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Letter

Spatial filtering of radiation from wire lasers

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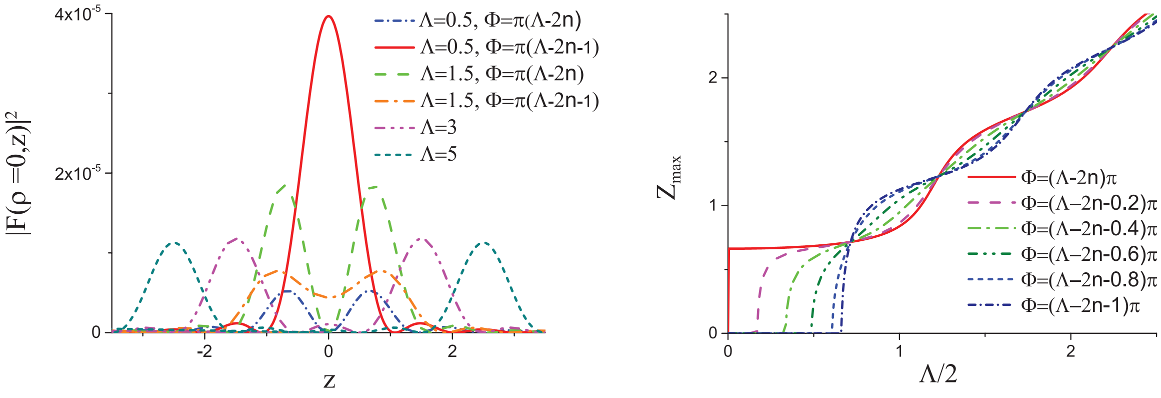
Abstract
In this letter we propose an approach to obtain directive radiation from wire lasers with subwavelength transverse dimensions and length much larger than the radiation wavelength (wire lasers) based on spatial filtering of their radiation using a combination of a spherical lens and a diaphragm. Theoretical modeling based on the antenna model for wire lasers shows that a directive beam with the uniform phase front can be formed when the diaphragm separates the maximum of the image field of the laser created by the lens. We demonstrate spatial filtering of wire laser radiation experimentally using a terahertz quantum cascade laser.

Keywords: wire laser, terahertz quantum cascade laser, spatial filtering

(Some figures may appear in colour only in the online journal)

1. Introduction

Terahertz (THz) frequencies ($f = 0.3$–10 THz) remain one of the least developed frequency ranges, even though the potential applications in remote sensing and imaging, spectroscopy, and communications are great. This is mainly due to the lack of coherent sources with high output power levels. A new type of terahertz laser based on quantum cascade semiconductor hetero-structures (THz QCL-s) is attractive for numerous applications due to their compact size, high output power, ability to control the radiation spectrum by methods of band-gap engineering, and the possibility of continuous generation regime [1]. However, the broad application of such lasers is hindered due to peculiarities of their beam profile. Typical waveguides of THz QCL-s have wire geometry with sub-wavelength transverse dimensions and length much larger than the radiation wavelength (wire lasers). Such geometry of THz QCL-s waveguides is linked with the requirements of single mode generation, minimizing the radiation losses, efficient heat transfer, and the limitations of the crystal growth time. However, sub-wavelength transverse size of laser waveguides leads to high radiation divergence. Additionally, strong intensity modulations were observed in the far field of such lasers [2], with the pattern of modulations more dense for longer lasers. It was shown that the far-field pattern of wire lasers is formed by the interference of radiation from the longitudinal distribution of sources along the laser waveguide [3]. Directive emission from wire lasers with a narrow, almost axially symmetric beam along the laser axis has been achieved experimentally using gratings with appropriate periodicity, acting as a discrete array of phased sources along the laser waveguide [4–7]. This practical approach enables the formation of a narrow beam with uniform phase front, but it leads to an increase of radiative losses for the laser mode producing directive radiation, and thus may cause an increase of their radiation threshold. Moreover, this method does not solve the problem of directivity of wire lasers operating in the multimode regime, as the conditions of directive emission and the angle between the radiation maximum and the laser axis depend on the longitudinal phase velocity of the mode.



(a) (b)

Figure 1. The axial structure of the image field of a wire laser: axial dependence of the square modulus of the structural factor (a); axial position of the maximum of the image field (b), $z = \pm\Lambda/2$ correspond to the coordinates of the images of the edges of the laser waveguide.

Here we investigate the possibility to improve the spatial structure of radiation of wire lasers using spatial filtering by external optical elements. The significant advantage of this approach is that it does not change the level of radiative loss and conditions of generation. Moreover, it does not require complicated waveguide design that increases the price of the device. Additionally, as it is shown by theoretical analysis given below, our approach is applicable to multi-mode lasers.

It should be noted that the methods of laser optics developed for lasers with apertures much larger than the wavelength [8] are not applicable for wire lasers. Few results can be mentioned in the field of development of specific methods of transformation of radiation of wire lasers. Recently it was proposed to use spherical lenses to form a narrow beam as an image of a wire laser placed on the lens axis [9]. However, the conditions of formation of such a beam include the limitation on the number of interference rings within the lens aperture, thus limiting the fraction of the omnidirectional radiation from a slow mode of a wire laser radiation collected by the lens. Furthermore, even when this condition is satisfied, the structure of the image beam is not always uniform and depends on the laser mode longitudinal phase velocity. However, the transverse structure of the image field of a wire laser in the vicinity of intensity maxima does not depend much on the parameters of the laser mode. It has been shown that about half of the radiation power of a wire laser collected by the lens is concentrated into a maximum with the uniform phase, and the transverse width of this maximum is equal to that of the point source image [10]. We investigate the influence of a diaphragm on the radiation field of a wire laser focused by a spherical lens and show that the separation of the area near the radiation maximum enables the formation of a directive beam with uniform phase front containing about one half of the radiation power collected by the lens.

2. Analysis of the transformation of wire laser radiation field

Calculation of the transformation of wire laser radiation field cannot be performed with the standard aperture diffraction methods, which have been used to develop the beam shaping techniques for the lasers with the apertures much larger than the wavelength, since a considerable part of radiation of wire lasers propagates outside the laser waveguide. This part of the radiation carries information about the longitudinal structure of the laser mode and enables the formation of the laser image. The influence of the longitudinal structure of the waveguide on the radiation distribution can be adequately described using the approach based on the equivalence of displacement currents in dielectrics and conductivity currents [11]. The radiation field of a wire laser is expressed within this method in terms of the field values inside the volume of the cavity, enabling the account of the influence of laser length on the field structure. Assuming the equivalent current of the laser mode in the form of a standing wave along the laser axis, the expression for the far field of a wire laser has been obtained containing only a few integral parameters of the laser mode, such as the first non-vanishing momentum of transverse distribution of equivalent current, laser length and the phase shift between the mode and free space plane wave along the waveguide [3]. Based on this expression, the radiation field of a wire laser placed along the axis of a spherical lens is calculated using the Fresnel integral over the aperture of the lens [9]. The resulting field distribution in the paraxial approximation is described by the product of a spherical wave from the center of the lens and a structural factor:

$$F(\rho, z) = \int_0^1 J_0(\rho\sqrt{x})\exp(j2\pi xz)\frac{\sin(\Phi/2 - \Lambda\pi x)}{\Phi/2 - \Lambda\pi x}\mathrm{d}x, \qquad (1)$$

where ρ and z are the radial and the axial dimensionless coordinates defined as $\rho = kR\rho_i/z_i$, and $z = (z_c - z_l)/z_l$, with R—the lens radius, ρ_i and z_i—radial and the axial coordinates in the image space, z_c—the axial coordinate of the point conjugate to the point of observation, z_l—the distance between the laser and the lens. The two dimensionless parameters, that determine the structure of the image are: Λ, the laser length L normalized to the lens axial resolution $\mathrm{d}z_l = 2\lambda z_l/R$, and Φ—the phase shift between the laser mode and the free space radiation travelling along the laser waveguide ($\Phi = (k - q)L$, q is the longitudinal wave number of the laser waveguide mode and $k = 2\pi/\lambda$, $\Phi < 0$ for slow modes, and typically for wire lasers $|\Phi| \gg 1$).

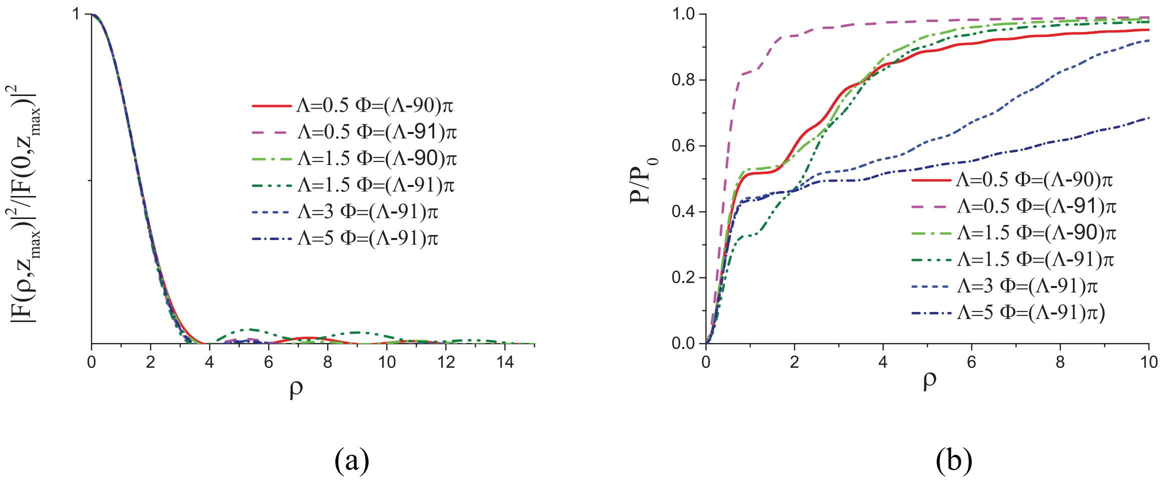


Figure 2. Transverse distribution of the image field of a wire laser: transverse dependence of the square modulus of the structural factor (a); the power integrated within the disc with radius ρ perpendicular to the lens axis placed near the maximum of the axial distribution of the image field normalized to the power P_0 collected by the lens (b).

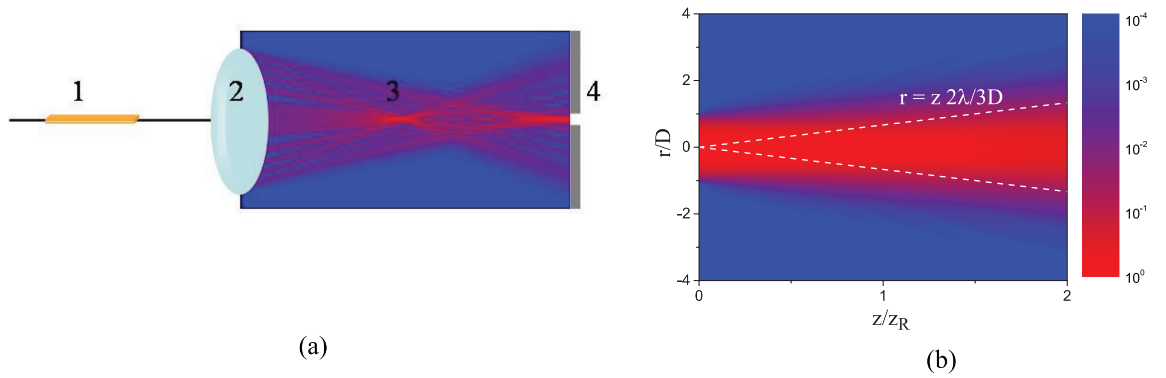


Figure 3. (a) The scheme of the optical system: 1—laser waveguide, 2 and 3—spherical lenses, 4—intensity distribution of the radiation field of a wire laser after transformation by spherical lens 5—diaphragm. (b) The field intensity distribution in the plane containing the axis of the optical system with the radius of the diaphragm $D = D_p$ corresponding to the width of intensity maximum of the wire laser image, $z_R = D^2/\lambda$ is the Rayleigh range.

The region of maximum values of expression (1) is extended along the lens axis and corresponds to the position of the image of the laser waveguide determined within the geometrical optics approach. However, the field distribution within the laser image is not always uniform. For slow modes with large negative Φ that are typical for wire lasers, longitudinal dependence of the image field (figure 1(a)) is a superposition of two components with the maxima corresponding to the images of the ends of the laser waveguide. Such an image structure is caused by the evanescent character of the slow components of the spatial spectrum of the source, and the presence of spatial frequencies corresponding to propagating waves at the edges of the laser. The axial width of the maxima of the image components at the level of half maximum is the same as that of a point source image $\Delta z_p \approx 0.9$. When $\Lambda < \Delta z_p$ the two image components overlap and may form a single maximum, but even for small Λ the image can have a double maximum structure due to destructive interference of the two components of the image field (figure 1(b)).

The transverse field distribution in the center of the image is determined by Fourier transformation of the field amplitude in the lens plane. For large Λ the radius of the transverse field decay in the center of the image is about $\pi\Lambda$, the transverse field structure may contain multiple oscillations accompanied by rapid phase shifts, and depends strongly on the parameters Λ and Φ. However, the radial dependence of the image field near the maxima of the axial distribution (figure 2(a)) is remarkably stable and does not depend much neither on the laser mode phase shift Φ, nor on the normalized laser length Λ. The phase near the maxima is uniform in the transverse plane within the radius $\rho_p \approx 3.83$ corresponding to the first zeros of a point source image. Radiation power within the disc with the radius ρ_p varies with Φ when Λ is small, and for large Λ is always about one half of the power collected by the lens. The other part of the radiation power is distributed within the radius $\rho \approx \pi\Lambda$ (figure 2(b)).

These peculiarities of the distribution of the field of a wire laser transformed by a spherical lens can be used to produce a narrow beam placing the diaphragm with the radius $D_p = \rho_p z_i / kR$ in the transverse plane near the maximum of the axial distribution of the image field of a wire laser (figure 3(a)). The structure of the beam obtained with a combination of

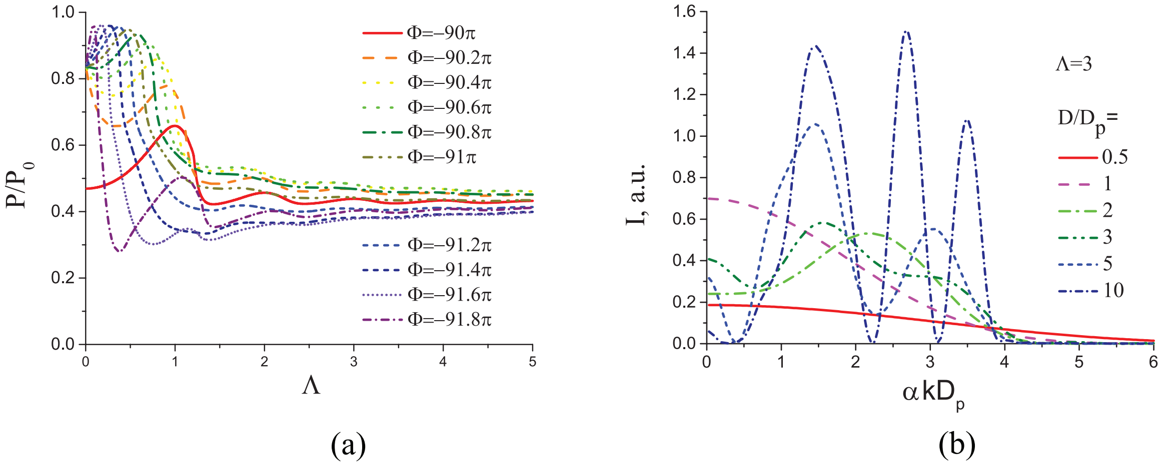


Figure 4. The power of the beam formed with a combination of a lens and a diaphragm with radius D_p perpendicular to the lens axis placed near the maximum of the axial distribution of the image field normalized to the power P_0 collected by the lens (a). Dependence of the angular structure of the far field of a wire laser after spatial filtering with a spherical lens and a diaphragm on the size of the diaphragm (b).

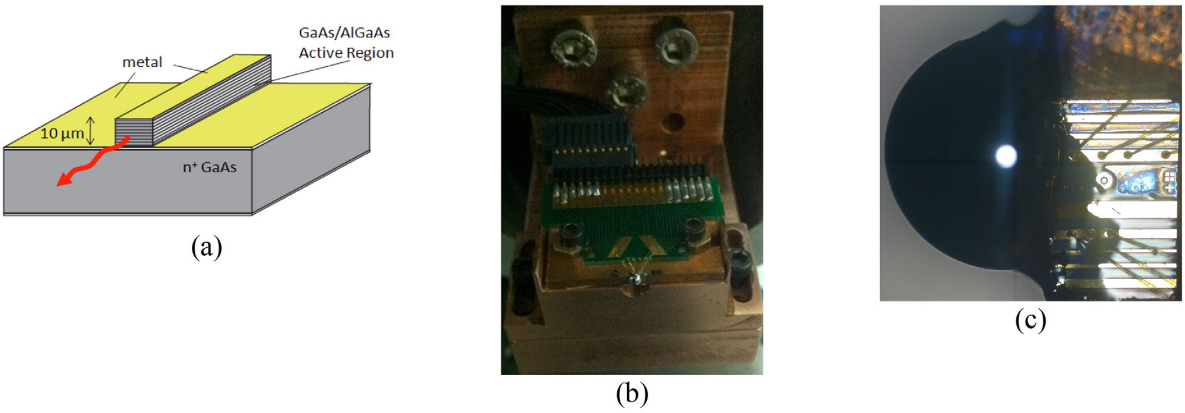


Figure 5. The drawing of the laser waveguide (a); the photo of the QCL with the mount (b); the micro-photo of the QCL with the collimating lens (c).

a lens and a diaphragm is calculated using Fresnel integration for the field distribution given by (1) over the aperture of the diaphragm. The angle of divergence at a half maximum of intensity of a beam obtained using the diaphragm with the radius corresponding to the first zero of the transverse intensity distribution of a point source image is determined by the ratio of the wavelength to the diaphragm radius: $\alpha \approx 2\lambda/3D_p$ (figure 3(b)). Such a beam contains about one half of the radiation power of a wire laser collected by the lens (figure 4(a)). The increase of the diaphragm radius beyond the optimum radius D_p leads to formation of a non-uniform beam, and when the radius of the diaphragm is larger than $D = \Lambda z_i/kR$, the far field may contain phase singularities (figure 4(b)).

Let us compare the divergence of the beam, produced using a combination of a lens and a diaphragm with that of the other methods of directive beam formation from wire lasers. The divergence of the beam $\alpha \approx 2\lambda/3D_p$ obtained within our approach can be expressed in terms of the lens radius R and the distance between the lens and the maximum of the image field z_i: $\alpha \approx 2R/3z_i$. Thus, the beam divergence can be made arbitrarily small by bringing the laser closer to the lens focal point, and filtering the maximum at a larger distance. For comparison, the divergence of the directive beam obtained

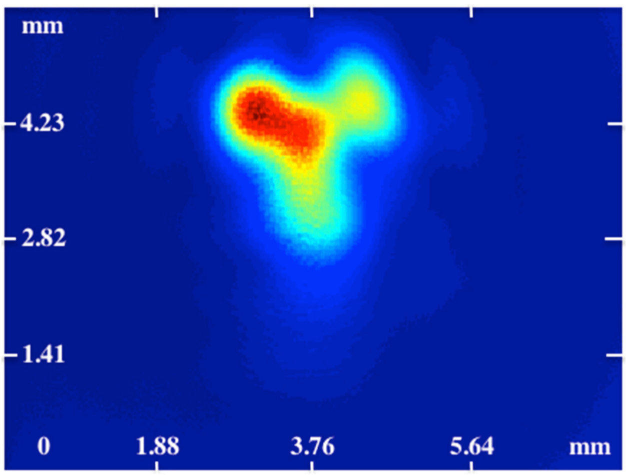


Figure 6. Transverse distribution of the intensity of focused QCL radiation. Color corresponds to intensity in au.

as an image of a wire laser [9] is determined by the ratio of the wavelength to the lens radius: $\alpha \approx \lambda/4R$, which is limited by the condition of the uniform beam formation: $\Lambda \leqslant 1.5$. This limitation leads to a divergence not smaller than $LR/8z_l^2$ where z_l is the distance between the lens and the laser. The

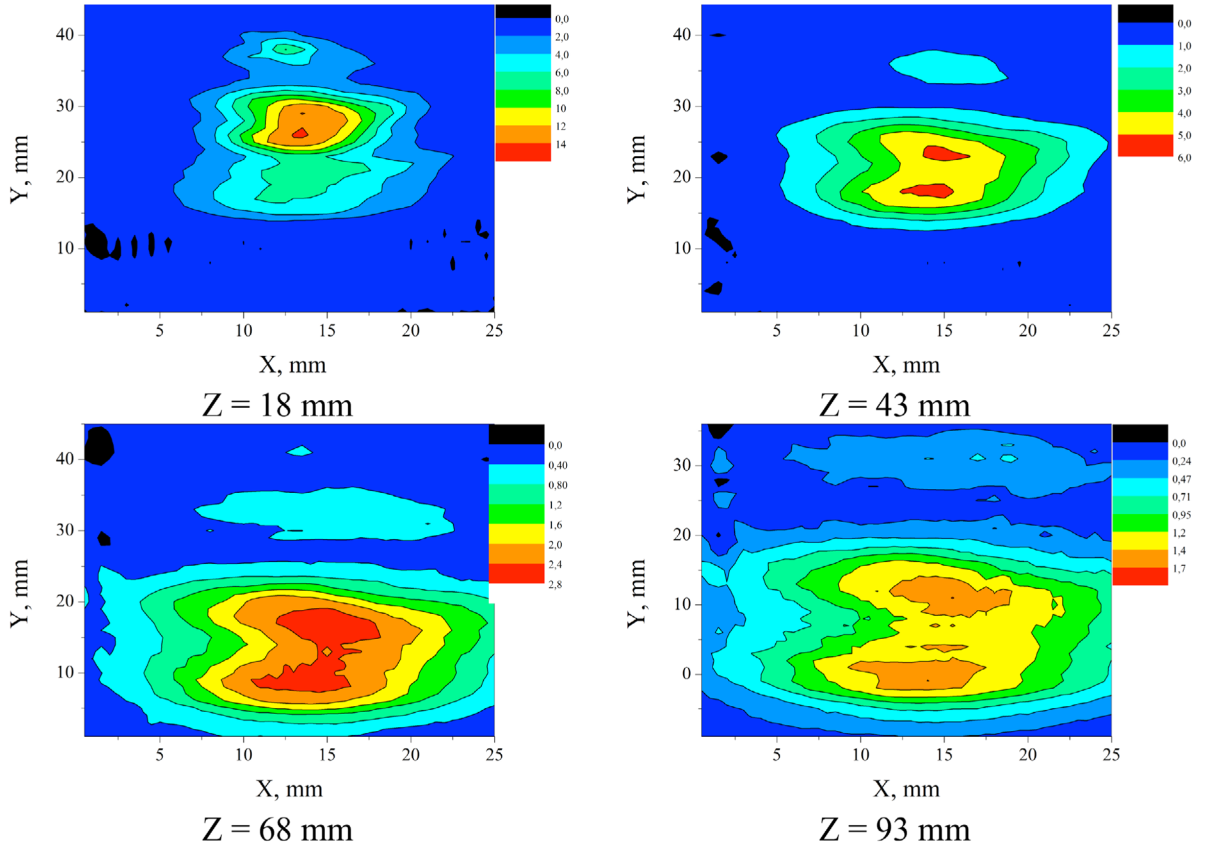


Figure 7. Transverse distribution of the QCL radiation intensity. *Z*—the distance from the waveguide edge. Color corresponds to intensity in au.

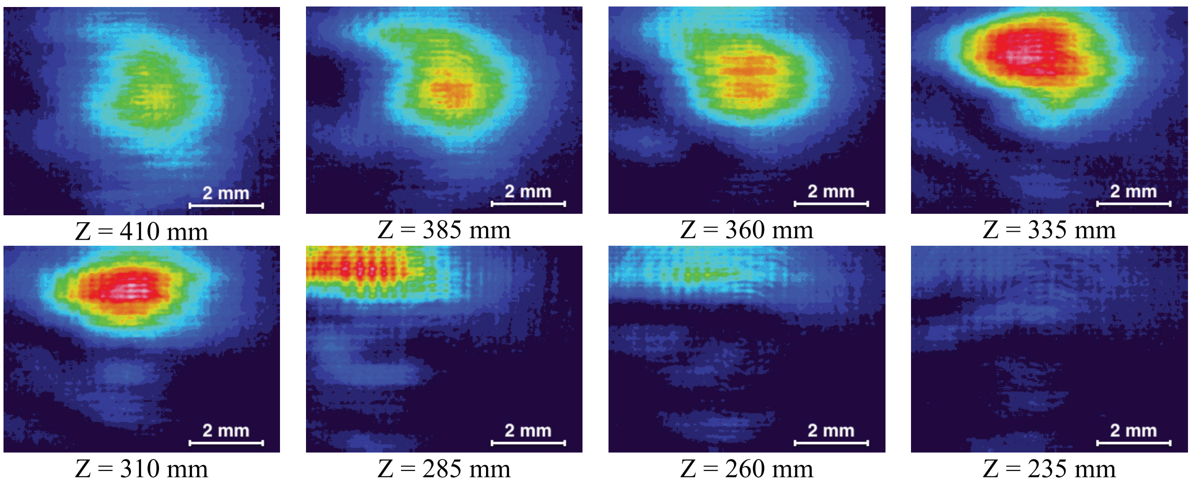


Figure 8. Transverse radiation intensity distribution of the focused QCL beam. *Z*—the distance from the waveguide edge. Color corresponds to intensity in au.

increase of z_l reduces the minimum beam divergence of a wire laser image beam at the expense of a fast decrease of collected power, which reaches maximum when z_l is equal to the focal distance of the lens. The approach to formation of a directive beam from a wire laser based on the longitudinal modulation of the laser waveguide [4–6] enables the collection of the whole power emitted by the laser. The divergence of the beam is then determined by the ratio of the wavelength to the length of the laser: $\alpha \approx \sqrt{\lambda/2L}$, provided the laser waveguide modulation is perfectly phase matched.

The use of an additional collimating lens on a distance from the laser smaller than the focal one can be interpreted as replacement of the source by its virtual image that is shifted along the lens axis to a bigger distance from the lens, and has a longer length. The structure of the image field of a wire laser obtained using an additional collimating lens is similar to that described above, with the transverse field distribution near the maxima described by (1) with Λ determined by the ratio of the laser length to the axial resolution of the collimating lens, provided that the radius of the focusing lens is larger than the

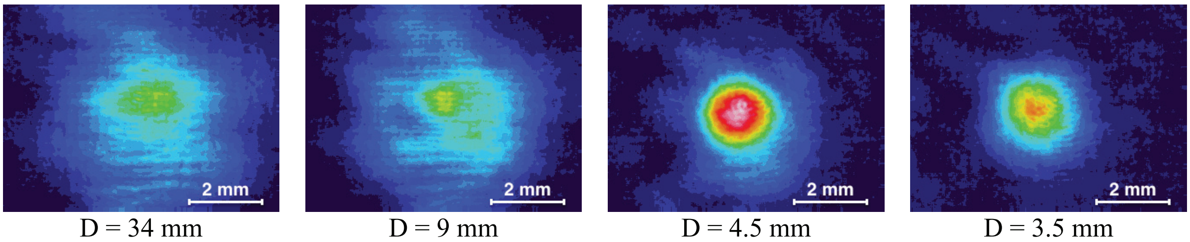


Figure 9. Dependence of the transverse radiation intensity distribution after transformation by a lens and a diaphragm on the diaphragm diameter (D), the distance from the cryostat window to the lens is 15 mm, the diaphragm—315 mm, to the camera—400 mm. Color corresponds to intensity in au.

collimated beam width. Thus, a narrow beam can be obtained using the same approach, placing the diaphragm with the radius of a point source image in the transverse plane corresponding to the maximum of the axial field distribution of the focused field.

3. Experimental results

We experimentally studied the effect of the spatial filtering on the output spatial distribution of a wire laser radiation using quantum cascade laser (QCL) emitting radiation at 1.965 THz. The laser consisted of a multi-layer ($GaAs/Al_{0.15}Ga_{0.85}As$) heterostructure with metallic contacts forming the so-called double-metal waveguide (figure 5(a)). The size of the laser waveguide was $1000 \times 100 \times 10$ μm. Such a waveguide provided single transverse mode generation and effective cooling. Collimation of the laser radiation was reached by using an additional hyper-hemispherical high resistivity silicon micro-lens with the radius $R = 1$ mm at the edge of the waveguide (figures 5(b) and (c)). Such a micro-lens attached to the QCL facet increased the outcoupling and reduced the reflectivity. We used an optical microscope for matching the micro-lens against the laser waveguide. After alignment the micro-lens was fixed with the cryogenic glue.

The laser module was mounted on a copper pad of a cryogenic cooler in a vacuum chamber; a fluoroplast output window was used to deliver the radiation from the cryostat. The distance between hyper-hemispherical micro-lens and the output window was 10 mm.

Transverse distribution of the focused QCL radiation intensity is shown in figure 6. This picture was registered using THz camera NEC IRV-T0831 with 320×240 pixels focal plane array. QCL beam was focused using high resistivity silicon lens with focal distance 25 mm and diameter of 25.4 mm. The field distribution is non-uniform and for certain applications the correction is required.

The intensity distribution along the QCL beam was investigated near the exit window of the vacuum chamber. High resistivity silicon lens was not used in this experiment. Measurements were carried out using a Golay cell with an additional aperture diameter of 2 mm. Various images obtained for different values Z—the distance from the waveguide edge ($Z_{\min} = 18$ mm, pitch 25 mm) are shown in figure 7. It is seen that the beam has a complex structure. There is an offset downwards on 7 mm in the case of 25 mm distance, corresponding to the angle of the beam axis at 15°. Such behavior can be explained by the non-optimal position of the hyper-hemispherical micro-lens relative to the QCL waveguide structure.

The laser radiation intensity after focusing by a spherical lens has been registered using THz camera NEC IRV-T0831 (figure 8). The high resistivity silicon lens with the focal distance $F = 25$ mm and the radius $R = 20$ mm has been placed at the distance of 15 mm from the cryostat window. The maximum of the axial distribution was observed at the distance about 300 mm from the lens. The transverse size of the field distribution near the maximum at the level of half maximum of intensity is 1.2×2.0 mm, which is close to that of a point source image located at the same distance from the lens.

The diaphragm was inserted in the plane perpendicular to the lens axis at the distance 300 mm corresponding to the maximum of the axial field distribution. The dependence of the transformed field distribution on the size of the diaphragm is demonstrated in figure 9. The axially symmetric uniform beam is formed when the radius of the diaphragm is close to that of the first zeros of a point source image (about 2.7 mm). The reduction of the diaphragm size leads to a decrease of the beam power, while with the increase of the diaphragm size the beam structure becomes less uniform.

4. Conclusion

We reported on the method of formation of a directive beam from slow modes of a laser with subwavelength transverse dimensions and the length much larger than the wavelength using spatial filtering by means of a spherical lens and a diaphragm. This method has natural limitations, as only a part of the omnidirectional radiation of wire lasers falls within the entrance aperture of the optical system and a half of this power can be collected into a beam with uniform phase using a diaphragm. However, unlike the method of producing directive beam as an image of a wire laser created by a lens, this method does not impose limitations on the aperture of the optical system. The method provides a cheap and robust alternative to the approach to improving the directivity of wire lasers by fabrication of laser waveguides with longitudinal modulation. Moreover, spatial filtering can provide a directive beam for multimode wire lasers.

Acknowledgments

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