioned as close as possible to the QCL inside the cryostat. The overall view of the setup and the measurement diagram are shown in Fig. 2, *b*. A current source based on a MOSFET switch with a frequency of 1 kHz and a pulse duration varying from 500 ns to 2  $\mu$ s was used for QCL excitation. QCL radiation was fed into a waveguide made of polished stainless steel 18 mm in diameter with a Ge:Ga receiver immersed in liquid helium. The overall length of the waveguide was 1.5 m, and its section  $\sim 50$  cm in length was kept in atmospheric conditions. The signal from the detector was amplified by a current amplifier and recorded by a digital oscilloscope.

The QCL radiation intensity was calculated as a function of spacer thickness at a hemispherical lens diameter of 6 mm. These calculations were carried out in the geometric optics approximation. It was assumed that the end of the laser closest to the lens is located at the QCL/TPX interface on the lens axis and emits a spherical wave. The dependence of intensity of collected QCL radiation on spacer thickness was plotted for spacer-waveguide distances of  $D = 3.5$  and 4 cm (Fig. 3).

The experimental results corresponding to the use of the lens with spacer thicknesses of 2.5, 3, and 3.4 mm are denoted by squares in Fig. 3; the measured relative intensities of collected radiation were 0.22, 1, and 0.48, respectively. The maximum signal in Fig. 3, which is observed at an increased spacer thickness, corresponds to optimal beam collimation. The difference in positions of the measured and calculated radiation intensity maxima is attributable to the small number of experimental points and to the specific features of experimental geometry that are hard to take into account in calculations. QCL radiation intensity distributions with and without the lens and the



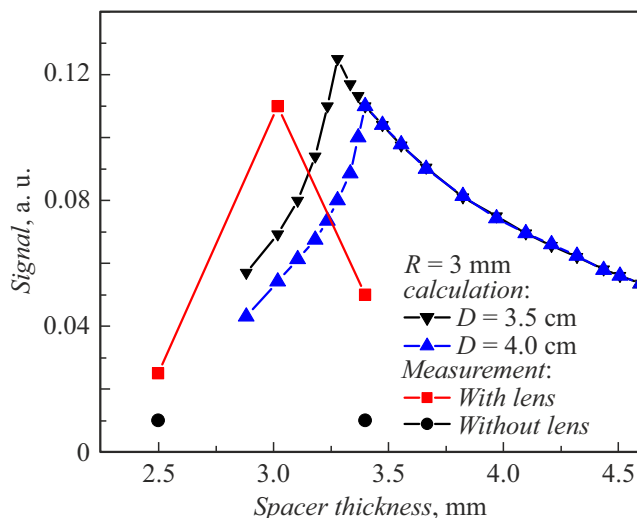
**Figure 2.** *a* — QCL with a spacer and a lens mounted on a copper heat sink in a closed-cycle cryostat; *b* — Diagram of the setup for collecting QCL radiation with the use of a lens and a TPX spacer. Distance  $D$  is 50 mm.

spacer were also measured in the process of scanning with a diaphragm 5 mm in diameter along two coordinates in the plane of the input aperture of the receiving waveguide. The distance from the end of the QCL to the end of the waveguide was 50 mm. When the hemispherical lens with a diameter of 6 mm was combined with the spacer 3 mm in thickness, the signal intensity increased by a factor of 14 compared to the signal without the lens and the spacer. The measurement results are presented in Fig. 4. Several emission intensity maxima correspond to different laser modes set by the geometry of the structure. With a certain adjustment of the optical system, one mode may be selected from the set of emitted modes to form a parallel beam, which is impossible to do for a number of modes emitted at different angles from the QCL.

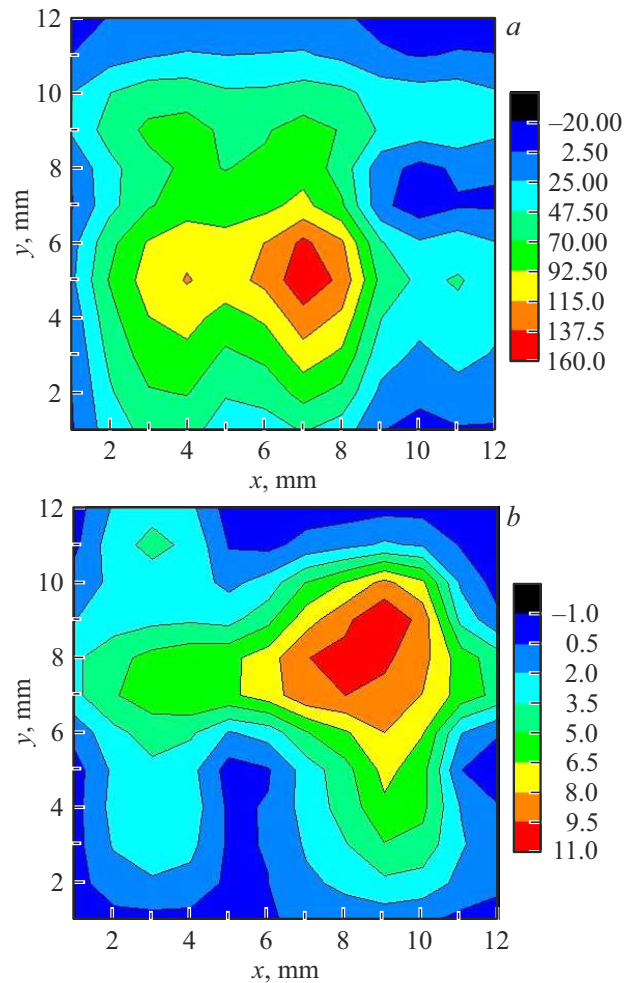
Thus, the use of an optical collecting system consisting of a spacer plate and a hemispherical lens made of TPX plastic increases the intensity of QCL radiation with a frequency of 4.08 THz incident on the receiver input aperture by a factor of 14. The low dispersion of TPX and its transparency within the visible wavelength range allow one to use sources of visible radiation for precise alignment of terahertz QCL–lens combinations generating within the range from 2.4 to 6.4 THz.

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**Figure 3.** Dependence of intensity of collected QCL radiation on spacer thickness for spacer–waveguide distances  $D = 3.5$  and 4 cm.



**Figure 4.** Distribution of radiation intensity of the QCL with the lens and the spacer 3 mm in thickness (a) and without them (b) in front of the receiver waveguide aperture.

### Conflict of interest

The authors declare that they have no conflict of interest.

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