Characterization and modeling of gain spectra of single-layer InAs/InP(100) quantum dot amplifiers

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In this contribution we present the small signal net modal gain measurement results of single-layer InAs/InP(100) quantum dot amplifiers in 1.6 to 1.8 μm wavelength range. The material shows sufficient optical gain to be used in the long-wavelength optical coherence tomography. The modal gain has been observed as a function of current density and temperature. An improved rate equation model has been applied to analyse the measurements. A good fit of the theory to the measurements was obtained with a temperature dependent carrier injection efficiency which is below 2%.

Introduction

The wavelength range from 1.6 to 1.8 μm is of interest to be used in the optical coherence tomography (OCT) systems. This wavelength range lies inbetween two strong water absorption peaks. Due to the longer wavelength compared to what is commonly used (0.8 and 1.3 μm) in OCT systems, the imaging depth can be improved since the scattering of light is reduced [1].

The InAs/InP(100) quantum dot (QD) platform with the QDs tuned to 1.7 μm with wide bandwidth, in combination with the butt-joint active-passive photonic integration scheme [2] can be used for the development of integrated optical devices for the long-wavelength OCT applications. In our previous work, a five-layer InAs/InP(100) QD material system at 1.6 to 1.8 μm wavelength range has been successfully used in a tunable laser [3] and a photodetector [4] for the swept-source OCT (SS-OCT) application. The measured modal gain for the five-layer QD semiconductor optical amplifier (QD-SOA) is relatively low compared to bulk or QW materials. This has limited the performance of the tunable laser and photodetector. One way to improve the output power of the laser and electrical bandwidth of the photodetector is to use a new QD material with higher gain (absorption).

In this contribution, we present measurement results and analysis of QD-SOAs based on a single-layer InAs/InP(100) QD platform. This single-layer material is based on a QD-on-QW system which is different from which was used previously in the five-layer QD-SOAs. The measured net modal gain spectra at different current densities and temperatures as well as the analysis of temperature-dependent carrier dynamics using an improved RE model will be presented.

Gain characterization results

The measurement method used in this paper is based on the analysis of ASE spectra from SOAs of different lengths [5]. We have fabricated a series of shallowly etched ridge waveguide amplifiers of varying length that have been divided into two sections on a single chip. One part is the optical amplifier from which the ASE output is measured. The other section is reverse-biased and acts as an absorber which prevents detectable feedback into the amplifier.

The net modal gain spectra of the single-layer QD-SOAs have been derived at a range of injection current densities (from 500 A/cm^2 to 5000 A/cm^2 with 500 A/cm^2 increments) and at four different chip temperatures (from 273 K to 303 K with 10 K increment). Figure 1 shows the measured gain spectra for a selection of current densities and all temperatures. The measurement shows a relatively higher optical gain than the previous five-layer QDs.

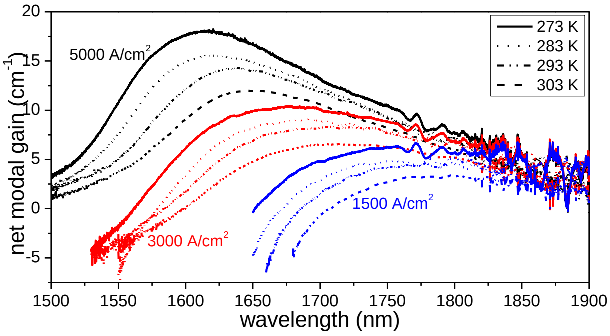

Fig. 1. The net modal gain spectra for different chip temperatures (from 273 K to 303 K with 10 K increment) and three injection current densities (1500, 3000 and 5000 A/cm^2).

From Fig. 1 a blue shift of peak wavelengths of the gain spectra can be observed as the injection current density increases. This blue shift of gain peak as increased current density has been explained in [6] as a combination of two effects. One effect is the contribution of optical transitions from the ES at higher current density. The second effect is the dot-size dependent carrier escape rate from QD levels to WL. It can also be seen from Fig. 1 that the peak of the gain shifts to shorter wavelength as the temperature drops. This blue shift due to temperature drop will be analyzed using an improved rate equation (RE) model.

Improved rate equation model

In this contribution we have modified the RE model presented in [6]. The first improvement on the previous RE model is the introduction of the carrier injection efficiency. Since the active layer of the single-layer QD-SOA is very thin (1 monolayer (ML) of InAs QDs + 1.6 nm InAs QW) compared to the active region in five-layer QD-SOA (200 nm in total), and the layer stack of the active region is different, only a small portion of the injected carriers are collected by the active layer. Thus the improved model includes an additional carrier escape mechanism out of the QD amplifier. This escape rate out of the SCH layer (τ_{esc}) is fitted for each temperature with the results as shown in Fig. 2(a). The fast escape rate represents a low injection efficiency which is calculated to be about 1.7 %. We attribute this low injection efficiency mainly due to the thin active layer.
Besides several parameters of which the temperature dependency is already defined in the RE model, we also discovered that a temperature dependency of parameters which were previously defined as constants [6] is required. Thus the second improvement is the incorporation in the model of temperature-dependency of the homogeneous broadening of the QD and the escape rate out of SCH as mentioned above. The FWHM of homogeneous broadening is also fitted separately for each temperature with the results as shown in Fig. 2(b).

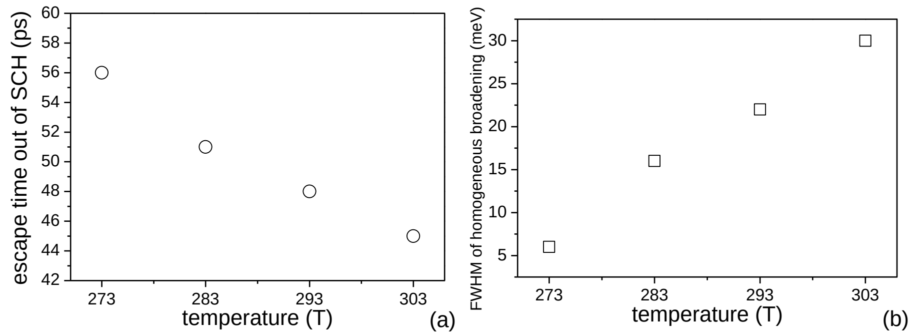

Fig. 2. (a) The carrier escape time out of SCH layer of QD versus temperature. (b) FWHM of the homogeneous broadening of the QD versus temperature.

Good fitting could be obtained using this improved RE model. The simulations are performed in which the separate contributions from the ES and GS as well as the total modal gain at four different temperatures (273, 283, 293 and 303 K) are calculated. Fig. 3 shows the simulated gain for ES and GS and the total gain at 293 K as an example. The fitting is good for all other temperatures. The measured gain spectra are plotted together with the total simulated gain for easy comparison. The total simulated modal gain has a good match with the measured gain spectra (Fig. 3(b)). A small deviation between simulation and measured data can be seen at low current densities (1000 and 2000 A/cm^2) for all temperatures. It is probably due to an underestimation of the temperature dependency of the carrier injection efficiency. The actual temperature inside the QD-SOA could be strongly dependent on the injection current density.

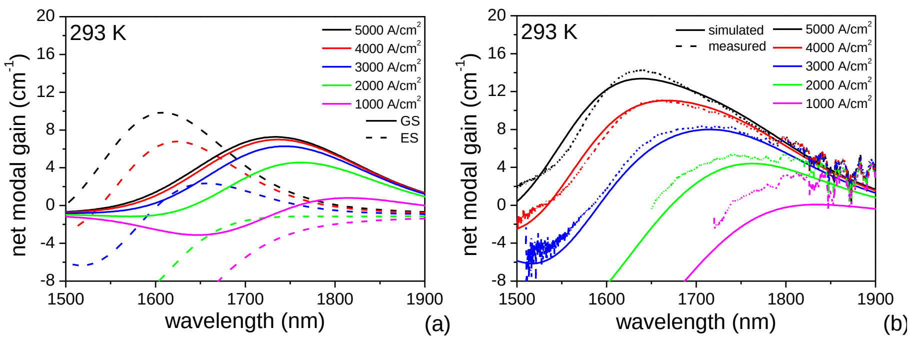

Fig. 3. Simulated modal gain of single-layer QD-SOA at 293 K. The contributions from ES and GS are shown in (a), the total simulated modal gain and the measured gain spectra are plotted in (b).

The blue shift of the peak wavelength of the gain spectra due to temperature change is analyzed. It is found that there are two mechanisms that contribute to the shift of the peak of the gain spectra. The first mechanism is due to an increased filling of carriers into smaller QDs as temperature drops. When carriers are injected into the amplifier, the larger dots will be more populated than the smaller dots, since the escape rate for larger dots is lower than that of the smaller dots. Thus the carrier capture rates will be lower for larger dots due to a higher occupation probability. As temperature drops, there will be more carriers captured into WL and those carriers will have a higher chance to be captured in smaller dots rather than larger dots since most of the larger dots are already occupied. As a result there are more carriers filling into smaller QDs as temperature drops while the number of carriers filled in larger QDs keeps almost the same. This will result in a more contribution of gain from smaller QDs (shorter wavelengths) and the gain peak will shift towards shorter wavelength. This mechanism exists for all range of current densities and temperatures, and for both ES and GS.

The peak gain shift due to the temperature dependency of the carrier escape rates from QD levels to the WL is also investigated. The temperature dependency of the escape times from ES to WL and from GS to ES are predefined in the RE model. It can be concluded from the definition of the escape times that the larger dots will have a larger escape time (slower escape rate) from ES to WL (τ_{eES}) than the smaller dots. As temperature drops, the escape rate for larger dots will decrease more than smaller dots. Thus there will be a higher contribution of gain from larger dots due to this lower escape rate. This will shift the peak of gain to longer wavelength. Similarly, the temperature-dependent escape time τ_{eGS} from GS to ES will result in more contribution of gain from GS since the rate will also decrease as temperature drops. This also results in a red shift of the peak of gain.

The two mechanisms discussed above both give contribution to the shift of the gain peak. But they result in opposite directions of the shift. Since both measurement and simulation show an overall blue shift, it can be concluded that the mechanism of carrier filling is more significant than that of carrier escape when temperature changes.

Conclusion

In this contribution we have presented the measured temperature-dependent gain spectra for single-layer InAs/InP(100) QD-SOAs in the 1.6 to 1.8 μm wavelength range. The measured QD-SOAs which are InAs dots grown on a thin InAs QW, show higher gain values than that of previous five-layer QD-SOAs. The blue shift of peak gain as temperature change has been analyzed using an improved RE model. A good match can be obtained for all temperatures when all effects are taken into account. This type of QD material can be a good candidate to be used in QD lasers or photodetectors for long-wavelength OCT applications.

Acknowledgements

This work is supported by the BrainBridge project (collaboration between Zhejiang University, Eindhoven University of Technology and Philips Research), China Scholarship Council (CSC) and the NRC Photonics grant.

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