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# Development of the Methods of Control of Radiation Structure of THZ Quantum Cascade Lasers

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**Abstract**

Specific features of radiation structure of terahertz quantum cascade lasers are determined by wire geometry of their waveguides with small and sub-wavelength transverse dimensions and the length much larger than the wavelength. Here we present an overview of the results of beam profile investigations and of the methods proposed for the control of radiation structure of such lasers.

## Introduction

Terahertz Quantum Cascade Lasers (THz QCL-s) are unipolar devices operating on intersubband transitions in semiconductor heterostructures. The ability to engineer the frequency of lasing transition (presently from 4.8 THz to 1.2 THz), high output power (more than 100 mW in pulsed mode at cryogenic temperatures), narrow linewidth (tens of kHz for single mode devices) together with compactness and ease of high speed modulation make the THz QCL-s promising sources for a wide range of applications. However, a number of important applications of THz QCL-s, including using such lasers as a local oscillator for heterodyne spectroscopy, have been hindered until recently due to specific features of their radiation structure. Peculiarities of THz QCL-s radiation pattern stems from their wire geometry: transverse dimensions smaller or comparable to the wavelength, while their length is much larger than the wavelength. Standard methods of laser optics are targeted at the lasers with transverse dimensions much larger than the wavelength. One can expect that the methods of microwave antenna theory dealing with sub-wavelength sources can be used to control the radiation features of wire lasers. However laser physics sets up specific tasks that have not been addressed by physics of microwave devices: to combine high directivity with high mode confinement, to provide the possibility of frequency tuning, to control and optimize the level of radiation losses providing maximum laser output power. Here we present an overview of the methods developed for the control of the radiation structure of THz QCL-s. It should be mentioned that THz QCL is a convenient model system for investigation of the properties of wire lasers in general, and the approaches developed can further be applied to lasers of similar waveguide geometry operating in other frequency ranges and based on different active media.

## Waveguide geometry

Wire geometry of THz QCL-s is determined by practical requirements: limitation of the structural growth times, the need of single mode operation, effective cooling, and minimization of reflection losses. There are two main types of the waveguides that have been used for THz QCL-s: the semi-insulating surface-plasmon, and metal–metal waveguide. They consist of an active semiconductor structure about 10-μm-thick between two contact layers placed on a dielectric substrate. Both contact layers of metal–metal waveguides are metallic, while one of the contact layers of the surface-plasmon waveguide is formed by a thin heavily doped layer underneath the active region, on top of a semi-insulating substrate. Considerable penetration of the modes of surface-plasmon waveguides into the substrate leads to a smaller mode confinement $\Gamma = 0.1-0.5$, that is reduced additionally in the ridges narrower than 100 μm, higher mirror losses, and non-uniform radiation intensity along the waveguide. Metal-metal waveguides allow high mode confinement $\Gamma \approx 1$, with the width of the waveguide smaller than the wavelength, high reflection at the ends of the waveguide up to $R \approx 0.9$ enables uniform longitudinal distribution of the mode intensity.

## Radiation structure of THz QCL-s

Radiation pattern of THz QCL-s with metal-metal waveguide differs drastically from that of the lasers operating at higher frequencies, with transverse dimensions much larger than the wavelength. The small size of laser waveguide leads to a high divergence of output radiation due to diffraction. Additionally we have discovered short range variations of the far field intensity of lasers with sub-wavelength cross section [1], which have not at all been expected based on traditional aperture methods of beam profile calculations used for larger lasers. We developed antenna model of wire lasers, explaining such beam structure by the interference of radiation from longitudinal distribution of sources along the laser waveguide [2]. This theoretical model shows that intensity modulations are accompanied by the rapid change of the phase of the signal, thus leading to drastic decrease of coupling efficiency.

## Control of radiation structure of THz QCL-s

Several approaches have been proposed by a number of teams worldwide to improve directivity and beam patterns of THz QCL-s. Hyperhemispherical lens placed next to the facet of a wire laser [3] collimates the beam, however it is found to increase the density of interference rings. Considerable improvement of directivity without significant increase of threshold current has been reached using plasmonic antenna [4] and hollow external waveguide [5]. Surface emission design [6] and integration of a waveguide with horn antenna [7] allowed enlargement of effective aperture and considerable increase of collected power due to improved relation of radiation and dissipation losses. We note that interference of radiation from longitudinal distribution of sources being a typical feature of wire lasers is not merely a negative factor when directivity is concerned. Further improvement of beam quality is possible within approaches using specific properties of beam profiles formed by longitudinal interference.

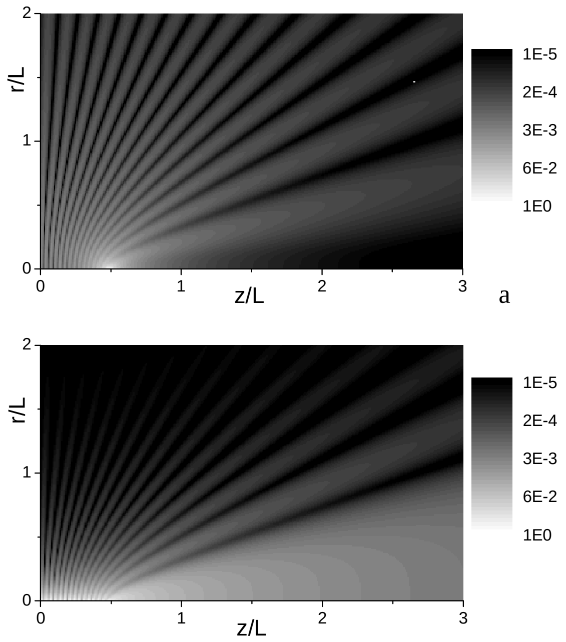



Fig. 1.
Distribution of the square vector potential of radiation field from a wire laser in the plane containing the longitudinal axis of the waveguide, perpendicular to polarization of equivalent source current (laser length L=15 λ, transverse integral of equivalent current is nonzero): (a) slow mode; (b) synchronous mode.

Radiation of wire lasers, though non-uniform and divergent, has a regular pattern. This regularity can be used to produce a narrow beam along the laser axis. Our model [2] predicts the possibility to combine small laser aperture and low beam divergence in the case of synchronism of laser mode phase velocity with that of light in air (Fig. 1.). All the sources along the laser length for such modes emit in phase in the direction of longitudinal axis, producing axially symmetrical beam with the angular width determined by a square root of relation of radiation wavelength to the waveguide length. Such synchronous modes may exist in open dielectric waveguides near propagation cut off. However, intrinsic property of synchronous modes is the vanishing of the parameter of exponential field decay outside the waveguide, leading to low mode confinement.

### *External optics for THz QCL-s*

Alternative approach is based on the transformation the radiation of a wire laser externally without altering the cavity design and mode losses by means of specially designed lenses. The method is based on the compensation of the phase shifts in the plane perpendicular to the laser axis (Fig. 2(a)).

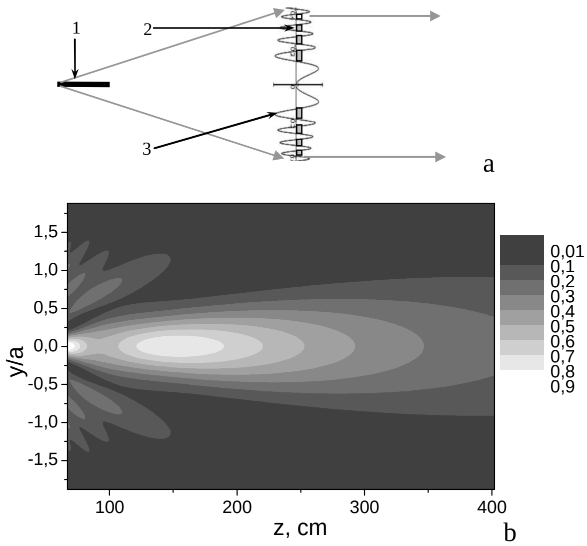



Fig. 2.
(a) The scheme of the phase correction of wire laser radiation: 1 – laser cavity, 2 – the lens with half wavelength thickness shifts at the rings of zero radiation amplitude combined with a spherical lens on the focal distance from the laser, 3 – the field amplitude in the lens plane; (b) distribution of radiation intensity after phase correction, calculated using Fresnel integral over the lens surface (laser length L=13 λ, wavelength λ=105.6 μm, lens radius a=1.5 cm, focal distance F=3 cm).

Such compensation can be reached using a plate with rings of different optical thickness. This method allows formation of a narrow beam with divergence determined by the relation of the wavelength to the radius of the lens (Fig. 2(b)).

However only a part of laser radiation can be collected this way, and the optical system requires careful alignment. Using ordinary spherical lens can provide a narrow beam too, as an image of a wire laser located on the lens axis. However, such image may have regions with a dense ring structure of intensity modulations accompanied by rapid phase shifts. Presence and location of such regions depend on the parameters of the laser, the lens focal distance and size, and details of alignment.

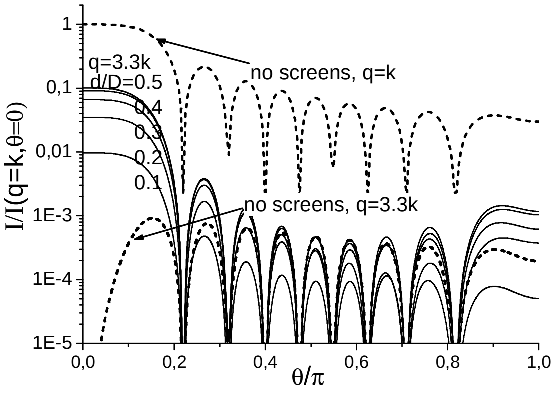
***Waveguide design using the interference of radiation from longitudinal distribution of sources***

Formation of a narrow beam by the interference of radiation from longitudinal distribution of sources from a wire laser is possible without considerable changes to laser mode structure and confinement. It can be realized using periodic modulation of the waveguide. Indeed, there is always a set of points along the waveguide, where emission sources emit in phase in forward direction. Such points are separated by the interval

$$D = 2\pi/(q-k)\,, \tag{1}$$

where $q$ is the longitudinal wave vector of the laser mode, and $k = 2\pi/\lambda$. Radiation from periodic non-uniformities of the wire laser waveguide with period $D$ for a mode with $q > 3k$ can form a narrow beam pattern similar to that of synchronous mode. The power of the radiation from such periodic elements does not suffer from destructive interference, it grows linearly with the length of the waveguide and can be much higher than that of the core of the waveguide. The dependence of the output power on the level of radiation losses is not monotonic, and the highest output power is reached at $\alpha_r = (\alpha_0\alpha_d)^{1/2} - \alpha_d$, where $\alpha_0$ is the small signal gain, $\alpha_r$ and $\alpha_d$ are the coefficients of radiation and dissipative losses respectively. The level of radiation losses in THz QCL-s with sub-wavelength transverse dimensions is usually smaller than this optimum, thus the increase of the radiation losses in the lasers with periodic non-uniformities can lead to an increase of the output power.

The first low divergence THz QCL waveguide design using the interference from longitudinal distribution of sources within the laser waveguide has been realized using 3-d order DFB providing both the feedback and the resonant scattering forward [8]. Such grating did not provide exact phase matching, and thus had a finite maximum length emitting in phase. Solution of the problem of phase matching of 3-d order DFB has been realized in [9], by insertion of periodic air gaps in the waveguide structure. It should be noted that the output power from high directivity lasers increased several times compared to a standard waveguides of similar dimensions. However the design based on 3-d order DFB is not robust, as it influences considerably the mode structure inside the cavity, and it does not allow tuning of the radiation losses.



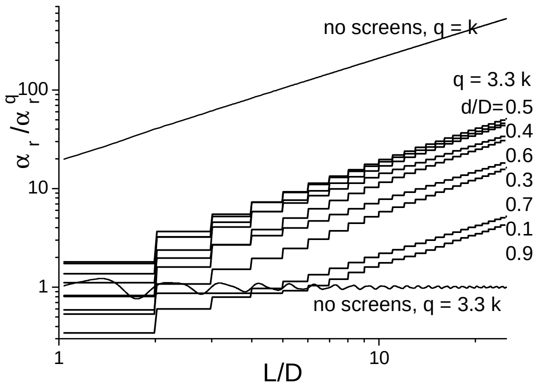




Fig. 3.
(a) Angular distribution of radiation intensity from wire laser with and without system of screens along the side facets with the period D, normalized by the radiation intensity of the wire laser without screens in the direction of longitudinal axis, d is the width of the sleets between the screens, laser length L=10D; (b) radiation losses of wire laser with and without the system of screens, normalized by that of the unperturbed laser mode with q=3.3.k in a laser with L>>D.

Alternatively, narrow beam from a wire laser can be obtained using a system of screens with the period D along the laser side facets (Fig. 3(a)). Owing to the decay of the mode field outside the core of the waveguide the influence of such screens on the mode confinement and gain is small. Radiation losses of wire laser with the system of screens calculated using Fresnel-Kirchhoff integral over the laser side facet and the surface, closely wrapping the laser waveguide with the screens, is presented on the Fig. 3(b). The maximum of the ratio of radiation losses in the system with screens to that of the unperturbed laser mode in the limit of laser lengths L>>D it is given by:

$$\alpha_r / \alpha_r^q = \sin^2(\pi d)(q^2/k^2 - 1)L/2\lambda\,, \tag{2}$$

where $d$ is the ratio of the length of the slit to the length of the screen. The decay of the field of the laser mode outside the laser waveguide enables the control of the level of radiation losses by changing the distance between the laser waveguide and the system of screens, while the feedback can be provided by a separate grating. Thus the system of periodic screens on a distance from the laser side facets enables both narrow beam formation and the optimization of radiation losses.

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