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TERAHERTZ RADIATION

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Formation of beams with nonuniform polarisation of radiation in a cw waveguide terahertz laser

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Abstract. **A method for obtaining non-Gaussian light beams with azimuthal field polarisation in a waveguide quasi-optical cavity is described. The method is based on the employment of polarisation-selective diffraction structures as laser mirrors. Efficient excitation of such beams at the output from an optically pumped waveguide HCOOH laser (λ = 0.4326 mm) with an inhomogeneous reflecting input and semitransparent output mirrors is confirmed theoretically and experimentally.**

Keywords: *terahertz range, waveguide laser, cw emission, beam formation, inhomogeneous mirror, azimuthal polarisation.*

1. Introduction

Output radiation of most modern lasers has uniform polarisation. Nevertheless, interest is presently growing to optical fields with nonuniform spatial polarisation, which in the scientific literature are called 'vector beams' [1–3]. Among them, laser beams with radial and azimuthal polarisation possessing specific features are often employed in many research and applied problems. Taking into account propagation and focusing features of such beams, they are applied in laser physics [4], biomedical diagnosis [5], technological metal treatment processes [6], high-speed communication [7], electron acceleration [8], etc.

Various types of modes with nonuniform spatial polarisation are formed by employing both extracavity and intracavity approaches [9]. The polarisation devices are based on a local change in the polarisation state at each cross-section point of a laser beam. The extracavity methods usually utilise a coherent superposition of a pair of modes in free space by using, for example, an interferometer [10]. An important advantage of the extracavity methods is universality, and a drawback is complicated realisation and high sensitivity to environment conditions. Intracavity methods are based on laser cavity modifications, which help eliminate these limitations. In recent years, a branch in optics has been developed, which is related to the employment of diffraction mirrors possessing high polarisation selectivity [11–13]. However, these methods operate with a particular type of radiation polarisation.

Let us mention several papers devoted to generation, propagation, and focusing of beams with various spatial polarisation of radiation in the terahertz (THz) frequency range [14–18], as well as papers [19–25], which describe methods of and approaches to forming laser beams with a required polarisation structure in this range. Nevertheless, they all pertain to the group of extracavity methods and utilise pulsed radiation emitted upon nonlinear conversion of IR femtosecond laser radiation.

Here we report a new method for intracavity generation of THz laser beams with azimuthal polarisation by using polarisation-selective azimuthally symmetric diffraction structures as mirrors of an optically pumped waveguide molecular laser. The suggested method utilises a cavity input mirror fabricated as a large-scale ($\kappa = l/\lambda > 1$, where λ is the wavelength and l is the structure period) reflecting metal diffraction grating or an output semitransparent mirror in the form of a metal small-scale ($\kappa < 1$) multi-ring diaphragm arranged on a dielectric layer. The present work is aimed at development, creation, and studying an experimental sample of a THz laser for obtaining radiation beams with azimuthal polarisation basing on a waveguide cavity comprising such mirrors.

2. Experimental setup

A block diagram of an optically pumped waveguide THz laser and an experimental setup for studying the laser is presented in Fig. 1. A working molecule of the HCOOH laser is excited by a cw dc-discharge CO_2 laser described in [26].

A system of folding mirrors comprised of three plane mirrors (*11*) and a spherical mirror (*13*) with a focal length of 0.5 m provides the focusing of CO_2-laser radiation on a coupling hole of an input mirror (*17*) of a cavity THz cell. Such a system for introducing the pump radiation into the THz cell provides good isolation of the CO_2 laser from the emission of the latter reflected by the cell.

The THz cell is a vacuum chamber fabricated from a round pyrex tube (*16*) with an internal radius of 35 mm and a length of 1848 mm closed with mirrors *17* and *18*. Mirror *17* has a central coupling hole of diameter 3 mm for introducing the pump radiation into the THz cell. Calculations performed show that with such a diameter of the coupling hole, the field on mirror *17* actually does not differ from that on a mirror without a hole. The input mirror is arranged on a plane-parallel shift actuator (*14*), which provides mirror movement to a distance of longer than 2 mm keeping it parallel with an

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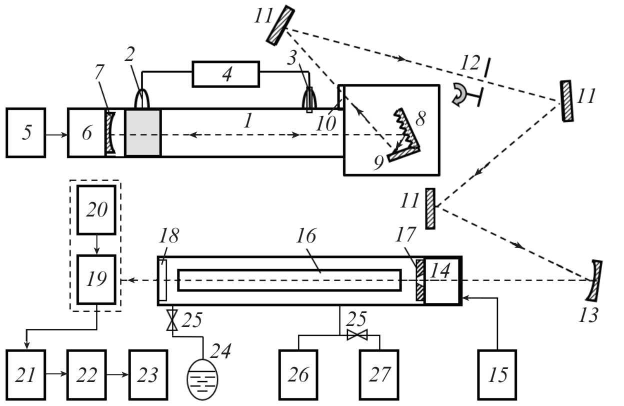

Figure 1. Schematic of the experimental setup: (*1*) CO_2 laser; (*2*) cathode; (*3*) anode; (*4*) high-voltage power supply; (*5*) dc power supply; (*6*) piezoelectric actuator; (*7*, *13*) spherical mirrors; (*8*) echelette; (*9*) corner reflector; (*10*) NaCl plate; (*11*) plane mirror; (*12*) mechanical modulator; (*14*) mirror motion unit; (*15*) electric driver; (*16*) dielectric waveguide; (*17*) input mirror; (*18*) output mirror; (*19*) detector; (*20*) beam scanning unit; (*21*) selective amplifier; (*22*) ADC; (*23*) computer; (*24*) retort with HCOOH; (*25*) valves; (*26*) vacuum gauge; (*27*) vacuum pump.

accuracy no worse than 10′. The mirror can be automatically moved by an electric drive (*15*).

Parameters of inhomogeneous mirrors of the waveguide quasi-optical dielectric resonator were preliminarily calculated according to the BOR FDTD algorithm (for details, see [27]). The reflection and transmission coefficients were calculated for symmetric and nonsymmetric waveguide modes with various spatial field polarisations for axially symmetric diffraction mirrors arranged inside a hollow circular dielectric waveguide.

The system for evacuating and filling the THz cell with a working mixture comprises elements *24* – *27*. Such a construction provides maintaining the working mixture pressure in the THz cell at a level of ~1 dPa. A system for detecting THz radiation consists of a pyroelectric detector (*19*) with a spatial resolution of 0.2 mm arranged in the special electromechanic unit for scanning a transverse distribution of output laser intensity corresponding to prescribed azimuths. The detector was placed at a distance in the range from 100 mm to 1.5 m from the THz cell output mirror (*18*). A detector signal is amplified by a selective amplifier (*21*) and then passes to an ADC (*22*) and a computer (*23*).

The radiation power of the THz laser was determined by a BIMO-1 bolometric power transducer, and the power of the CO_2 laser is measured by an IMO-2N calorimetric power meter. Spectral parameters were measured similarly to [28]. The spectrum of cavity eigenmodes was recorded by varying the cavity length with an electric drive (*15*). Transverse modes were identified by the intermode intervals, which were calculated from phase shifts per cavity round trip and from theoretically known transverse intensity distributions and polarisation states for waveguide modes [29, 30].

The polarisation state for a generated mode was determined as follows. The radiation detector with a small input diaphragm moved with various azimuths in the transverse plane of a radiation beam, and the polarisation plane was determined at the points of maximal radiation by using a polariser. The latter was a one-dimensional wire grating with a step of 40 μm and wire diameter of 8 μm.

3. Comparison of experimental and numerical results

3.1. Laser cavity with a large-scale input and homogeneous output mirrors

Excitation of azimuthally polarised radiation in a waveguide quasi-optical cavity of a THz-laser requires high-selectivity mirrors with minimal energy losses at a considered mode and high losses at undesired modes.

The cavity output homogeneous mirror (*18*) (Fig. 1) was a capacitive 2D grid fabricated by depositing aluminium through a matrix onto a plane-parallel plate of crystalline quartz of thickness 4 mm. For the matrix, an inductive strip grid with a period of 103 μm and width of 17 μm was used. Such a mirror has a transparency of 18% at the laser operation wavelength of 0.4326 mm. The input reflector (*17*) was an inhomogeneous mirror with a central coupling hole of diameter $d = 3$ mm. The reflecting surface of the mirror was formed as an azimuthally symmetric large-scale metal diffraction grating. The grating had various numbers of reflecting rings and grooves absorbing radiation with width b and prescribed period l. In order to fulfil the short-wavelength approximation condition $l > \lambda$, the grating period l was chosen 1.75 μm issuing from technological possibilities. The grating filling factor $\eta = b/l$ varied within the range of 0.1 – 0.9.

The reflection coefficient for waveguide TE_{01} and EH_{11} modes possessing the least losses were calculated as a function of the filling factor of an axially symmetric diffraction mirror arranged inside a hollow circular dielectric waveguide. The calculations show that the mirror with a surface diffraction grating and $\eta > 0.8$ placed in a waveguide provides the reflection coefficient $R \geqslant 60\%$ for azimuthally polarised vibrations TE_{01}, and for linearly polarised mode EH_{11} R is less than 50%. This favours selective excitation of the TE_{01q} mode in the laser cavity.

Taking into account the calculation results, an inhomogeneous input mirror was mechanically fabricated by using a special cutter. The mirror had nine interlaced reflecting rings and absorbing grooves with a period $l = 1.75$ mm and width $b = 0.35$ mm. A profile of the reflector used in the experiment is shown in Fig. 2. The absorbing grooves were formed by a cutter to a depth of ~0.2 mm (~0.5λ) at an angle of 30° with respect to the mirror reflecting surface. This provided removal of the rays reflected by groove surfaces from the laser cavity,

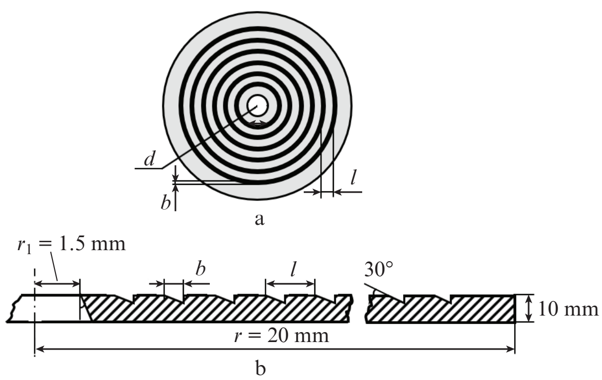

Figure 2. Profile of the output diffraction mirror: (a) relief of mirror surface and (b) transverse cross section of the mirror.

which is identical to actually perfect absorption of radiation at these mirror domains.

Figure 3 shows spectra of excited laser modes obtained experimentally with this input inhomogeneous mirror and a homogeneous capacitive output mirror. Cavity length tuning reveals two cavity modes with the least losses. The second (by the Q-factor) mode has linear polarisation. From its transverse field intensity distribution, we identified it as EH_{11q} mode. The frequency separation between EH_{11q} mode and the mode with the highest Q-factor made us to conclude (through theoretical considerations) that it is the TE_{01q} mode. A far-field transverse intensity distribution of this mode at the laser output is shown in Fig. 4. Issuing from this transverse distribution, mode frequency separation, and position of an electric field vector for various azimuths, we identified this mode as TE_{01q} mode with azimuthal polarisation.

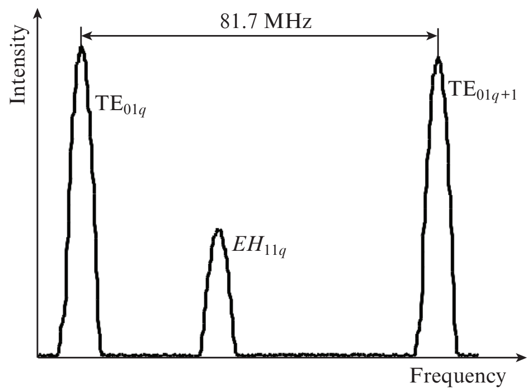

Figure 3. Mode spectrum of the HCOOH laser with an input large-scale reflecting mirror.

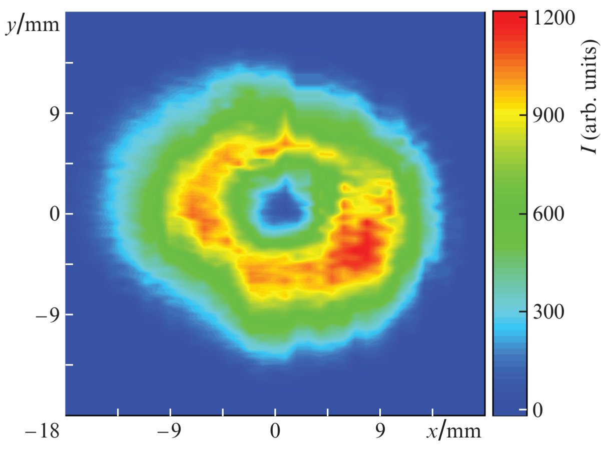

Figure 4. (Colour online) Experimental transverse distribution of the radiation intensity I at the output of the HCOOH laser with an input large-scale mirror in the far-zone for the TE_{01q} mode.

The radiation power of the THz laser in the TE_{01q} mode is 8 mW, and in the EH_{11q} mode it is 3.75 mW. If the diffraction mirror is substituted with a homogeneous one, the laser emission power in the EH_{11q} mode raises to 18 mW. The reduction of the radiation power in this mode in the case of an inhomogeneous mirror is explained by a lower reflection coefficient of the mirror.

One can see that the proposed azimuthally symmetric large-scale diffraction mirror efficiently selects undesired modes and can be simply realised in laboratory conditions. Nevertheless, because of its poor energy efficiency, further investigations were performed with small-scale diffraction structures arranged on the mirror surface.

3.2. Laser cavity with uniform input and small-scale output mirrors

In this case, the input mirror (*17*) of the laser cavity (see Fig. 1) was a plane uniform aluminium mirror with a coupling hole of diameter 3 mm. For the laser output semitransparent reflector (*18*), two variants of diffraction mirrors were tested. In the first variant (mirror I), the mirror surface was fabricated by the photo-lithography method in the form of metal azimuthally symmetric small-scale ($\kappa < 1$) multi-ring diaphragm on a dielectric layer. To fulfil the long-wavelength approximation ($l < \lambda$), the diaphragm period was chosen 120 μm. Figure 5 shows the dependences of the diaphragm reflection coefficient R and transmission T for waveguide modes TE_{0m} and EH_{1m} on the filling factor η for the case where the small-scale mirror is arranged inside a hollow circular dielectric waveguide. The calculations take into account the quartz substrate thickness (4 mm in the experimental mirror sample). One can see from Fig. 5 that introduction of the ring mirror with $\eta > 0.3$ substantially increases the reflection coefficient ($R \geqslant 90\%$) for azimuthally polarised vibration modes TE_{0m}, which favours generation of the latter in a laser. Additionally, the mirror provides sufficiently small reflection coefficients ($R \approx 30\%$) for linearly polarised EH_{1m} modes. Here, $m = 1-3$, and for all such modes the reflection and transmission dependences on the filling factor are similar to those from Fig. 5. However, such a mirror cannot provide uniform generation at a required mode.

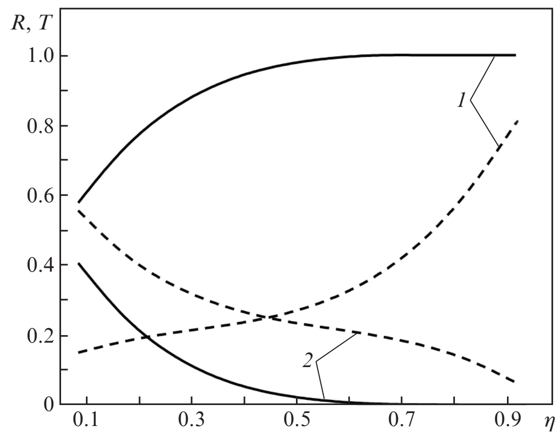

Figure 5. Calculated dependences of reflection R (*1*) and transmission T (*2*) coefficients for waveguide modes TE_{0m} (solid curves) and EH_{1m} (dashed curves) on the filling factor η of a multi-ring diaphragm.

Possibility of generating the particular lowest TE_{01} mode with highly discriminated undesirable modes was studied by calculating the dependences of coefficients R and T for waveguide modes on the radius a_0 of the 'bleached' part of the diffraction mirror, from which central part a number of reflecting rings have been removed. The calculation results are shown in Fig. 6. One can see that a choice of the radius for the 'bleached' mirror part from the range a_0 = 6–8 mm allows one to selectively excite the required TE_{01} mode with $R \approx$ 60%–70%, whereas modes EH_{11} and EH_{12} with $R \approx$ 10% and $T \approx$ 40% are mainly converted to other vibration types. Modes TE_{02}–TE_{04} with similar azimuthal polarisation are also efficiently suppressed by such mirror.

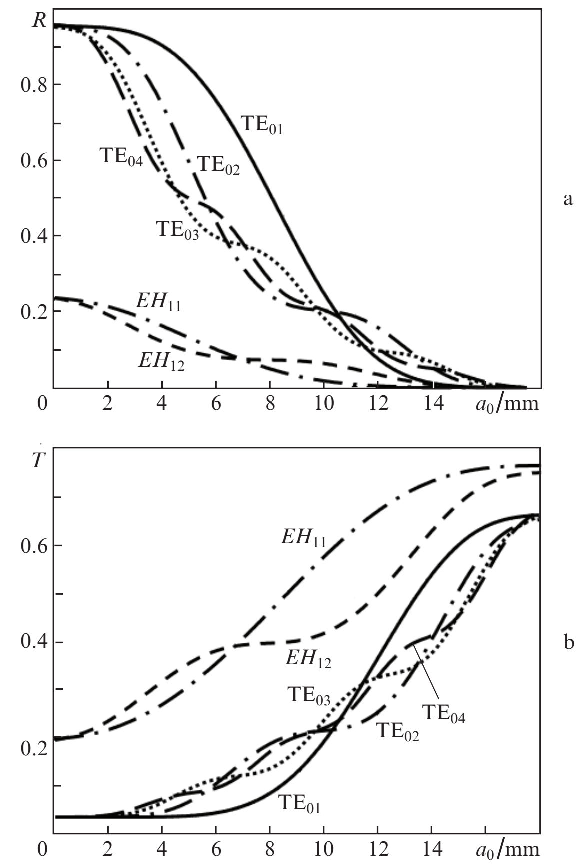

Figure 6. Dependences of (a) reflection R and (b) transmission T coefficients for waveguide modes on the radius a_0 of the 'bleached' part of the mirror.

Issuing from the calculation results, an inhomogeneous output mirror II was fabricated by the photolithography method in the form of a multi-ring diaphragm arranged on a dielectric layer with a number of central reflecting rings being removed. An aluminium layer of thickness 0.5–0.6 μm was deposited on a 4-mm-thick crystalline quartz plate, and domains of desired shape were etched. Taking into account the condition of the long-wavelength approximation, the taken diaphragm period l was 120 μm, the width of metallised reflecting rings b was 50 μm, and the filling factor η was 0.4. A diameter of the central 'bleached' part of the mirror was 14 mm.

In initial experiments, the above discussed uniform capacitive mirror with the transparency of 18% at the laser generation wavelength was used as an output mirror. Tuning characteristics of THz laser radiation were recorded by moving the input mirror (*17*) (Fig. 7). The spectrum had five transverse modes, from which four modes with the highest Q-factors were linearly polarised, and the most intensive mode was identified as the EH_{11q} mode.

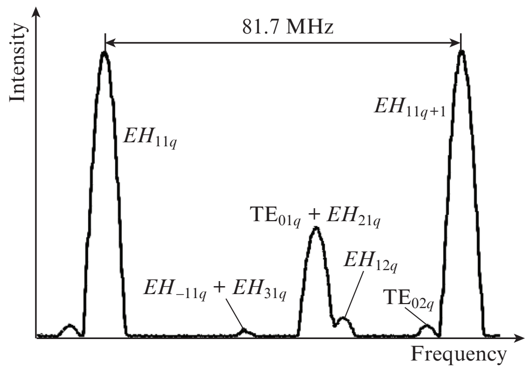

Figure 7. Mode spectrum of the HCOOH laser with an output uniform capacitive mirror.

If mirror I is used as an output mirror (*18*), then the tuning characteristic exhibits six generation modes (Fig. 8a). There are three cavity modes with azimuthal polarisation in the spectrum. The mode with the highest Q-factor was identified as the TE_{01q} mode.

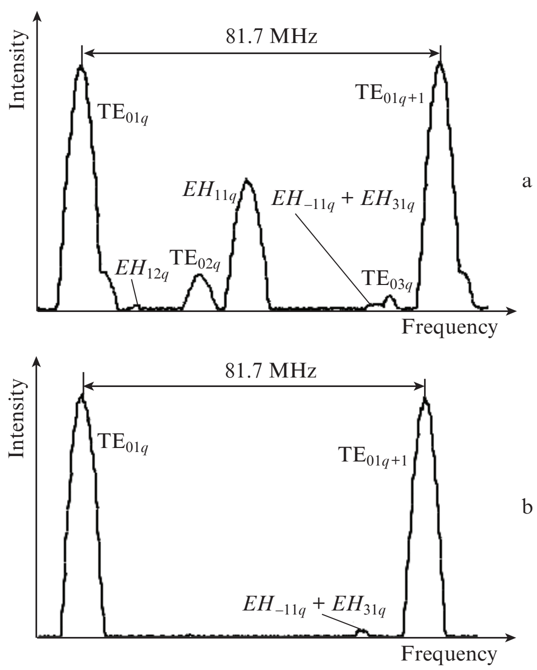

Figure 8. Mode spectra of the HCOOH laser with an output semitransparent small-scale diffraction mirrors I (a) and II (b).

For enhancing the selective properties of the laser cavity and generating the single lowest TE_{01q} mode with a high discrimination of undesired modes, the laser included the diffraction mirror II with a 'bleached' central part. Figure 8b presents an experimental spectrum of laser modes in such a configuration. One can see that the employment of mirror II substantially suppresses undesired modes and yields an actually single transverse mode TE_{01q}. The radiation power of the laser with such a diffraction mirror in the mode TE_{01q} was 16 mW, whereas laser operation in the mode EH_{11q} with the 2D capacitive grid used as the output homogeneous mirror yielded 18 mW. Thus, the employment of a relatively complicated diffraction structure on a mirror surface did not actually reduce the laser power.

Thus, the possibility of developing an optically pumped molecular laser for generating cw laser beams of THz radiation with azimuthal polarisation by using polarisation-selective azimuthally symmetric diffraction structures as the output mirrors of a waveguide quasi-optical cavity is demonstrated. Two schemes are proposed for obtaining such beams at the output from an optically pumped waveguide HCOOH laser (λ = 0.4326 mm), differing in the energy efficiency and simplicity of realisation.

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