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Authors

Kimura, T
Bjorlin, S
Piprek, J
et al.

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High-Temperature Characteristics and Tunability of Long-Wavelength Vertical-Cavity Semiconductor Optical Amplifiers

Toshio Kimura, Staffan Björlin, *Member, IEEE*, Joachim Piprek, *Senior Member, IEEE*, and John E. Bowers, *Fellow, IEEE*

***Abstract*—In this study, we investigate the high-temperature characteristics and the temperature tuning of long-wavelength vertical-cavity semiconductor optical amplifiers (VCSOA). The temperature shift of the peak-signal gain is shown to depend on the mirror reflectivity of the VCSOA. Experimental results of temperature tuning of a 1.3-μm VCSOA are presented. We demonstrate 10 dB of fiber-to-fiber gain over a tuning range of approximately 8 nm.**

***Index Terms*—Laser amplifiers, optical pumping, semiconductor optical amplifiers (SOAs), temperature tuning.**

I. INTRODUCTION

THE CURRENT market for metropolitan networks requires low-cost and small-size amplifiers. Present solutions are conventional erbium-doped fiber amplifiers, erbium-doped waveguide amplifiers, and semiconductor optical amplifiers (SOAs). Low cost and compact size are the main advantages of using vertical-cavity SOAs (VCSOAs). Additional advantages include high coupling efficiency, polarization independent gain, and the potential for fabricating two-dimensional arrays. An important feature of VCSOAs is the narrow signal-gain bandwidth, which is typically less than 1 nm [1]. The narrow bandwidth allows VCSOAs to function as optical filters with gain. The peak-signal gain wavelength is given by the design and fabrication of the VCSOA. However, this may not coincide with the emission wavelength of the transmitter in the system. In reconfigurable networks with dynamic wavelength changes, it is desirable to dynamically tune the peak-signal gain wavelength of VCSOAs.

VCSOAs have been analyzed both experimentally [2] and theoretically [3], [4]. These publications cover fixed-wavelength devices and operation at a constant temperature. The high-temperature characteristics of VCSOAs have not yet been considered. This letter analyzes the high temperature characteristics of long-wavelength VCSOAs. Experimental results from wafer bonded 1.3-μm VCSOAs are presented. Temperature tuning is used to achieve 10 dB of fiber-to-fiber gain over an 8-nm wavelength range.

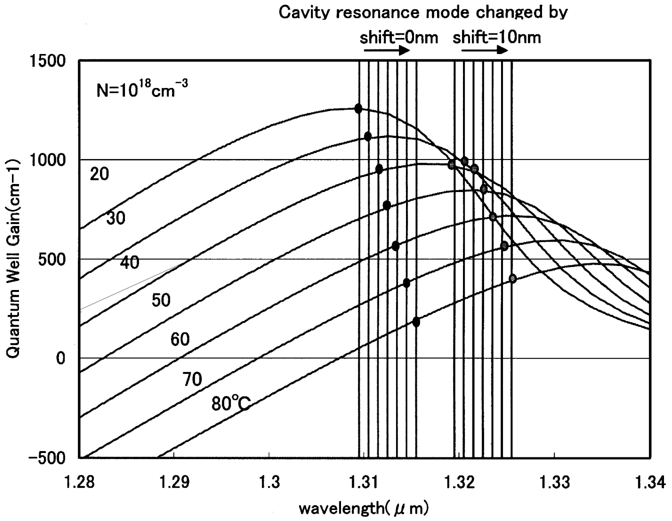

Fig. 1. Calculated QW gain spectrum and cavity mode position at temperatures from 20 °C to 80 °C. The FP mode positions are shown by vertical lines.

II. THEORY

For in-plane traveling-wave SOAs and fiber amplifiers, the signal gain spectrum is determined by the gain medium only. For Fabry–Pérot (FP) SOAs, including VCSOAs, on the other hand, the resonance in the cavity constricts the signal gain to the linewidth of the FP mode. The signal-gain spectrum is, therefore, given by the overlap of the FP mode with the material gain spectrum. Both the cavity mode and the material gain spectrum change with temperature [5]. The temperature dependence of the FP SOA signal gain, therefore, depends on both the material gain and the temperature dependence of the cavity mode. In a properly designed VCSOA, only one FP mode overlaps the material gain. The wavelength of the peak-signal gain of VCSOA is, therefore, determined only by the temperature dependence of the FP mode.

Fig. 1 shows calculated material gain for strained $InAs_{0.5}P_{0.5}$ quantum wells (QWs), for temperature from 20 °C to 80 °C. This is the same QW material that was used in the device presented later in this letter. The carrier density used in the calculation is 10^{18} cm^{-3}. The position of the FP mode for each temperature is also shown in the Fig. 1. For the materials used here, we calculate the wavelength shifts with temperature to be

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The authors are with the Electrical and Computer Engineering Department, University of California, Santa Barbara, Santa Barbara, CA 93106 USA (e-mail: toshio@ece.ucsb.edu).

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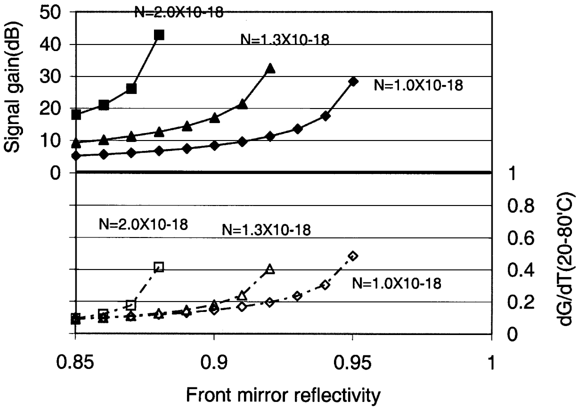

Fig. 2. Peak-signal gain (top) and its temperature dependence (bottom) as function of the front mirror reflectivity for different QW carrier densities N [cm^{-3}].

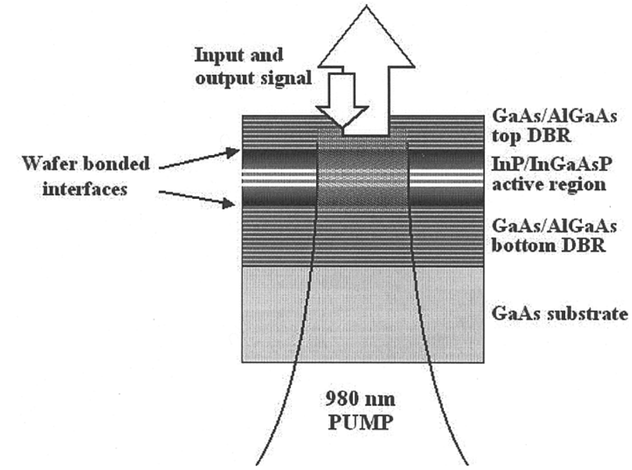

Fig. 3. Schematic of our wafer bonded VCSOA structure.

0.5 nm/K for the material gain and 0.1 nm/K for the cavity mode. For each temperature, the peak gain is determined by the overlap of the material gain and the FP mode. These points are shown as dots in the figure. Because of the different temperature dependence of the cavity mode and the material gain, the signal gain decreases rapidly. The rate at which the signal gain decreases is determined by the reflectivity of the mirrors and the offset between the gain peak and the FP mode. Two cases are shown in Fig. 1: 0- and 10-nm gain offset. Zero offset produces higher room temperature gain, but 10-nm offset results in a smaller QW gain variation over this temperature range.

The theoretical analysis of VCSOAs is presented in [4]. We discuss here temperature characteristics of gain. In the same way as [4], we can start with well-known gain formulas of FP amplifiers. G_R is signal gain for reflection mode

$$G_R = \frac{\left(\sqrt{R_f} - \sqrt{R_b}G_s\right)^2 + 4\sqrt{R_f R_b}G_s \sin^2\Phi}{\left(1 - \sqrt{R_f R_b}G_s\right)^2 + 4\sqrt{R_f R_b}G_s \sin^2\Phi} \tag{1}$$

with the front mirror reflectivity R_f and the back mirror reflectivity R_b, the single pass gain G_s, cavity length L_c (which included the penetration depth of both distributed Bragg reflector (DBR)], and the single pass phase detuning is Φ, given by

$$\Phi = 2\pi n_c L_c \left(\frac{1}{\lambda} - \frac{1}{\lambda_c}\right) \tag{2}$$

with the cavity refractive index n_c and the cavity resonance wavelength λ_c, and G_s is

$$G_s = \exp[\xi g L_a - \alpha_c L_c] \tag{3}$$

with the active region material gain g, the gain enhancement factor ξ, the total thickness of QWs, L_a, and the average cavity loss coefficient α_c.

Based on (1), Fig. 2 shows the calculated signal gain and its temperature dependence versus front mirror reflectivity for a reflection-mode VCSOA. Three different carrier densities are shown. A high mirror reflectivity produces high signal gain for low carrier density, but also results in high temperature dependence. Using low mirror reflectivity, higher carrier density is required, but higher signal gain and lower temperature dependence can be achieved. Low mirror reflectivity also results in high saturation output power and lower noise figure [3], [4].

Using the temperature characteristics discussed above, the main concept for the temperature tuning of our VCSOA is: 1) to change the peak-signal gain wavelength by changing the temperature and 2) to increase the intensity of the pump light to maintain the desired signal gain level. Theoretically, it is possible to tune more than 20 nm by changing the temperature more than 200 K. This would require either cooling to very low temperatures (below −100 °C for our present devices) or a device that can operate at very high temperatures. Considering current state-of-the-art high-temperature performance of long-wavelength vertical-cavity surface-emitting lasers to be the upper limit (134 °C) [6] and 0 °C to be the lower limit, a temperature change of about 130 K can be considered practically feasible. This would produce a tuning of 13 nm.

III. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

Fig. 3 shows the structure of the VCSOA that was used in this study. It consists of an InGaAsP–InP active region wafer bonded to two GaAs–AlAs DBR mirrors. The active region contains three stacks of seven compressively strained InAs$_{0.5}$P$_{0.5}$ QWs, which are placed at the three central peaks of the standing optical wave. The reflectivities of the DBR mirrors are 0.96 for the top mirror and 0.999 for the bottom mirror. The device is optically pumped through the bottom DBR using a 980-nm laser diode. The gain-mode offset of the un-pumped device at room temperature is about 20 nm. The VCSOA is operated in reflection mode, i.e., the signal is sent in and out through the top DBR. Details about the VCSOA structure and the basic characteristics can be found in [2]. The temperature of the VCSOA was controlled by a thermoelectric cooler using a thermistor which was mounted close to the VCSOA. A 1.3-μm tunable laser was used as a signal source. A circulator separates the input and output signals. The total optical loss through the circulator was measured to be about 3.5 dB. The coupling loss was estimated to be about 2.5 dB. The output signal was monitored using an optical spectrum analyzer. Our setup allows for the temperature to be changed from 15 °C to 85 °C.

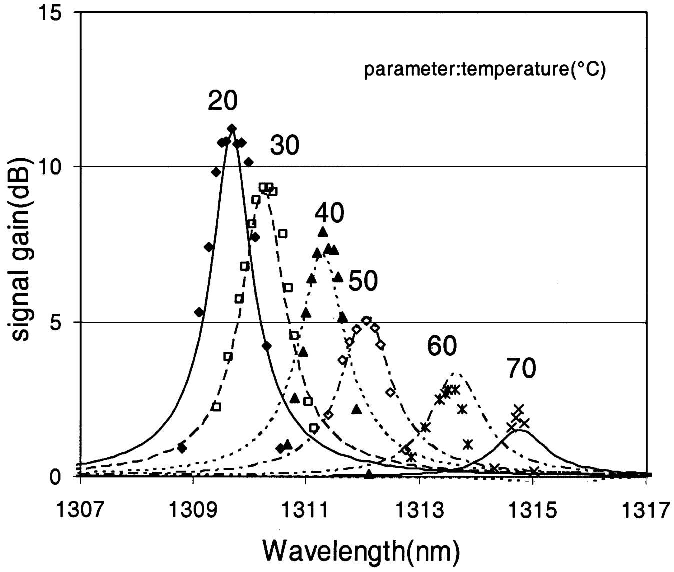

Fig. 4. Temperature dependence of VCSOAs gain spectrum for constant pump power. Dots are measurements, lines are curve fits based on (1).

IV. RESULTS AND DISCUSSION

The signal-gain variation with temperature was first measured for a constant pump power of 64 mW. These results are shown in Fig. 4. The dots are measurement results and the lines are fitted curves based on (1). The gain-mode offset during operation is smaller than the value mentioned previously, due to the heating caused by the optical pump. A gain-mode offset of 10 nm was used in the calculation to obtain a good fit. The temperature dependence of the peak-signal gain wavelength is approximately 0.1 nm/K, in agreement with our calculations. The temperature dependence of the signal gain is approximately −0.2 dB/K. As the gain decreases with increased temperature, the optical bandwidth of the gain spectrum increases. This is also in agreement with theoretical calculations. In order to be able to maintain constant signal gain over a wide tuning range, the pump power has to be increased to compensate for the decreased gain. Fig. 5 shows 10 dB of fiber-to-fiber gain over 8-nm tuning range. The input signal power was −30 dBm. To achieve this tuning, the temperature was changed from 15 °C to 70 °C. At room temperature, 10 dB of gain is reached for 60 mW of pump power. At 70 °C, 160 mW of pump power is needed to reach 10-dB fiber-to-fiber gain. The pump power used at each temperature is shown in Fig. 5. Over 70 °C, we cannot get sufficient gain even though the pump power is increased. At temperatures lower than 15 °C, it is possible to expand the tuning range. However, this can not be measured with the present setup. The change in wavelength is larger at higher temperatures. This is attributed to the heat generated by the optical pumping. The saturation output power is around −13.5 dBm, caused by the high front mirror reflectivity.

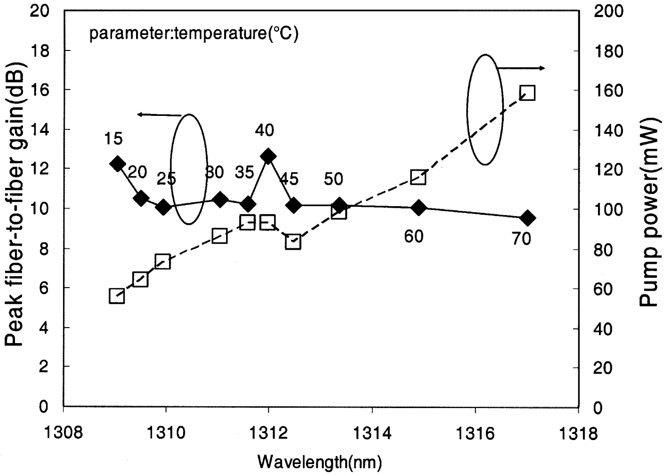

Fig. 5. Measured peak gain and pump power at temperatures from 15 °C to 80 °C. 10 dB of fiber-to-fiber gain over 8 nm is demonstrated.

V. CONCLUSION

In this study, we have investigated the temperature dependence of VCSOAs. The temperature dependence of the peak-signal gain is approximately −0.2 dB/K for our present devices. Smaller temperature dependence can be achieved by lowering the top mirror reflectivity. The change of peak gain wavelength is 0.1 nm/K. Using temperature and pump power tuning, we have achieved 8 nm of peak wavelength change while maintaining 10 dB of fiber-to-fiber gain.

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