Diode lasers with front surface high-order distributed Bragg reflector

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Abstract. Control of spectral and spatial parameters of semiconductor lasers is a key element of their development and application. Surface integrated high-order distributed Bragg reflector (DBR) is the way to narrow diode laser spectrum preserving the conventional postgrowth process of laser diodes. On the other hand, high-order DBR has specific optical losses, which reduce optical output power. In this work we analyzed these specific optical losses and present design of laser resonator containing short front DBR, that allow to significantly reduce losses. With this approach, slope efficiency was greatly increased in contrast with conventional rear DBR laser diodes and 4 W optical output power with spectral width of less than 3 Å was attained.

1. Introduction

Nowadays semiconductors lasers with distributed Bragg reflector (DBR) is a key element of photonics integrated circuits. The ability of engineering of spectral and spatial behavior of lasers emission allow to significantly widen the application field. Current approach seeks to simplify postgrowth processing of diode lasers with distributed Bragg elements. In this concept the idea of integrated surface high-order DBR looks the most advantageous [1,2]. Such design of resonator may be formed by relatively simple technological processes of photolithography and reactive ion etching. DBR location in the upper cladding layer of heterostructure eliminates the process of epitaxial overgrowth.

This paper is devoted to study of the semiconductor lasers with high-order DBR characteristics. Experimental samples are based on separate-confinement double heterostructure InGaAs/AlGaAa/GaAs, emitting in 1000-11000 nm wavelength range.

Specific features of high-order DBR lasers, which is new sort of optical losses, were investigated. The mechanism of new type of optical losses, which limits output power, is described. The alternative design of diode lasers resonator utilizing DBR as a front mirror is presented. This design decreases specific optical losses and narrows the spectrum. With this approach, we increase slope efficiency of power-light characteristic of laser by three times for

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nonoptimal DBR devices. Output power was increased up to 4 W. Spectral widths was at least 3 Å over the whole current range.

2. Specific optical losses in high-order surface DBR

Utilizing of simple and conventional technological process of photolithography and reactive ion etching requires to increase DBR period. According to the Bragg law period increase leads to the growth of diffraction order:

$$\Lambda = \frac{N\lambda}{2n} \tag{1}$$

where Λ - DBR period, λ/n - wavelength in medium, N - diffraction order (natural number). Increasing of order result in emergence of a new direction of constructive interferes of emission, diffracted at edge of each groove [3]. Electromagnetic wave running in planar dielectric waveguide with periodical variation of dielectric index generates modes that propagate at the angle to the plain of waveguide according to:

$$\Phi_i = 90^\circ + \arcsin(\frac{2i}{N} - 1),\ \text{i=0,1,2,3…N} \tag{2}$$

For N>1 high-order interfering radiation modes (IRMs) are appeared. These IRMs are the parasitic optical output losses, emitting from the surface of DBR. If we neglect the internal optical losses in heterostructure, the losses corresponding to the interfering high-order modes could be calculated as 1-R-T, where R and T are reflection and transmission of the DBR. In this work we used couple mode theory describing the behavior of light in waveguide with weak periodic variation of optical parameter. This theory was presented by Kogelnik and Shank [4] and Yariv [5].

According to the theory under consideration, two resonance modes exchange energy determined by coupling coefficient:

$$\kappa = \frac{k_0^2}{2\beta}\int \Delta\varepsilon_N(x)\cdot U^2(x)dx \tag{3}$$

k0 – wavenumber in air, β - wavenumber in media (complex value), U(x) - normalized profile of transvers guided mode (TEM_0), ΔεN- N-Fourier coefficient of periodic function of permittivity expansion. Coupling coefficient determines energy exchange value. Fourier coefficient presence determines coupling coefficient (and reflection coefficient as well) dependence on geometric shape of the groove of the Bragg grating.

The dependence of the reflection on geometric shape of the groove is demonstrated on figure 1. The shape of the groove is schematically shown in the inset figure. According to the results of calculation, we can observe almost complete reduction of reflection during the transition from V-shaped groove to the rectangular-shaped. However, transmission increasing is not observed, indicating on parasitic optical losses increase corresponding to the IRMs. Thus, we can conclude, taking into account the potential of reactive ion etching technology, that the V-shape is the most optimal form of Bragg grating groove. However theoretical calculation shows, that even this optimal form does not allow to completely avoid IRMs optical losses and 1-R-T≠0.

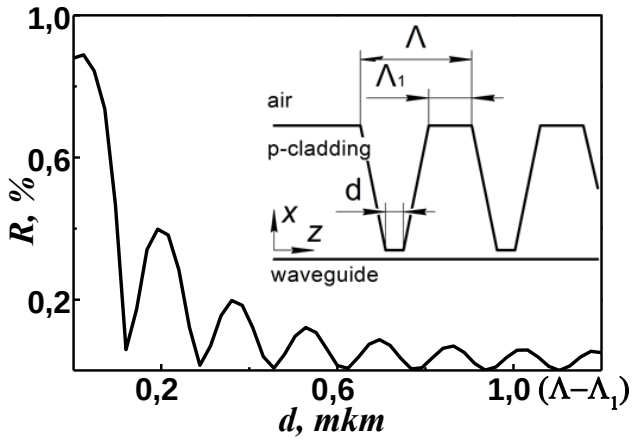


Figure 1. The dependence of the reflection on geometric shape of the Bragg grating groove.

Dependences of R, T, 1-R-T on DBR length are presented on figure 2. The effective length (saturation length) is determined by coupling coefficient. Reflectance (R) and losses IRMs (1-R-T) saturation value are determined by geometric shape of groove. However, it is clear that for any geometrical shape shorter grating provides smaller losses related to IRMs. Also, reducing the length causes reflectance reduction and DBR transmission increase. In the case of fabricating experimental laser diode samples with nonoptimal groove geometrical shape which are characterized by high rate of parasitical optical losses, the only solution to obtain high optical power is laser with front DBR. Reducing the length of the grating will significantly reduce losses of IRMs in the cavity and therefore significantly increase optical power of the laser.

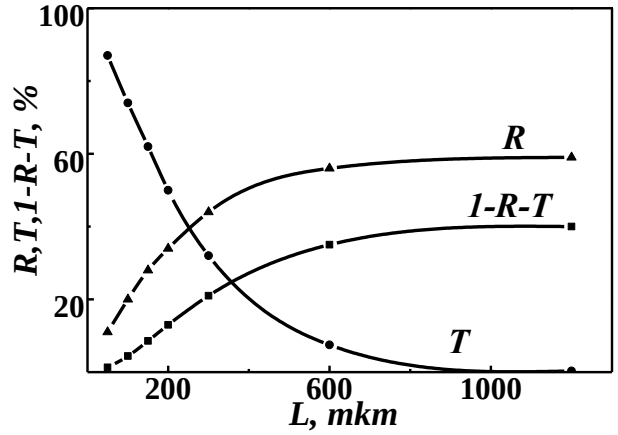


Figure 2. The dependence of reflectance, transmission coefficients and optical losses of IRMs on length of DBR.

In addition to typical high-order IRMs losses there are two more loss mechanism in integrated surface DBR. Since DBR is electrical passive, there is no gain in this section of cavity. At the same time the internal optical losses related to electromagnetic waves scattering

on defects and dopant remain. Thus, in the case of light penetration in DBR on depth L_{eff}, reflected light intensity diminishes according to the Buger law:

$$I = I_0 \cdot R \cdot \exp(-2\alpha_i L_{eff}) \quad (4)$$

I_0 and I – intensity of the incident and reflected light, respectively, α_i – internal optical loss in heterostructure. Modern separate-confinement double heterostructure InGaAs/AlGaAa/GaAs are characterized by very small value [6] of α_i, but it is still necessary to take into account its contribution.

The second mechanism is associated with the etched surface roughness – the technological feature of reactive ion etching. Presence of roughness on the facets of the grating groove also leads to the light scattering. The magnitude of these losses is also determined by the length of way, that light passed through DBR.

All of the three abovementioned optical loss mechanism depend on the length of DBR. Increasing the laser power requires a reduction of optical losses. According to the provided calculations, solution of problem under consideration is construction of laser resonator with short DBR as a front mirror with R≤20%. In this case it is necessary to deposit antireflection coating front facet of laser, and high reflection coating (R=99%) rear facet.

3. Semiconductor laser with a front DBR

Experimental samples of semiconductor lasers with integrated high-order surface DBR based on InGaAs/$Al_{0.1}Ga_{0.9}$Aa/$Al_{0.25}Ga_{0.75}$As heterostructures (figure 3) have been fabricated. DBR period was Λ=2.4 μm. Diffraction order – N=16. Wavelength – λ=1028 nm. The samples didn't have optimal DBR parameters. Grating groove geometric pattern was d=0.35μm that produced parasitic loss of 50% differential efficiency [7]. Three types of samples have been studied. The first group consisted of lasers with 1 mm length rear DBR which was a totally reflecting mirror. The front facet was low-reflection coated down to R=5%. Two other groups included semiconductor lasers with 0.5 mm and 0.25 mm DBR that were front mirrors. The samples differed only by DBR length. The rear facet was high-reflectance coated up to R>95%. The front facet was antireflection coated (AlN) down to R<0.5% in order to sufficiently increase Fabry-Perot mode threshold conditions.

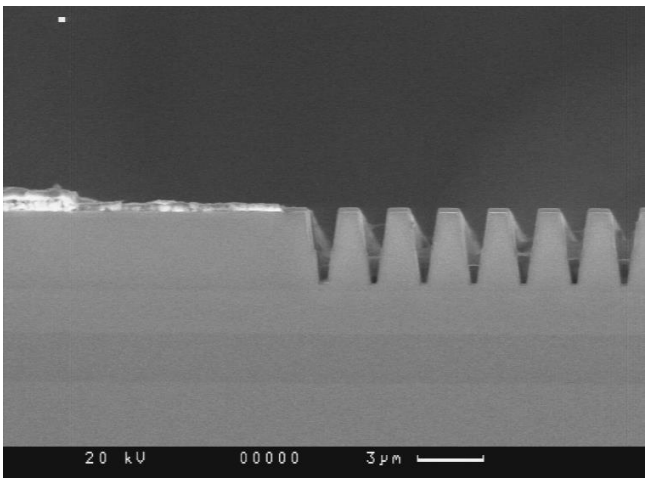


Figure 3. SEM image of a surface high-order DBR.

Light-current characteristics of the samples are shown on the figure 4. DBR length decrease leads to output optical power increase. An increase in external differential quantum efficiency gives evidence of optical loss decrease in the laser cavity. It can be seen that even in spite of nonoptimal DBR implementation one can get high values of optical power. Spectra set of the sample which had demonstrated the highest slope of a light-current characteristic is shown on the figure 5. Spectrum structure is multimode but it's width does not exceed 3 Å in the whole range of pump currents. Wavelength shift is due to temperature induced permittivity change [8].

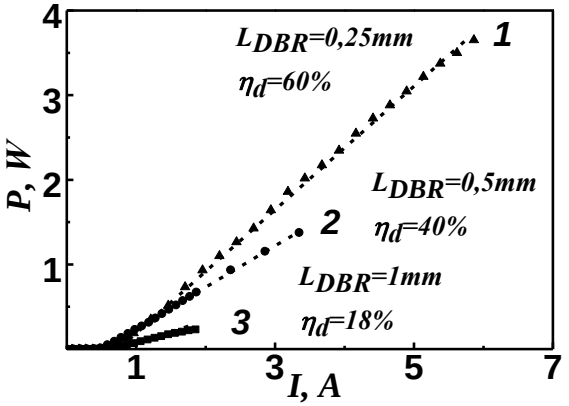


Figure 4. Light-current characteristics of the three sample types. 1, 2 – front DBR of L=250mkm, 500mkm respectively, 3 – DBR rear facet of L=1000mkm.

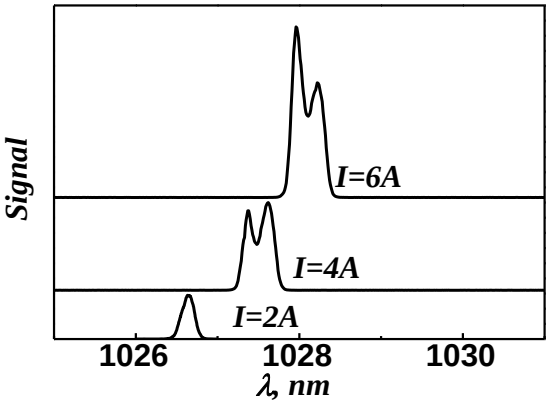


Figure 5. Spectra of a semiconductor laser with a front DBR of 0.25 mm length.

4. Conclusion

Surface high-order distributed Bragg mirror provides a semiconductor laser spectrum narrowing. However, the DBR also has specific optical loss that limits output optical power. Loss mechanisms deal with high-order interfering radiation modes, lack of gain in the DBR section and accidental light scattering on the groove roughness. Loss value for each case is proportional to DBR length.

Therefore, DBR length decrease leads to optical loss reduction in the cavity, reflection coefficient decrease and light transmittance increase. Use of DBR as a front mirror allows one to narrow a semiconductor laser spectrum keeping at the same time a high value of output optical power. Even in the case of nonoptimal DBR groove geometrical pattern that results in gigantic loss of higher-order IRMs the presented laser cavity design approach allowed reaching of 60 % external differential quantum efficiency and 4 W optical power at spectrum width of less than 3 Å.

Acknowledgments

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