Optical losses of a waveguide with superconducting plates in terahertz quantum cascade lasers

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The paper calculates the optical losses of a waveguide with superconducting YBCO plates for a quantum cascade laser with a generation frequency of 1.2 THz at a temperature of 10 K. It is shown that the use of such plates in terahertz quantum cascade lasers with a small number of cascades (~ 20) will significantly reduce losses compared to traditionally used gold and silver plates.

Keywords: waveguide, terahertz range, quantum cascade laser, superconductor.

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1. Introduction

One of the promising compact sources of coherent radiation are terahertz quantum cascade lasers (THz QCL) based on semiconductor structures with GaAs/AlGaAs quantum wells [1]. They find application in spectroscopy and analysis of complex compounds, environmental monitoring, fundamental research, etc. [2]. Over the twenty-one years of their existence, THz QCL have achieved significant progress both in maximum operating temperatures [3] and in their power [4]. However, usually the thickness of the active region of a THz QCL is $> 10\,\mu$m and includes on the order of a thousand nanometer semiconductor layers of precisely controlled thickness and composition, which prevents the widespread use of THz QCL. On the other hand, the use of a double metal waveguide in a THz QCL allows to significantly reduce the number of cascades required for lasing, since the optical limiting factor in such waveguides is ~ 1. For example, for a laser with a frequency of 3.5 THz, it was previously possible to reduce the number of cascades to 37, each with a thickness of 43.7 nm [5]. This allowed to make a laser with a waveguide thickness of only $1.75\,\mu$m, which is 50 times less than the wavelength of laser radiation in vacuum.

Unfortunately, a decrease in the width of the active region leads to a sharp increase in losses, which are associated with absorption in the metal plates of the waveguide [6]. Therefore, it is very important what metal is used for the waveguide plates. Typically, gold (Au), copper (Cu), and more rarely silver (Ag) [7–9] are used as metal contacts. However, noble metals cannot be deposited directly onto semiconductor surfaces due to poor adhesion and the opportunity of solid-state diffusion between the semiconductor and the noble metal during high-temperature processes. Therefore, an intermediate metal is applied, which functions as a firmly attached adhesive layer and a diffusion barrier. A typical adhesion layer is titanium (Ti), the absorption of THz radiation in which is significantly higher than in gold and silver.

An alternative to metal plates of THz QCL can be layers made of superconducting materials. Indeed, if the energy of a radiation quantum is less than twice the energy of the superconducting gap Δ ($\Delta = k_B T_c$, where k_B — Boltzmann constant, T_c — the critical temperature below which a superconducting state appears), then superconductivity will exist [10]. Therefore, with a radiation quantum energy up to ~ 7 meV (radiation frequency 1.7 THz), a high-temperature superconductor such as yttrium oxide–barium–copper (YBCO), the T_c of which depends on the material on which it is deposited, can be used. When YBCO is deposited on GaAs without an additional adhesion layer, T_c reaches 40 K [11]. In this work, a theoretical study of the opportunity of significantly reducing losses in low-frequency THz QCL was carried out by using YBCO layers as plates.

2. Model and the calculation results

In our simulation, the superconductor is described using the well-known two-fluid model, which assumes the existence of two non-interacting electronic subsystems contributing to the electromagnetic response of the superconductor at non-zero temperatures: superconducting electrons (Cooper pairs) with purely inertial dynamics of motion forming the supercurrent, and normal electrons participating in scattering and scattering of energy [12]. To simulate the dielectric function of such a two-component electron plasma at frequencies below the superconducting slot frequency $2\Delta/\hbar$, the generalized Drude model is used [12]:

$$\varepsilon_{sc}(\omega) = 1 - \frac{\omega_s^2}{\omega^2} - \frac{\omega_n^2\tau^2}{\omega^2\tau^2+1} + i\,\frac{\omega_n^2\tau}{\omega(\omega^2\tau^2+1)}. \quad (1)$$

The second term in equation (1) represents the contribution of the non-scattering supercurrent of Cooper pairs with the plasma frequency

$$\omega_s = \sqrt{N_s e^2/m\kappa_0} = c/\lambda_L,$$

where λ_L — London penetration depth, N_s — concentration of superconducting electrons, m — their effective mass and κ_0 — dielectric permittivity of free space, c — speed of light in vacuum, e — electron charge. The third and fourth terms refer to normal electron plasma with a resonant frequency

$$\omega_n = \sqrt{N_n e^2/m\kappa_0},$$

where N_n — concentration of normal electrons, τ — their relaxation time. The balance between the concentrations of superconducting and normal electrons is described by the empirical Gorter–Casimir relation:

$$N_s = N\big(1 - [T/T_c]^4\big),$$

where N — temperature-independent total concentration of free carriers, in $N_n = N - N_s$ [13]. The superconductor model parameters are chosen to describe YBCO with $T_c = 40\,\mathrm{K}$ and $N = 1.255 \cdot 10^{27}\,\mathrm{m}^{-3}$ [12]. The value τ was obtained from the experimental temperature dependence of the quasiparticle scattering rate for YBCO [14] films. At the critical temperature $\tau_c = 1/\gamma_c = 3.57 \cdot 10^{-14}\,\mathrm{c}$, and the experimental temperature dependence of the scattering rate can be accurately approximated by a curve of the form [12]:

$$\gamma(t) = \frac{\gamma_c t}{1 + 10t(t^{-1.5} - 1)}, \quad (2)$$

where $t = T/T_c$.

As an example, we will simulate and compare losses in a QCL with a double metal waveguide emitting at a frequency of 1.2 THz and experimentally implemented with Au/Ti [15] plates. We will review $T = 10\,\mathrm{K}$ when absorption in YBCO is close to minimum. In this case, according to formula (1), the complex refractive index $\big(n_{sc} = \sqrt{\varepsilon_{sc}(\omega)}\big)$ YBCO will be equal to $0.026 + 264.993i$.

The dielectric permittivity in the THz range of a metal can be expressed through the Drude formula (j = Au, Ag, Ti):

$$\varepsilon_j(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma_d)}, \quad (3)$$

where for Au, Ag and Ti from experimental works [16,17] for temperature $T = 10\,\mathrm{K}$ the constants are determined: $\hbar\omega_p = 9.02\,\mathrm{eV}$ and $\hbar\gamma = 5.68\,\mathrm{meV}$ for Au, $\hbar\omega_p = 8.98\,\mathrm{eV}$ and $\hbar\gamma = 1.51\,\mathrm{meV}$ for Ag, $\hbar\omega_p = 8.74\,\mathrm{eV}$ and $\hbar\gamma = 242\,\mathrm{meV}$ for Ti. Then, according to formula (3), the complex refraction indices will be equal to: $610 + 1343i$ (Au), $260.8 + 1751i$ (Ag) and $176.5 + 180.2i$ (Ti).

Dielectric permittivity of both the contact layers n^+-GaAs (with an electron concentration $n_1 = 2 \cdot 10^{18}\,\mathrm{cm}^{-3}$ [15]) and the active region GaAs/$Al_{0.1}Ga_{0.9}As$ (with an average electron concentration $n_2 = 2 \cdot 10^{15}\,\mathrm{cm}^{-3}$ and a fraction of 0.13 layers $Al_{0.1}Ga_{0.9}As$ over the full thickness [15]) was determined from the following expression for GaAs [18]:

$$\varepsilon(\omega, n) = \varepsilon_\infty + \frac{\omega_{\mathrm{TO}}^2(\varepsilon_0 - \varepsilon_\infty)}{\omega_{\mathrm{TO}}^2 - \omega^2 - i\Gamma\omega} - \frac{\omega_{ps}^2(n)\varepsilon_\infty}{\omega^2 + i\gamma_s(n)\omega}, \quad (4)$$

where ε_0 and ε_∞ —low-frequency and high-frequency dielectric permittivity of undoped GaAs; ω_{TO} — transverse optical phonon frequency; Γ — phonon wave attenuation coefficient; $\gamma_s(n) = e/m^*\mu(n)$ — wave attenuation coefficient when absorbed by free carriers; $\omega_{ps}^2(n) = 4\pi n e^2/m^*\varepsilon_\infty$ — plasma frequency squared; n and m^* — concentration and effective mass of electrons; $\mu(n)$ — electron mobility. The value of $\gamma_s(n)$ was determined from the data on the dependence of mobility on the dopant concentration: $\mu(n_1) = 2000\,\mathrm{cm}^2/(\mathrm{B}\cdot\mathrm{c})$, $\mu(n_2) = 20000\,\mathrm{cm}^2/(\mathrm{B}\cdot\mathrm{c})$ [18]. The values m^*, Γ, ω_{TO}, ε_0 and ε_∞ were taken from there.

The loss of the waveguide (α) can be determined from the longitudinal component of the mode wave vector: $\alpha = 2\,\mathrm{Im}(k_x)$. To determine k_x numerically using the transfer matrix method, we solved the equation for the coordinate dependence of the magnetic field strength $H_y(z)$ propagating in the direction x in the QCL mode TM_0 (the z axis is directed across the layers of the structure) [19]:

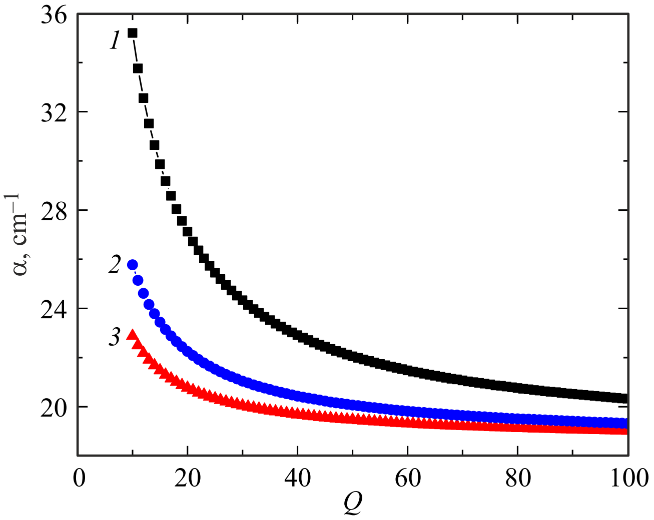
$$\varepsilon(z)\,\frac{d}{dz}\left[\frac{1}{\varepsilon(z)}\,\frac{dH_y(z)}{dz}\right] + \left(\varepsilon(z)\,\frac{\omega^2}{c^2} - k_x^2\right)H_y(z) = 0, \quad (5)$$

and the dielectric permittivity changes along the coordinate z as follows:

$$\varepsilon(z) = \begin{cases} \varepsilon_j(\omega), & z < 0,\ z \ge 2(d+W) + QD, \\ \varepsilon_{\mathrm{Ti}}(\omega), & 0 \le z < d,\ z \ge d + 2W + QD, \\ \varepsilon(\omega, n_1), & d \le z < d + W, \\ & d + W + QD \le z < d + 2W + QD, \\ \varepsilon(\omega, n_2), & d + W \le z < d + W + QD, \end{cases} \quad (6)$$

where j = Au, Ag, sc, W — thickness of the contact layer n^+-GaAs (50 nm [15]), d — thickness of the layer Ti, Q and D — number and thickness of cascades in the QCL ($Q = 85$ and $D = 134.7\,\mathrm{nm}$ in work [15]).

Calculation of the dependence of waveguide losses at a frequency of 1.2 THz on the number of cascades for three types of plates (Au/Ti, Ag/Ti and YBCO) is shown in the Figure. The thickness of the cascade was chosen equal to 134.7 nm for comparison with experiment [15].



Dependences of losses of the waveguide (α) at a frequency of 1.2 THz on the number of cascades Q for three types of plates: *1* — Au/Ti, *2* — Ag/Ti and *3* — YBCO. $T = 10$ K, $D = 134.7$ nm.

In case of using Au and Ag plates, the thickness of the adhesion layer (Ti) was 20 nm; in case of using YBCO, the adhesion layer is not required [11]. Let us note the good agreement between the calculated absorption value (20.6 cm^{-1}) for the QCL from the work [15] and the experiment ($Q = 85$), where Au/Ti plates were used. It can be seen from the Figure that the use of Ag/Ti and YBCO plates for the experimental structure would slightly reduce losses by ~ 1.5 cm^{-1}. This is due to the fact that with a large thickness of the active region, the ground losses are determined by losses in the semiconductor layers. However, as the number of cascades in a THz QCL decreases, the role of losses in the waveguide plates increases and the total losses now strongly depend on them. Therefore, losses in a waveguide with Au/Ti plates increase very quickly to 35.2 cm^{-1} with a decrease in the number of cascades to 10. When using plates made of Ag/Ti and YBCO for a similar structure with $Q = 10$, the losses would be 25.8 and 22.9 cm^{-1}, respectively. This means that at the same loss level of 20.6 cm^{-1} for the considered THz QCL with Ag/Ti and YBCO plates, only 36 and 20 cascades, respectively, are sufficient to operate. It would then be required to grow semiconductor layers with thicknesses of only 5 and 2.8 μm for waveguides with Ag/Ti and YBCO plates, respectively, which is significantly smaller than the used structure with a thickness of 11.6 μm with Au/Ti plates.

3. Conclusion

In conclusion, let us note that the calculation of the losses of a THz QCL with a double metal waveguide with Au and Ag plates with an adhesion layer of Ti and with YBCO plates has been carried out. It was shown that losses in a waveguide for a frequency of 1.2 THz with Au plates are significantly greater than with Ag and YBCO plates. In addition, it was shown that the use of YBCO plates can significantly (by more than a factor of 4) reduce the number of cascades (thickness of the active region) required for the operation of THz QCL. The predicted results will greatly simplify the fabrication of THz QCL for various applications.

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Conflict of interest

The authors declare that they have no conflict of interest.

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