Gain spectra of lasers based on transitional dimension active region

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Abstract. We present an experimental study of the optical gain of edge-emitting lasers based on a new type of quantum-sized InGaAs active medium grown on GaAs substrates, which we refer to as quantum-well-dots (QWDs). It is shown that the single layer QWD active region provide at least 33 cm⁻¹ optical gain at 1030 nm comparable to the values typical for InGaAs quantum wells (QWs), and the width of the gain spectra characteristic for InAs quantum dots (QDs). Thus, QWD active region combines the advantages of both QW and QD heterostructures and has a great potential for improving characteristics of various semiconductor devices.

1. Introduction
Quantum-sized heterostructures such as quantum well (QW) and quantum dots (QD) are widely used as active media of modern semiconductor devices. Recently we have demonstrated that it is possible to fabricate quantum-sized heterostructures of mixed confinement in between 2D QWs and 0D QDs using metal-organic vapor phase epitaxial (MOVPE) growth of about 10 monolayers of In₀.₄Ga₀.₆As on GaAs substrate [1]. It could be considered as InGaAs QWs with irregular distribution of In concentration and nonuniform thickness serving as carrier localizing regions. The new QWD active region was successfully utilized in GaAs-based solar cells with broadened absorption band, microdisk lasers with record characteristics and high-power edge-emitting lasers with the internal optical loss as low as 0.5 cm⁻¹ [2]. QWDs are intermediate in properties between QWs and QDs and show some advantages of both. In particular, they provide reduced elastic stresses in the active region, reduced carrier diffusion in the plane of the active region and high optical gain per layer [3].

For designing semiconductor light-emitting devices one needs to know the optical gain per active layer as well as the shape of the optical gain spectrum of the active medium. In this paper, we present a study of the gain spectra of the QWD active region using the Cassidy technique [4]. Our results could be used for future optimization of the QWD-based lasers and other semiconductor devices.

2. Laser wafer design and sample processing
The laser heterostructure was grown on a GaAs substrate using MOVPE. The active region contains one layer of In₀.₄Ga₀.₆As QWDs with a nominal thickness of 3 nm located in the center of the 450 nm thick GaAs waveguide layer sandwiched between Al₀.₃₅Ga₀.₆₅As claddings. 4 µm ridge lasers were processed from the laser wafer using a standard photography technique. No facet coatings were used. Devices with various cavity length were tested in a pulse regime. The lasing wavelength for 2 mm devices was 1080 nm and the threshold current was 105 A/cm². The lasers with short cavities of 100–200 µm were selected for the gain measurements. Devices were mounted p-side down onto copper heatsinks to reduce...
self-heating in a cw regime. The samples were tested before and after mounting and the devices with the minimal current leakage were selected for further measurements.

3. Experiment details

B. Hakki and T. Paoli proposed to determine the optical gain from the interference pattern of Fabri-Perot modes in the amplified spontaneous emission (ASE) spectra using the following equation [5]:

\[ g(\lambda) = \frac{1}{L} \ln \left( \frac{\sqrt{\lambda_1^2 - 1}}{\sqrt{\lambda_2^2 - 1}} \right) - \frac{1}{2L} \ln \left( \frac{1}{R_1 R_2} \right), \]  \hspace{1cm} (1)

where \( g \) is the modal gain, \( L \) is the laser cavity length, \( R_{1,2} \) are the reflection coefficients of the front and rear facets, and \( r(\lambda) \) is the peak-to-valley ratio in the ASE spectra:

\[ r(\lambda) = \frac{(l_{\text{max}}(\lambda))}{(l_{\text{min}}(\lambda))}. \] \hspace{1cm} (2)

D. Cassidy proposed another way to analyze ASE to determine the gain by using \( p(\lambda) \) instead of \( r(\lambda) \) in (1) [4]:

\[ p(\lambda) = \frac{2}{\lambda_1 - \lambda_2} \left( \frac{1}{l_{\text{min}}(\lambda)} \right) \] \hspace{1cm} (3)

where \( \lambda_1 \) and \( \lambda_2 \) are the wavelengths of two neighbor minima. His approach allows obtaining a slightly higher optical gain due to its lower sensitivity to the instrument function of the spectrometer. The optical gain calculated by either of the approaches mentioned is reduced by the instrument function of the spectrometer, thermal and current drifts of the radiation spectrum, therefore such measurements provide its lower estimate.

Both gain measurement techniques require sub-threshold operation of the laser under test. One way to achieve it is to use a sufficiently short sample, as the external loss (second term in (1)) is inversely proportional to the cavity length. For example, the optical loss of the 120 \( \mu \)m GaAs based laser with uncoated mirrors at 1 \( \mu \)m is around 98 cm\(^{-1}\), meaning that it will require 98 cm\(^{-1}\) optical gain to lase. Besides, the cavity length determines the Fabry-Perot mode separation. For fundamental transverse mode it can be estimated using a well-known equation:

\[ \Delta \lambda = \left( \frac{\lambda^2}{2 n_{\text{eff}} L} \right), \] \hspace{1cm} (4)

where \( n_{\text{eff}} \) is the effective refractive index for the given transverse mode. For our 120 \( \mu \)m devices and wavelength of 1 \( \mu \)m equation 4 yields the mode separation of 1.2 nm. Hence, shorter lasers are preferred for these measurements.

ASE spectra were measured with a 0.6 m monochromator equipped with a 100x100 mm 600 gr/mm grating and a photo-multiplier tube. The signal from the photomultiplier was detected with a lock-in amplifier. To achieve maximum spectral resolution we placed our devices with the fast axis divergence perpendicular to the monochromator slits. Driving current was measured as the voltage drop over the resistor connected in series with the device under test. In order to avoid unwanted noise in the gain spectra we used Fourier filter to remove noise in ASE spectra.

We want to point out that current densities we provide are higher than actual, because of the current spreading, which is typically found in index guided lasers, and a small current leakage due to \( p \)-side down mounting.

4. Results and discussion

Figure 1a shows the gain spectra from 120 \( \mu \)m device calculated with the Cassidy method, the dots represent obtained values and the solid lines represent smoothed data. The inset shows a typical pattern of ASE spectra processed with the Fourier filter, which we used to calculate the gain. Figure 1b shows the dependence of the maximal gain and the corresponding wavelength on the current density. It is clear that above 4.2 kA/cm\(^2\) the device begins to overheat what can be seen from the dependence of the peak
position of the gain spectrum (figure 1b). Overheat stimulates an earlier filling of the ground state which results in saturation of the maximum gain value at 15 cm\(^{-1}\).

Figure 1. Modal gain spectra (a) and maximal modal gain and its peak wavelength (b) at different current densities for the 120 \(\mu\)m sample. The inset in (a) shows ASE spectrum measured at 6.2 kA/cm\(^2\).

Figure 2 shows the gain spectra of another device with 110 \(\mu\)m cavity calculated with the Cassidy method. The maximal modal gain was determined as 33 cm\(^{-1}\) at 1026 nm and the current density of 9 kA/cm\(^2\). At this current density grows of modal gain occurs due to the filling of high energy states (red tail below 1040 nm). The distinctive feature of these spectra is that they demonstrate the gain width as high as 90 nm.

Figure 2. Modal gain spectra of the 110 \(\mu\)m sample.

The record value for a single-layer QW obtained with the Hakki-Paoli technique is 48 cm\(^{-1}\) [6] and over 100 cm\(^{-1}\) for multiple QWs [7]. The width of the gain spectra of the single QW does not exceed 70 nm. QDs typically provide optical gain per layer of 5-7 cm\(^{-1}\). The record gain value of 60 cm\(^{-1}\) was achieved in the 19-layer structure [8]. Multilayer QD active regions can provide a gain width greater than 100 nm. Therefore, QWD active region offers high gain per layer comparable with the values for QW and broad gain spectrum typically found in QD based active regions, combining the advantages of both QW and QDs.
5. Conclusion
In conclusion, we have investigated the optical gain in the new type of InGaAs/GaAs active media. It is shown that the single layer QWD active region provide at least 30 cm$^{-1}$ optical gain at 1030 nm comparable to the values typical for InGaAs QWs, and the width of the gain spectra characteristic for InAs QDs. Thus, QWD active regions combine the advantages of both QW and QD heterostructures and have a great potential for improving characteristics of various semiconductor devices, such as high-power lasers, tunable lasers, multi-frequency lasers or superluminescent diodes.

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