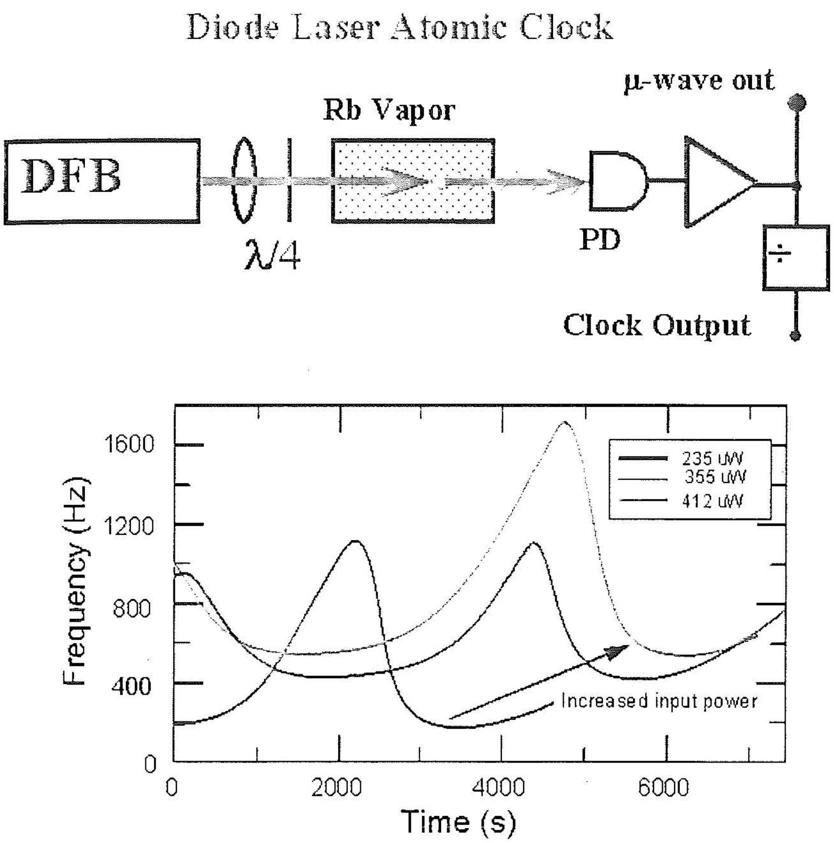
Trends in Optics and Photonics

TOPS Volume XXXI



Advanced Semiconductor Lasers and Their Applications

OSA
Optical Society of America

Edited by Leo Hollberg and Robert J. Lang

Quantum Dot Semiconductor Optical Amplifiers

Richard P. Mirin
NIST/MS 815.04
325 Broadway
Boulder, CO 80304
Telephone: (303) 497-7955
FAX: (303) 497-3387
e-mail: mirin@boulder.nist.gov

Daniel J. Blumenthal
Optical Communications and Photonic Networks Laboratory
Department of Electrical and Computer Engineering
University of California, Santa Barbara
Santa Barbara, CA 93106
Telephone: (805) 893-4168
FAX: (805) 893-5705
e-mail: danb@ece.ucsb.edu

Introduction

Semiconductor optical amplifiers (SOAs) are important components for future generations of wavelength division multiplexed (WDM) lightwave systems. The traveling-wave semiconductor optical amplifier (TW-SOA), in which both facets of the semiconductor chip are anti-reflection (AR) coated, is the most heavily studied type of SOA because of its favorable properties as compared to Fabry-Perot type SOAs. One problem facing TW-SOAs in multiwavelength optical systems is interchannel crosstalk due to cross-gain modulation (XGM). Current SOAs have a bulk (three-dimensional) or quantum well (QW) (two-dimensional) gain medium with carriers (electrons and holes) that are in thermal equilibrium (Fermi-Dirac distribution). Thus, when a signal photon at frequency ω_n generates a stimulated photon and simultaneously reduces the net excited carrier population, the carriers redistribute themselves to maintain equilibrium. Therefore, the number of carriers at any given energy, and thus the gain at any given energy, is affected by photons at all wavelengths, leading to XGM.

In this paper, we propose the use of self-assembled semiconductor quantum dots (QDs) as the gain medium of a SOA. By using electronically-uncoupled QDs in place of a QW or bulk gain medium, the XGM can be greatly reduced or eliminated, and the saturated gain can be increased.

Quantum Dots

The study of self-assembled QDs has been increasingly popular in the last few years[1-3], particularly for use as the active region of semiconductor lasers. Performance improvements in QD lasers (as compared to bulk or QW lasers) have been predicted[4, 5], but fabrication of undamaged, high-density arrays of QDs that are suitable for laser active regions[6-8] have only been achievable in recent years. During growth, nucleation of the QDs does not happen simultaneously, which leads to a size distribution of the QDs. The emission from the array of QDs is inhomogeneously broadened due to the size distribution of the QDs.

The most important property that QDs have for SOA applications is that carriers in each individual QD can be electronically uncoupled, i.e., the carriers in each individual QD are not in thermal equilibrium with the carriers in any other QD. The strong evidence for this is demonstrated by photoluminescence excitation (PLE) experiments[9]. Note that it is also possible to have coupled or partially-coupled QDs, but we will not consider those systems in this paper. The nonequilibrium properties of carriers in QDs allows us to examine a new type of SOA, the

OSA TOPS Vol. 31 Advanced Semiconductor Lasers and Their Applications
Leo Hollberg and Robert J. Lang (eds.)

quantum dot semiconductor optical amplifier (QD-SOA). We shall analyze XGM and gain saturation in a QD-SOA.

Quantum Dot Semiconductor Optical Amplifiers

The main advantage of using a QD-SOA instead of a QW or bulk active region SOA is that the gain medium is inhomgeneously broadened in a QDSOA. The reason for this inhomogeneous broadening is that the QDs are electronically uncoupled. Thus, when a signal at some frequency ω_n is the input to the QDSOA, it will create stimulated photons only from those QDs whose emission is also at ω_n; all carriers in other QDs are unaffected.

This is illustrated by examining the carrier rate equation that describes a TWSOA in a multichannel system:

$$\frac{dN}{dt} = \frac{\eta_i I}{qV} - \frac{N}{\tau_c} - \sum_{\omega} \frac{g(N,\omega)}{\hbar\omega} \left\langle \left| E_{sig}(\omega) + E_{SE}(\omega) \right|^2 \right\rangle, \tag{1}$$

where N is the net carrier concentration, η_i is the injection efficiency, I is the injected current, V is the volume of the active region, τ_c is the carrier lifetime, $g(N,\omega)$ is the gain at frequency ω and net carrier concentration N, $E_{sig}(\omega)$ is the electric field amplitude of the injected optical signal at frequency ω, and $E_{SE}(\omega)$ is the spontaneous emission . The summation is over all channels that are inputs to the amplifier. In order to describe the QD gain medium, with its electronically uncoupled QDs, the following modifications are needed:

$$\rho(E) = (\rho_D D)(2\pi(\Delta E)^2)^{-1/4} \exp\left[-\left(\frac{E - E_Q}{2\Delta E} \right)^2 \right], \tag{2}$$

describes the density of states distribution in the array of QDs, where $\rho(E)$ is the areal density of states at some energy E, ρ_D is the areal density of QDs, D is the degeneracy of the quantum state at energy E_Q, and ΔE is the linewidth of the optical transition at centered at E_Q. The overall carrier concentration N is replaced by N_ω, where N_ω represents the carrier concentration in the QDs with emission energy $\hbar\omega$. $g(N,\omega)$ is replaced by $g(N_\omega)$, where the gain is now explicitly only a function of the carrier density in the QDs with transition energy $\hbar\omega$. Note that in the previous equation the gain was simply a function of net carrier concentration, at a particular wavelength. So we can now replace equation (1) by a series of *independent* equations at each input frequency:

$$\frac{dN_\omega}{dt} = \frac{\eta_i I_\omega}{qV} - \frac{N_\omega}{\tau_c} - \frac{g(N_\omega)}{\hbar\omega} \left\langle \left| E_{sig}(\omega) + E_{SE}(\omega) \right|^2 \right\rangle. \tag{3}$$

Equation (3) describes a situation in which an input channel at frequency ω only induces radiative transitions in those QDs that have emission energies at the same frequency as the input channel. The uncoupled carriers at other frequencies are unaffected by the input signal.

Another advantage of using a QD-SOA is the saturated gain can be higher than a SOA with a homogeneously broadened gain medium. Furthermore, the saturated gain is reached at a slower rate in the QDSOA. These two points are illustrated in Figure 1. It can be shown[10] that in a homogeneously broadened gain medium the expression for saturated gain is $g=g_o/(1+I/I_{sat})$. It can also be shown that for an inhomogeneously broadened gain medium $g=g_o/(1+I/I_{sat})^{1/2}$. This measurement should provide evidence on the broadening mechanism for the QD-SOA.

Conclusions

We have examined some properties of a proposed new SOA, the QD-SOA. The QD-SOA has some important advantages over conventional TW-SOAs, particularly the elimination of XGM. Furthermore, the QD-SOA is expected to be linear over a wider range of input powers than a conventional TW-SOA since the QD-SOA has an inhomogeneously broadened gain medium. Further examination of properties such as polarization sensitivity and time response are needed to determine what types of networks will be suitable for QDSOAs.

References

[1] Goldstein, L., Glas, F., Marzin, J., Charasse, M., and LeRoux, G., *Appl. Phys. Lett.*, V.47 (10), p.1099-1101.
[2] Leonard, D., Krishnamurthy, M., Reaves, C.R., DenBaars, S.P., and Petroff, P.M., *Appl. Phys. Lett.*, V.63 (23), p.3203-3205.
[3] Moison, J. M., Houzay, F., Barthe, F., Leprince, L., Andre, E., and Vatel, O., *Appl. Phys. Lett.*, V.64 (2), p.196-198.
[4] Arakawa, Y., and Sakaki, H., *Appl. Phys. Lett.*, V.40 (11), p.939-941.
[5] Asada, M., Miyamoto, Y., and Suematsu, Y., *IEEE J. Quantum Electron.*, V.QE-22 (9), p.1915-1921.
[6] Bimberg, D., Ledentsov, N., Grundmann, M., Kirstaedter, N., Schmidt, O., Mao, M., Ustinov, V., Egorov, A., Zhukov, A., Kopev, P., Alferov, Zh., Ruvimov, S., Gosele, U., and Heydenreich, J., *Jpn. J. Appl. Phys.*, V.35 p.1311-1319.
[7] Kamath, K., Bhattacharya, P., and Phillips, J., *Journal Crys. Grow.*, V.175/176 p.720-724.
[8] Mirin, R., Gossard, A., and Bowers, J., *Electron. Lett.*, V.32 (18), p.1732-1733.
[9] Fafard, S., Leonard, D., Merz, J.L., and Petroff, P.M., *Appl. Phys. Lett.*, V.65 (11), p.1388-1390.
[10]Yariv, A., *Optical Electronics*, 3rd ed. (Holt, Rinehart, and Winston, New York, 1985).

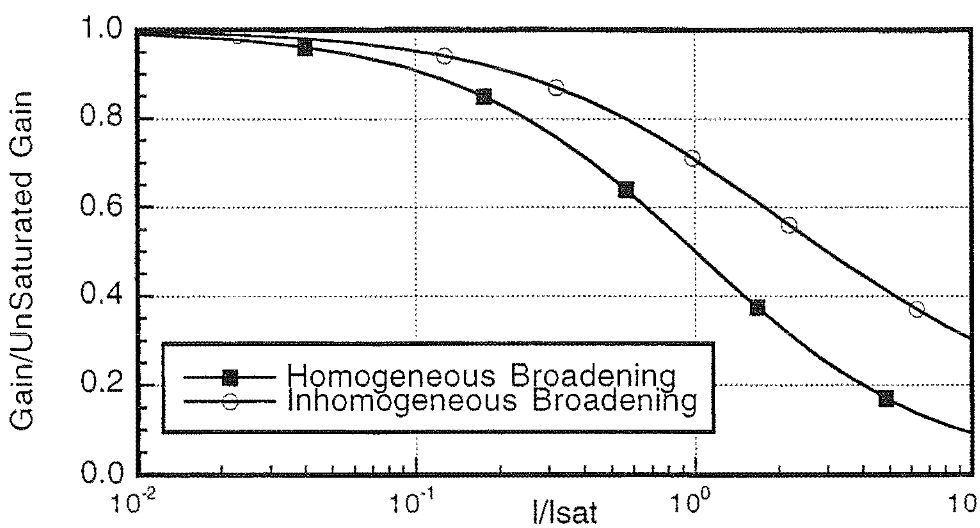


Figure 1 The inhomogeneously broadened gain medium has a higher saturated gain and approaches the saturation value more slowly than the homogeneously broadened gain medium.