Optimization of a stripe laser waveguide based on an HgCdTe heterostructure for single-mode generation of far-IR radiation

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The parameters of an optically pumped stripe waveguide laser based on an HgCdTe heterostructure with quantum wells for single-mode generation of radiation in the wavelength range of $25-41\,\mu$m are optimized. It was shown that the width of the ridge should not exceed $15\,\mu$m to implement single-mode generation in a laser with an etching depth covering the active region.

Keywords: laser, waveguide, mode, HgCdTe, far-infrared region.

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1. Introduction

Sources of coherent far-IR radiation for various applications in gas spectroscopy, medicine, and environmental monitoring are highly sought after at the present moment [1–3]. Monopolar quantum cascade lasers (QCLs) based on $A^{III}B^{V}$ compounds dominate the market of semiconductor radiation sources in this wavelength region. However, the operation of QCLs based on these compounds is impeded (or, more often than not, is made completely impractical) due to strong absorption at polar optical phonons in the wavelength range of $25-55\,\mu$m [4]. Only one study into the possibility of laser generation in this range at a wavelength of $28\,\mu$m has been published to date [5].

Semiconductors with the frequencies of polar optical phonons lying far from the interval discussed above may serve as an alternative to $A^{III}B^{V}$ materials. HgCdTe solid solutions with the wavelengths of optical phonons being around $75\,\mu$m are an example of such semiconductors; notably, the band gap in HgCdTe may be varied within a wide range (from zero to 1.6 eV) by adjusting the Cd fraction. These materials are used widely in the design of detectors and sensor arrays of the middle IR range (see, e.g., [6] and references therein). It has recently been proposed to use quantum wells based on HgCdTe in the design of a QCL [7] emitting in the wavelength range that is out of reach for QCLs based on $A^{III}B^{V}$ compounds.

However, QCLs (including those based in HgCdTe) are fairly hard to construct, since a great number of quantum-dimensional layers of a required quality need to be grown. Therefore, amplification at interband optical transitions [8] may be a viable alternative to amplification at intersubband optical transitions, which is utilized in QCLs. Until fairly recently, interband lasers based on HgCdTe generated radiation only at wavelengths shorter than $5.3\,\mu$m [9]. However, refinement of the experimental procedure for HgCdTe structure growth by molecular beam epitaxy made it possible to observe superluminescence at wavelengths up to $31\,\mu$m in the studies of planar waveguide HgCdTe structures with quantum wells [10].

Single-mode lasing is often needed in practical applications. The determination of parameters of a stripe waveguide for generation of a single mode transverse to the propagation direction is the first step toward the production of such lasers. The application of common principles of construction of distributed-feedback lasers [11] should then allow one to achieve single-mode lasing for longitudinal modes.

2. Modeling and its results

We assume that the buffer CdTe layer thickness in the considered structure (see the table and Fig. 1) designed for optical pumping is $15\,\mu$m, since it has been demonstrated earlier that a waveguide for the wavelength range of $25-41\,\mu$m optimized in terms of the ratio of internal losses α to optical limiting factor Γ may be fabricated by growing a HgCdTe laser structure on a GaAs substrate with a CdTe buffer layer of exactly this thickness [12].

Varying the thicknesses of waveguide layers D_1 $Hg_{0.25}Cd_{0.75}Te$ and D_2 in solving the Maxwell equations for TE modes [13], we determined the optimum thickness values (see Fig. 2) at which the generation threshold for the TE_0 mode was minimized (this corresponds to the minimum α/Γ ratio) [12]. The generation threshold for non-fundamental modes was $1-2$ orders of magnitude higher. It can be seen from Fig. 2 that α/Γ increases rapidly with decreasing mode frequency. This is associated with an absorption spike observed when the mode frequency approaches the frequencies of polar optical phonons in CdTe, ZnTe, and GaAs [14]. The absorption maximum at 35 meV, which corresponds to the two-phonon absorption peak in CdTe [14], should also be noted. The frequency dependence of permittivity for $Hg_{0.25}Cd_{0.75}Te$ was approximated from [15].

Parameters of the studied structure

№ of layer	Description	Composition	Thickness, nm
1	Substrate	GaAs	–
2	Buffer layer	ZnTe	50
3	Buffer layer	CdTe	15000
4	Waveguide layer	$Hg_{0.25}Cd_{0.75}Te$	D_1
5	Active layer (10 QWs/barrier)	$HgTe/Hg_{0.25}Cd_{0.75}Te$	6/30
6	Waveguide layer	$Hg_{0.25}Cd_{0.75}Te$	D_2
7	Cover layer	CdTe	50

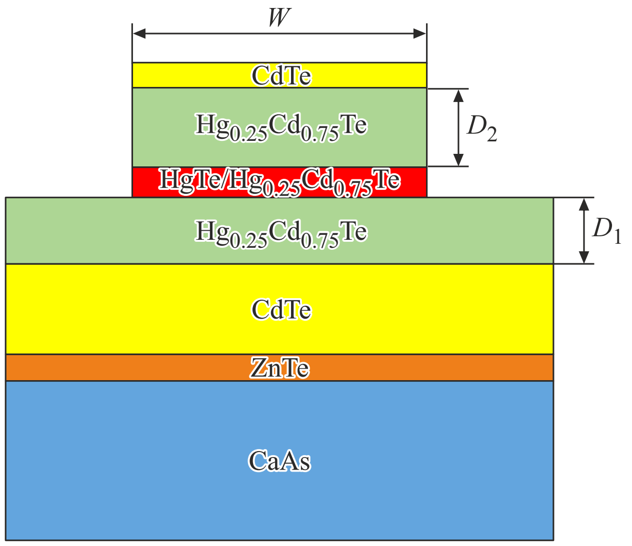

Figure 1. Growth diagram of the laser structure (not to scale). (A color version of the figure is provided in the online version of the paper).

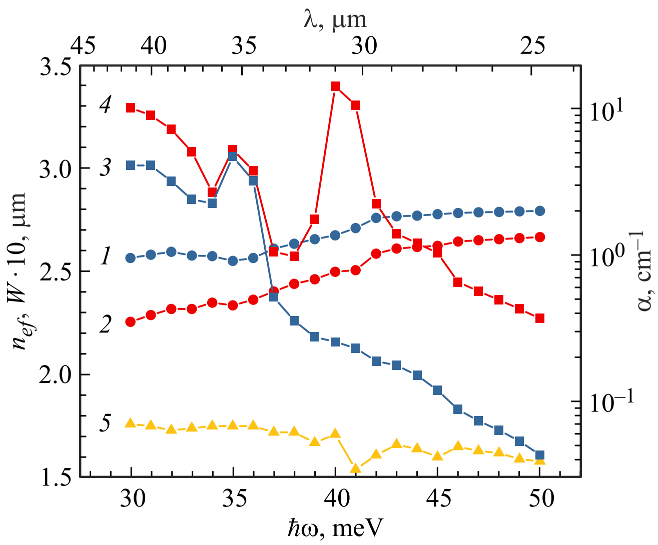

Figure 3. Frequency dependences of n_{ef} (*1*) and α (*3*) below the ridge, n_{ef} (*2*) and α (*4*) outside of it, and the maximum width W (*5*).

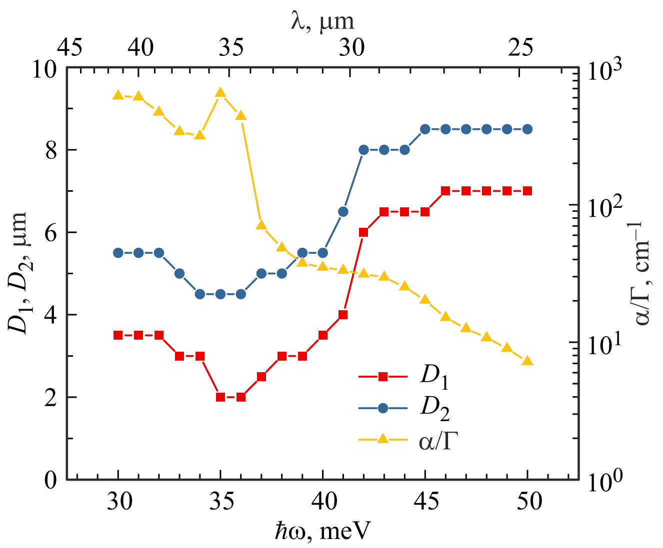

Figure 2. Frequency dependences of the minimum α/Γ ratio and the corresponding optimum D_1 and D_2 values.

The effective refraction index method [13] was used to determine the maximum width W of a stripe waveguide at which only a single transverse mode is present. It was assumed that etching in the process of ridge formation would be performed down to the waveguide layer lying below the layer with an active region. This is needed in order to confine lasing to the ridge under optical pumping. Having calculated effective refraction indices n_{ef} and losses α of TE_0 modes under the ridge and outside of it (see Fig. 3), one may determine the sought-for W value as a function of the radiation frequency. Note that the frequency dependence of α for the TE_0 mode outside of the ridge features a peak around 40 meV. This is associated with a reduction in the overall thickness of the waveguide layer during etching, which translates into an increase in losses due to mode leakage into the GaAs substrate and leads to α growth.

Figure 3 shows the frequency dependence of W of the considered stripe waveguide in the wavelength range of 25–41 μm. It can be seen that the dependence of W is rather weak, and single-mode generation at TE_{00} should be observed within the entire considered wavelength range at width W values lower than 15 μm.

3. Conclusion

Numerical modeling of the mode composition of a stripe laser waveguide based on CdTe/$Hg_{0.25}Cd_{0.75}Te$ with HgTe quantum wells was performed. It was demonstrated that the ridge width should not exceed 15 μm if single-mode generation in the wavelength range of $25-41\,\mu$m in a laser with an etching depth extending to the active region is to be achieved.

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Conflict of interest

The authors declare that they have no conflict of interest.

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