The concept for realization of quantum-cascade lasers emitting at 7.5 μm wavelength

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Abstract We consider the advantages and disadvantages of various designs of waveguide for heterostructures of quantum cascade lasers (QCL) in a spectral region of 7.5 μm. Based on a numerical calculation we make a comparison of light wave distribution in QCL waveguides with different designs. We demonstrate the benefits of practical QCL realization with an extended five-layered waveguide formed by introducing extra layers of InGaAs, which allows to modify the spatial distribution of the light wave and get the rectangular shape of the spatial distribution of light wave intensity in the laser active area.

1. Introduction
The operation principle of quantum cascade lasers (QCL) is based on intersubband electronic transitions between quantum states of semiconductor nanoheterostructure [1-2]. The wavelength of the radiation emitted by an active QCL area (by a set of quantum wells) is mainly determined by the thickness of semiconductor layers and not by their bandgap. Utilization of effects of resonant tunneling and miniband conductivity allows one to create an injector area and interconnect active zones. The combination of the injector and the active zone is called a cascade. Thus, alternating between active and injector areas [2-11], one can create a QCL heterostructures containing large number of connected cascades. This cascaded laser structure provides a relatively simple way for scaling of the output optical power of a single emitter. An electron, passing through each cascade, emits a photon. During its passage through the all QCL cascades, one electron emits multiple photons. The larger number of cascades in the QCL, the greater number of photons, one electron emits during its passage.

Hence, increasing number of cascades should lead to increasing of the optical output power of the device and to decreasing of the threshold current. The number of cascades which is required for realization of an efficient QCL is typically 30 or more. However, this is true only in the case of perfect identity of all cascades [12-14]. In practice, technical difficulties of maintaining stable parameters during the epitaxial process for a long period of time, that is needed for growing of a QCL...
nanoheterostructure, may cause changes in the thickness and composition of epitaxial layers that shifts the cascade amplification spectrum. As a result, the potential gain may be lost.

For creation of QCL with lasing wavelength 7.5 μm it is advisable to use In_{0.53}Ga_{0.47}As and InP layers in solid alloys. Mole fraction of indium (0.53 and 0.52) in these solid alloys is chosen in that way that the lattice parameter of the layer solid alloy matches to the lattice parameter of InP substrate. One of the most important physical parameter of semiconductor layers comprising QCL heterostructures is their refractive index, which contains real and imaginary parts. The refractive index depends on a selected material and wavelength, as well as on the doping level. For n-type doping of InP-matched solid alloys, silicon is commonly used. The influence of doping on the refractive index of the material can be calculated using Drude-Lorentz approach [15], where plasma frequency is defined by the expression:

$$\omega_p = \sqrt{\frac{n_e q^2}{\varepsilon_0 \omega m_e}}$$

where key parameter $n_e$ is the conduction electron density, $q$ is the elementary charge, $m_e$ is the electron mass, $\varepsilon_0$ is the permittivity of free space, $\varepsilon_\infty$ is the high-frequency permittivity, which is actually equal to the local level of doping. Then the total electric susceptibility can be expressed as:

$$\varepsilon = (n + ik)^2 = \varepsilon_\infty \left(1 - \frac{\omega_p^2}{\omega(\omega+i/\tau)}\right)$$

where $n$ is the real refractive index, $k$ is the extinction coefficient, $\omega$ is the frequency, $1/\tau$ is the scattering rate.

The calculated values of real and imaginary parts of refractive indexes of In_{0.53}Ga_{0.47}As and In_{0.52}Al_{0.48}As solid alloys and InP substrate for different levels of n-type doping are shown in Table 1.

| Doping level (×10^16 cm^-3) | $n$ | $k \times 10^{-3}$ | $n$ | $k \times 10^{-3}$ | $n$ | $k \times 10^{-3}$ |
|-------------------------------|----|-------------------|----|-------------------|----|-------------------|
| 1.0                           | 3.375 | 0.45        | 3.147 | 0.27             | 3.071 | 0.28            |
| 5.0                           | 3.369 | 2.27        | 3.143 | 1.29             | 3.067 | 1.42            |
| 10                            | 3.362 | 4.52        | 3.139 | 2.58             | 3.062 | 2.84            |
| 50                            | 3.300 | 23.1        | 3.104 | 13.0             | 3.024 | 14.4            |
| 100                           | 3.222 | 47.4        | 3.061 | 26.4             | 2.976 | 29.2            |
| 500                           | 2.526 | 302         | 2.687 | 150              | 2.559 | 170             |

The presented data shows that with an increase of doping levels the real part of the refractive index decreases and the imaginary part increases. An important consequence of the increasing of the imaginary part of the refractive index is that it causes in increasing of optical losses due to an increase of radiation absorption on free charge carriers with increasing of material doping.

During the formation of heterostructure active region consisting of alternating layers of solid alloys of In_{0.53}Ga_{0.47}As and In_{0.52}Al_{0.48}As, we have a significant energy gap in a conduction band equal to 520 meV, which enables the creation of QCL active area comprising In_{0.53}Ga_{0.47}As quantum wells and In_{0.52}Al_{0.48}As barriers. At the same time, the characteristic values of the real part of the average refractive index of the active region and the injector are usually in the range 3.27-3.29 [16]. The real part of the refractive index of In_{0.53}Ga_{0.47}As layers is equal to 3.375 [15], of In_{0.52}Al_{0.48}As layers is 3.147 [17], and of InP substrate is 3.071 (the shown values relate to low doping level).
The QCL number of cascades selected when designing the heterostructures determines the thickness of the light-emitting laser area and is equal to the product of the total thickness of one cascade by a number of cascades. Due to a smaller refractive index, InP and InAlAs materials are used as the claddings of the waveguide. Quantum cascades, which consist of alternating layers of InGaAs and InAlAs, form the core of the waveguide. In each QCL cascade electrons relax from the excited state of the quantum well to the ground state, in the result photons are emitted. One electron, while passing “h” cascades, can emit “h” photons. For this reason, the QCL threshold current density must decrease with the increasing number of cascades. Additionally, an important parameter is the overlap of the light-emitting region, which is also the gain region, with the light wave in the waveguide. A part of the light wave is located in the waveguide core and the other part penetrates into the claddings of the waveguide. With increasing thickness of waveguide core, the fraction of the light wave located in it increases (confinement factor increases) and the threshold current decreases. With further increase of waveguide thickness due to increasing the number of cascades, the confinement factor tends to unity. A further increase in the number of cascades will not lead to a reduction in threshold current density, since confinement factor has already reached its maximum value. For each individual cascade, the confinement factor will even decrease, since the light wave is redistributed between the greater number of cascades and the peak intensity of the light wave in the waveguide reduces. Furthermore, the efficiency of side cascades is quite low because of their low interaction with light wave.

2. Calculation results and discussion

The comparison of the light wave distribution in the narrow and broad waveguides is shown in Figures 1 and 2. The boundary conditions were used according [18]. As the bottom cladding, in these QCL designs we used InP substrate of n-type doped up to the level of $3.0 \times 10^{18}$ cm$^{-3}$, as the top cladding we used two layers of InAlAs having thicknesses 2.0 µm and 1.0 µm and doped with silicon up to levels of $1.0 \times 10^{17}$ cm$^{-3}$ and $1.0 \times 10^{18}$ cm$^{-3}$, respectively. Waveguide consists of 50 (or 99) quantum cascades with an average refractive index of 3.291. The confinement factors are 70% and 93%, and the optical waveguide losses due to the penetration of light waves into doped regions are equal to 90 cm$^{-1}$ and 22 cm$^{-1}$ for 50 and 99 cascades, respectively. Thus, one can see advantages of a broad waveguide.

![Graph](image_url)

**Figure 1.** Distribution of the refractive index and 7.5 µm light wave intensity in QCL heterostructure with a narrow waveguide (50 cascades) on InP substrate.
Figure 2. Distribution of the refractive index and 7.5 µm light wave intensity in QCL heterostructure with a narrow waveguide (99 cascades) on InP substrate.

However, one should keep in mind that the increase in the number of cascades results in a proportional increase in the operation voltage of the device and corresponding heating. Low efficiency of the side cascades should also be noted.

In practice, when constructing quantum-cascade lasers, for extension of the waveguide and reduction of optical losses one can use additional InGaAs layers, which have even greater refractive index compared with quantum cascades.

The use of such layers enables one to extend the waveguide and substantially modify the spatial distribution of the light wave. As a result, one can get not only an extended waveguide with reduced number of cascades, but equally efficiently use all the cascades due to forming of a rectangular profile of optical mode in the gain area of laser heterostructure. Utilizing of extended five-layered optical waveguide with a rectangular optical mode profile not only allows one to achieve maximum QCL quantum efficiency values at a fixed number of cascades, but also to increase a differential optical gain of active medium. In this case, one advantageously postpones the moment, when the gain saturation takes place, which is observed at higher pumping levels. Naturally, the gain saturation should primarily occur in the parts of the active medium, where the optical mode has its maximum. In an extended optical waveguide with a rectangular optical mode profile, the intensity of the optical mode is substantially the same throughout the whole gain region and the peak value of the optical mode intensity is decreased. Therefore, the start of gain saturation will occur at higher total optical power or at a higher pumping current. The calculations show that the start of gain saturation in the narrow optical waveguide (Figure 1) will occur when the optical power is by half lower compared with the optical waveguide with rectangular mode profile (Figure 3). Another advantage of the extended optical waveguide with rectangular optical mode profile is that it provides lower laser beam divergence, which in turn substantially facilitates focusing of laser radiation. The distribution of refractive indexes in QCL heterostructure with the extended five-layered waveguide, as well as the spatial distribution of the light wave intensity are shown in Figure 3.

The waveguide includes 50 quantum cascades with an average refractive index 3.291. Furthermore, InGaAs layers doped with silicon up to the level of 5.0 × 10^{16} cm^{-3} are additionally introduced into the waveguide. The optimal thickness of InGaAs layers, that is necessary to obtain a rectangular spatial distribution of the light wave in the laser active region, is equal to 2.17 µm from the side of InP and 1.67 µm from the side of InAlAs layers. The doping levels and thickness of all other layers for heterostructures shown in Figures 1, 2 and 3 are identical.
Figure 3. Distribution of the refractive index and 7.5 µm light wave intensity in QCL heterostructure with extended five-layered waveguide on InP substrate. The gain region includes 50 cascades.

The confinement factor for presented five-layered waveguide is 51%, and waveguide losses due to the penetration of light waves in the doped InGaAs layers and claddings are 36 cm⁻¹, this value is twice lower than for the case shown in Figure 1. At the same time this waveguide has all the advantages described above.

3. Conclusions
It has been shown that the use of QCL with extended five-layered waveguide formed by introducing extra layers of InGaAs with higher refractive index compared with quantum cascades, allows, on the one hand, to expand the waveguide core and reduce the proportion of the light wave penetrating the claddings of the waveguide and, on the other hand, to achieve significant modification of the spatial distribution of the light wave in the waveguide. By introducing sufficiently thick InGaAs layers on both sides of the light-emitting region, it is possible to obtain a rectangular spatial distribution of the intensity of the light wave in the active region of the laser (in quantum cascades) and to achieve high quantum efficiency of all cascades.

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