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Leaky wave in high-power AlGaAs/InGaAs/GaAs semiconductor lasers

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Abstract. **Lasers based on AlGaAs/InGaAs/GaAs heterostructures operating in the spectral range of 1.0–1.1 μm are investigated in order to optimise cladding layers. The effect of the thickness and composition of the cladding layers on the leakage of radiation from the laser waveguide is analysed. It is shown that for cladding thicknesses of 0.86–1.24 μm, it almost does not affect the output optical power. The effect of the crystal length and reflectivity of the laser mirrors on the leaky wave is demonstrated.**

Keywords: *laser diodes, spectral range of 1.0–1.1 μm, radiation leakage.*

1. Introduction

A wide range of applications of high-power semiconductor lasers is due to their unique features: a large wavelength range, compactness, high efficiency, and the possibility of modulating optical power. Optimisation of the compositions and thicknesses of the epitaxial layers of the laser heterostructure can significantly improve the characteristics of the laser. Thus, edge-emitting GaAs separate-confinement double heterostructure (SC DHS) lasers, which are the subject of this study, demonstrated a radiation power of 30 W in the cw operation mode at a wavelength of 976 nm [1].

Most attention is paid to the optimisation of the waveguide layers and the active region [2, 3], while the cladding layers are rarely considered, since they serve only to confine optical radiation and to transport charge carriers to the active region. However, it is obvious that minimising the cladding thickness in a laser heterostructure should lead to both an improvement in electrical and thermal characteristics, as well as to a decrease in the duration and increase in the efficiency of the growth process, which is especially important for large-scale production.

Optimisation of the cladding thickness is necessary for radiation sources based on epitaxially integrated heterostructures, such as tunnel-coupled laser heterostructures, thyristor lasers, etc. [4, 5]. The optimality of postgrowth operations to form the mesa-stripe structure of the active element depends on the total thickness of these heterostructures [6]. Such lasers have complex designs, consisting of several separate claddings and p–n junctions; therefore, a decrease in the cladding thickness can significantly affect the overall characteristics of the heterostructure.

The present paper is devoted to the study and optimisation of the cladding layer thicknesses in high-power strip AlGaAs/InGaAs/GaAs lasers (wavelength $\lambda = 1060$ nm) based on asymmetric SC DHS's with a quantum well (QW) and a broadened waveguide.

In planar semiconductor lasers, the natural limitation of reducing the cladding thickness is caused by the leakage of the optical mode from the waveguide. With an excessive decrease in the thickness of the n-cladding, it ceases to confine optical radiation in the waveguide, and part of the radiation begins to propagate in the substrate. This effect is used in leaky-mode lasers, which are characterised by low radiation divergence. To date, a number of theoretical and experimental studies have been carried out to increase the efficiency of the leaky-mode extraction [7–10]. Most often, a very thin (about 70 nm) n-cladding layer is used for this purpose, which ensures efficient tunnelling of radiation into the substrate [7].

In Ref. [8], the characteristics of single-mode InGaAs/GaAs lasers ($\lambda = 0.98$ μm) with an $Al_{0.3}Ga_{0.7}As$ waveguide about 0.2 μm thick, differing in composition and cladding thicknesses, were studied. It was found that mode leakage is observed at cladding thicknesses less than 1.32 μm. In this case, according to calculations, a change in the thickness of the cladding layers does not noticeably change the divergence angle of the leaky radiation, while the compositions of the waveguide and cladding layers significantly affect its value.

An investigation of the radiation directivity patterns as functions of the thickness of the n-cladding of InGaAs/GaAs lasers with a GaAs waveguide about 1 μm thick, carried out in [9], showed that no mode leakage was observed at an n-cladding thickness of 2 μm, whereas at thicknesses of 0.66, 0.55, and 0.42 μm, the far-field patterns had clearly distinguishable peaks corresponding to radiation leakage. The maximum power of leaky radiation for samples with the smallest cladding thickness was 65 mW (with the emitting region aperture of 100 μm), and the measured FWHM divergence was 0.45°. Since only a small range of cladding thicknesses was studied in [9], it is difficult to estimate the minimum thickness at which leakage will not be observed. Studies of leaky-mode lasers do not allow one to draw an unambiguous conclusion about the optimal cladding thicknesses for modern high-power semiconductor lasers with a broad waveguide.

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In this work, the leakage of a mode is experimentally investigated under boundary conditions, when it is already observed, but still does not significantly affect the laser output optical power. The main aim is to study the parameters and factors that influence the leakage effect.

2. Experimental samples and experimental techniques

The lasers were based on SC DHS's with quantum-dimensional active regions grown using MOCVD epitaxy process of AlGaAs/GaAs/InGaAs alloy system. The parameters of all grown heterostructures are summarised in Table 1. All heterostructures have an $\mathrm{Al_{0.1}Ga_{0.9}As}$ waveguide 1.7 μm thick with one InGaAs quantum well 90 Å thick, emitting at λ = 1060 nm. Heterostructures 1, 2, and 3 have cladding AlGaAs layers with a 27% aluminium content and differ from each other only in the thickness of the n-cladding. The cladding thicknesses of all heterostructures were measured with a scanning electron microscope and amounted to 0.86, 0.93, and 1.24 μm for heterostructures 1, 2, and 3, respectively. The thickness of the n-cladding of the $\mathrm{Al_{0.15}Ga_{0.85}As}$ heterostructure 4 is 0.96 μm.

The lasers were fabricated using the standard deep mesa technology with an aperture width of 100 μm, limited by oblique mesas etched through the heterostructure. For the measurements, lasers were made with different cavity lengths and mirror reflectivities.

At the first stage, the laser radiation far-field pattern along the fast axis was measured to reveal the presence of a leaky mode. The laser was mounted on a rotary platform, and the power of its radiation passing through an adjustable slit was recorded by a detector as a function of the angular coordinate.

At the second stage, we measured both the total output optical power P_{sum} and separately the radiation power P_{leak} of the leaky-mode. The lasers operated in a cw mode, the power was measured with a bolometer. To record the power of the leaky mode, the main radiation was cut off by a cooled shutter.

At the third stage, the spectra of the main and leaky laser radiation were recorded. The radiation averaged by the integrating sphere was introduced into an optical fibre and recorded with a spectrum analyser.

All measurements were carried out in a cw mode at several values of the injection current in the range up to 10 A at a temperature of 25 °C maintained on the laser heat sink.

3. Description of experiments and discussion of results

Far-field patterns along the fast axis, obtained for laser samples based on heterostructures 1 – 4 (hereinafter lasers 1 – 4) with a cavity length of 3 mm and coating-free mirrors (R = 0.3) are shown in Fig. 1. Lasers 1 – 3 demonstrate stable lasing at the zero-order transverse mode in the entire range of pump currents (up to 10 A) with a divergence of radiation of about 30° FWHM. The radiation divergence in laser 4 is slightly less (about 25°) due to a weaker-guiding waveguide.

In the far-field pattern of lasers 1 – 3, a separate narrow peak is observed in the region of negative divergence angles (towards the n-cladding), corresponding to the emission of

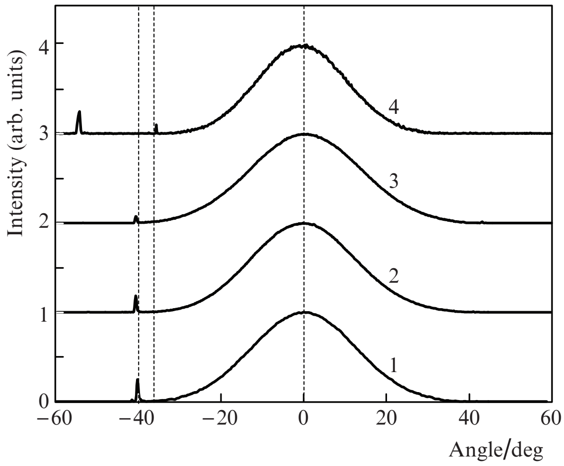

Figure 1. Far-field patterns along the fast axis of lasers 1 – 4. The vertical dashed lines indicate the calculated exit angles of the leaky radiation.

Table 1. Design, composition and layer thicknesses of the studied heterostructures.

Layers	Heterostructure			
	1	2	3	4
Substrate	GaAs	GaAs	GaAs	GaAs
Buffer layer	GaAs	GaAs	GaAs	GaAs
n-cladding	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 0.86 μm	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 0.93 μm	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 1.24 μm	$\mathrm{Al_{0.15}Ga_{0.85}As}$, 0.96 μm
Waveguide	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 1.05 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$ 1.05 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 1.05 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 1.05 μm
Active region	InGaAs QW, 90 Å GaAs spacers, 100 Å	InGaAs QW, 90 Å GaAs spacers, 100 Å	InGaAs QW, 90 Å GaAs spacers, 100 Å	InGaAs QW, 90 Å GaAs spacers, 100 Å
Waveguide	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 0.65 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 0.65 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 0.65 μm	$\mathrm{Al_{0.1}Ga_{0.9}As}$, 0.65 μm
p-cladding	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 1.1 μm	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 1.1 μm	$\mathrm{Al_{0.27}Ga_{0.73}As}$, 1.1 μm	$\mathrm{Al_{0.15}Ga_{0.85}As}$, 1.1 μm
Contact layer	GaAs, 0.3 μm	GaAs, 0.3 μm	GaAs, 0.3 μm	GaAs, 0.3 μm

the leaky mode, while laser 4 demonstrates several peaks. The position of the first peak for lasers 1, 2, and 3 with an $Al_{0.27}Ga_{0.73}As$ n-cladding is virtually the same (the angle is about 40°); for laser 4, the first peak is observed at an angle of 36°, and the second one at an angle of 56°. The divergence of the leaky-mode radiation of lasers 1–3 is about 0.5° FWHM, which is similar to the results of Ref. [9].

It is known [8] that the angle at which the emission peak of the leaky mode is observed should not change significantly with a change in the cladding thickness, which is the case for lasers 1–3. A noticeable change in the position of the peak occurs due to a change in the composition of the waveguide or cladding layers and a corresponding change in the effective waveguide refractive index of the mode [10]. Since the waveguides for all lasers are the same, in our case the peak shift in laser 4 is due to a decrease in the aluminium content in the cladding.

The angular distributions of the radiation intensity as a function of the pump current are shown in Fig. 2 for laser 2. It can be seen that the current value has practically no effect on the position of the peak of the leaky mode. Similar results were obtained for lasers based on heterostructures 1, 3, and 4.

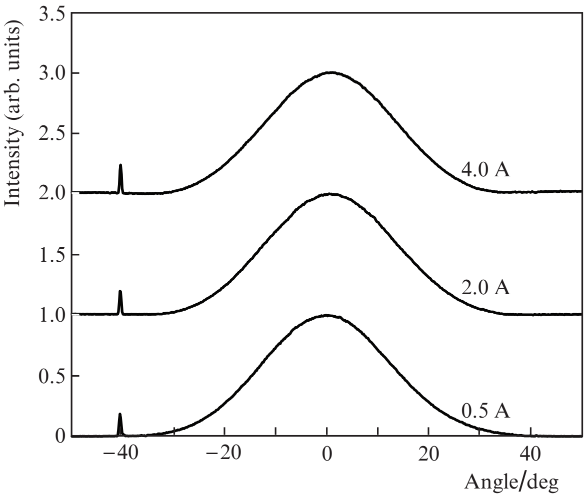

Figure 2. Far-field patterns along the fast axis of laser 2 at various pump currents.

The exit angle of the leaky radiation θ can be calculated by the formula [9]

$$\theta = \arcsin\sqrt{n_{\rm s}^2 - n_{\rm eff}^2}, \quad (1)$$

where $n_{\rm s}$ is the refractive index of the substrate; and $n_{\rm eff}$ is the effective refractive index of the heterostructure. The angle θ calculated by this formula is 40.2° for lasers 1–3, and 36.1° for laser 4, which is in perfect agreement with the experimental data. Obviously, laser 4 has a lower effective refractive index for radiation emitted at an angle of 56°. It probably corresponds to a higher-order mode, which, by definition, is characterised by stronger leakage. The radiation of such a mode can be weakly manifested in the main maximum of the directional pattern due to its low power caused by high optical losses.

This is indirectly confirmed by the lasing spectra measured separately for the main maximum of the directional pattern and the leaky radiation (Fig. 3). The black line in the figure denotes the spectra of the main radiation of the lasers under study, and the grey line shows the spectra of the leaky radiation. Measurements carried out at several levels of the pump current showed that with an increase in the current, the spectra broaden and shift to longer wavelengths, but no qualitative changes are observed. The spectra of the main and leaky radiation of lasers 1–3 completely coincide in the entire range of pump currents, while the spectra of laser 4 differ markedly. Most likely, this is due to the presence of a higher-order mode in the spectrum of leaky radiation.

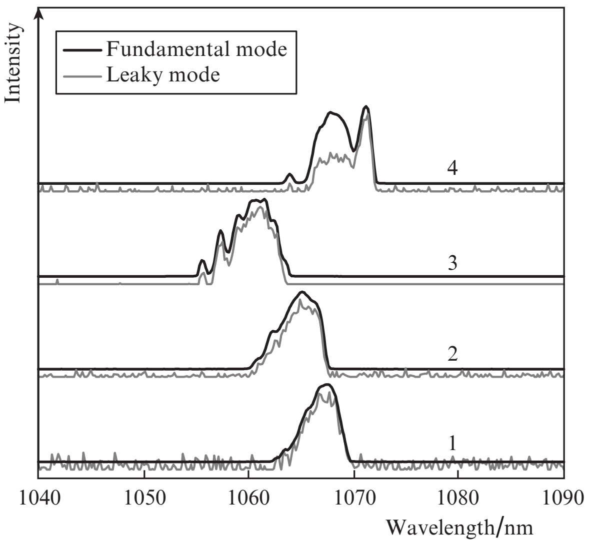

Figure 3. Emission spectra of lasers 1–4 recorded at the same pump currents.

The parameter that can characterise a leaky-mode laser is the coefficient K [11], which is the ratio of the power of the leaky radiation to the power of the radiation propagating in the waveguide (inside the Fabry–Perot cavity). In our work, it is more convenient to evaluate the laser by the fraction of leaky radiation, i.e., the ratio of the power of the leaky mode to the total power of the output radiation. We investigated lasers with different cavity lengths and mirror reflectivities to determine their effect on the fraction of leaky radiation. Figure 4 shows typical current dependences of both powers for a laser with a cavity length of 3 mm and dielectric coatings of mirrors with $R = 0.05$ and 0.95.

For convenience in comparing the fraction of leaky radiation of the lasers under study, we measured the power characteristics of samples with a cavity length of 3 mm and mirror reflectivities $R = 30\%$. Table 2 shows the average values of the laser power in both directions at a pump current of 5 A and the calculated fractions of the leaky radiation. The values of internal optical losses near the lasing threshold (Table 2), determined by the standard method, for lasers 1–3 are practically at the same level, while for laser 4 the losses are higher. This is due to its weaker-guiding waveguide, which allows the optical field to penetrate deeper into heavily doped claddings and, accordingly, to be absorbed by free carriers.

The laser based on heterostructure 3 with a thick n-cladding (1.24 mm) has the smallest fraction of leaky radiation,

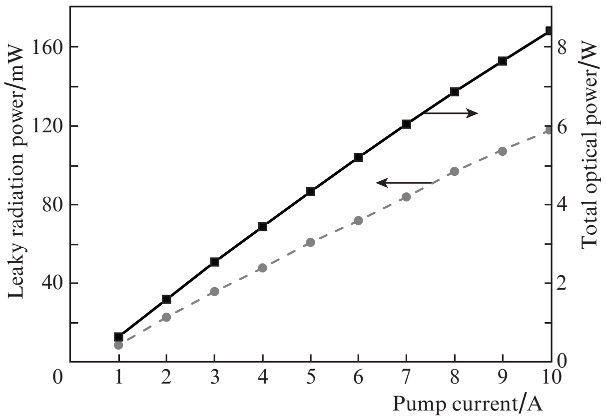

Figure 4. Light–current characteristics of laser 2, measured in the cw lasing mode at $T = 25\,°C$; the cavity length is 3 mm, the aperture is 100 μm, and the reflectivity of mirrors is $R = 0.05$ and 0.95.

Table 2. Power characteristics of lasers 1–4; cavity length of 3 mm and pump current of 5 A.

Laser	n-cladding thickness/μm	Internal optical losses/cm^{-1}	$P_{\rm sum}$/W	$P_{\rm leak}$/mW	$P_{\rm leak}/P_{\rm sum}$ (%)
1	0.86	0.6	4.354	74	1.70
2	0.93	0.6	4.402	44	1.00
3	1.24	0.8	4.114	5.3	0.13
4	0.96	1.2	3.828	86	2.28

0.13%, while for laser 4 with an $Al_{0.15}Ga_{0.85}As$ cladding 0.96 mm thick, this fraction is 2.28%. In general, the results obtained are in perfect agreement with the specific features of the heterostructure designs. The weaker guidance of the optical waveguide (a decrease in the aluminium content in the cladding) leads to an increase in the mode leakage; increasing the thickness of the n-cladding to 1.24 μm minimises this effect.

Studies of the power characteristics of lasers have shown that the pump current has practically no effect on the fraction of leaky radiation (Fig. 5). Theoretically, an increase in the pump current, and, consequently, in the temperature and concentration of charge carriers, should lead to a change in the refractive index of the heterostructure layers. In practice, however, it turned out that this change is not large enough to affect noticeably the amount of leaky radiation.

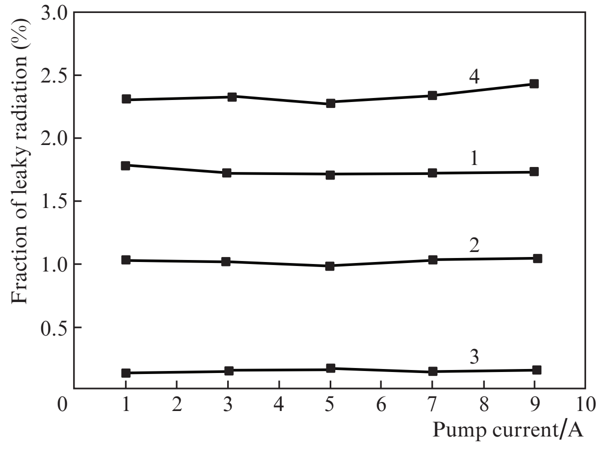

Figure 5. Dependences of the leaky-radiation fraction on the pump current for lasers 1–4 with a cavity length of 3 mm.

The influence of the cavity length and the mirror reflectivities on the fraction of the leaky power is demonstrated in Fig. 6 for several samples of laser 2. As the cavity length increases, the fraction of the leaky radiation also increases. Such dependences were theoretically predicted in [11]. It was also found that for lasers with coated mirrors ($R = 0.05$ and 0.95), the fraction of the leaky radiation is somewhat higher than for lasers with coating-free mirrors. On the one hand, the increase in the fraction of the leaky power can be explained by the change in the ratio of external optical losses for the fundamental mode and leaky wave. On the other hand, it is important to remember that in lasers with one highly reflecting and another antireflecting mirrors, the distribution of the optical field along the cavity axis changes, namely, the maximum of its distribution appears practically at the exit mirror, which can also affect the distribution of optical losses of the leaky mode.

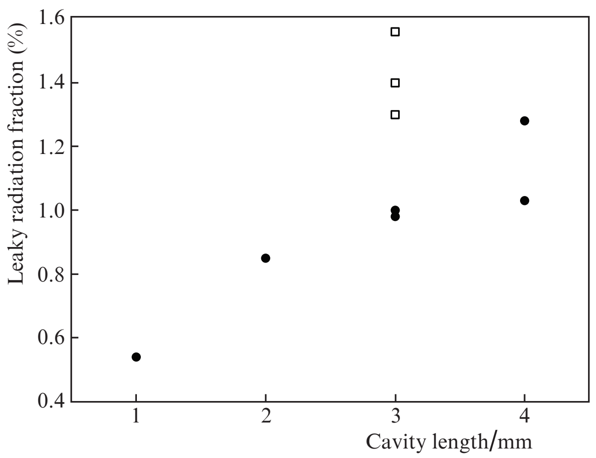

Figure 6. Dependences of the fraction of leaky radiation on the cavity length for the reflectivity of the mirrors (□) $R_1 = 0.05$, $R_2 = 0.95$, and (●) $R_{1,\,2} = 0.3$ for several lasers based on heterostructure 2.

4. Conclusions

It is shown that the output optical power of lasers based on heterostructures with a standard strongly guiding waveguide are practically the same, and the fractions of the leaky radiation power are only a few percent. The power of the leaky radiation from a laser structure with the smallest cladding thickness did not exceed 150 mW at a pump current of 10 A and a total power of 8 W. Thus, the presence of leaky radiation from these lasers did not affect the total output optical power and did not cause significant optical losses. If necessary, claddings up to 1 μm thick can be used in lasers and at the same time have a high output optical power; however, when designing a laser, it will be necessary to take into account the presence of leakage. It was found that the parameters of the laser cavity strongly affect the fraction of the leaky power, which is especially important for long (up to 6 mm) crystals with strong transmission of the output mirrors, which are used to achieve a record-breaking optical power [1].

For lasers with a small refractive index step at the waveguide–cladding interface, the leakage effect is enhanced and can lead to both a decrease in power and the appearance of specific features of the radiation mode structure. For such lasers, the cladding should be designed thicker or other means must be used to localise the optical field in the waveguide. If a side lobe in the directional pattern is to be suppressed, then either a stronger-guiding waveguide or a thicker n-cladding should be used.

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