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Long-Wavelength Monolithic GaInNAs Vertical-Cavity Optical Amplifiers

Antony H. Clark, Stephane Calvez, N. Laurand, Roberto Macaluso, H. D. Sun, M. D. Dawson, Tomi Jouhti, Janne Kontinnen, and Markus Pessa

Abstract—We report on the continuous-wave amplification characteristics of an optically pumped 1.3- μm multiple-quantum-well GaInNAs–GaAs vertical-cavity semiconductor optical amplifier (VCSOA). The VCSOA structure was monolithically grown by molecular beam epitaxy and operated in reflection mode in a fiber-coupled system. The maximum on-chip gain attained, limited by the onset of laser action, was 15.6 dB at 196 mW of 980-nm pump power. For a chip gain of 10.4 dB, the optical bandwidth was 10.8 GHz and the saturation output power was -9 dBm. By varying the pump laser power, a maximum extinction ratio of 22.3 dB was obtained. Temperature-controlled tuneable operation of the device is also presented and demonstration of 9 dB of chip gain obtained over 9.5 nm with an optical bandwidth of 12 GHz is reported.

Index Terms—GaAs, GaInNAs, optical pumping, optical switches, quantum-well devices, semiconductor optical amplifiers, vertical-cavity surface emitting lasers.

I. INTRODUCTION

RECENTLY, considerable attention has been given to the development of vertical-cavity semiconductor optical amplifiers (VCSOAs) [1]–[3]. These devices have a number of potential applications in communications systems including low-cost, small form-factor wavelength-selective preamplification [4], optical switching [5] and/or modulation [6], and optical interconnection [7]. The vertical geometry of these devices provides a number of advantages over conventional edge-emitting devices including inherent polarization insensitivity, superior coupling with single-mode fibers, lower noise figures, and suitability for production of on-wafer high-density two-dimensional device arrays.

Long-wavelength 1.3- μm VCSOA operation has been achieved with both InGaAsP–InP and GaInNAs–GaAs active regions [2], [3]. One of the main advantages of GaInNAs over InGaAsP is that it can be grown pseudomorphically on GaAs, allowing the monolithic growth of VCSOA/vertical-cavity surface emitting laser (VCSEL) structures. High-quality InGaAsP VCSOA structures, on the other hand, require separate growths for the InGaAsP–InP active region and GaAs–AlGaAs Bragg mirrors, followed by InP–GaAs wafer bonding. The polarization insensitivity offered by VCSOAs is especially important

with respect to GaInNAs–GaAs structures, because for acceptable nitrogen concentrations, this material can only be grown under compressive strain on, or lattice-matched with, GaAs [8]. Hence, in edge-emitting devices, the output light polarization is predominantly transverse electric [9] and polarization-insensitive amplification is, thus, not possible in standard structures.

In this paper, we present a comprehensive study of the continuous-wave (CW) amplifier performance of a GaInNAs–GaAs VCSOA, optically pumped in a fiber-coupled format. Characteristics including gain, optical bandwidth, gain saturation, and extinction ratio are explored in detail. Thermally induced wavelength tuning is also reported.

II. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

The semiconductor structure used in our experiments was designed for diode-pumped laser action [8]. It was grown by molecular beam epitaxy (MBE) with a radio frequency nitrogen plasma source at a growth temperature of 460°C and *in situ* annealed. It includes a $5/2\text{-}\lambda$ active region containing six nominally 6.7-nm-thick $\text{Ga}_{0.64}\text{In}_{0.36}\text{N}_{0.014}\text{As}_{0.086}$ –GaAs quantum wells (QWs) positioned on five antinodes of the standing optical wave pattern (two wells in the central maximum) to facilitate resonant periodic gain. The QWs are separated by 13-nm-thick GaAs barriers. The active region is sandwiched between two 520-nm $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ separate confinement layers resulting in a total cavity length of 5λ . The top mirror is a 19-pair GaAs–AlAs distributed Bragg reflector (DBR) and the bottom mirror is a 20.5-pair GaAs–AlAs DBR, respectively. The cavity supports two longitudinal modes within the high reflectivity band of the mirrors; the longer wavelength mode dominates due to the position on the photoluminescence peak (1290 nm at 300 K). The steady-state room-temperature reflectivity and photoluminescence characteristics of the as-grown structure, illustrating these features, are shown in Fig. 1. No transverse carrier or optical confinement schemes were employed, i.e., the device is gain guided. For the work described here, to allow better amplifier performance [3], two pairs of the top mirror have been etched off by standard reactive ion-etching methods utilizing end-point detection for process control.

Device characterization was conducted under CW pumping using the fiber-based system illustrated in Fig. 2. The common port (6.9- μm mode-field diameter at 980 nm) of the wavelength division multiplexing (WDM) coupler was butt-coupled to the device for signal (1300 nm) and pump (980 nm) copropagation. The 1.3- μm input signal was provided, as required, either by a superluminescent diode (SLD) or a tunable laser. The circulator

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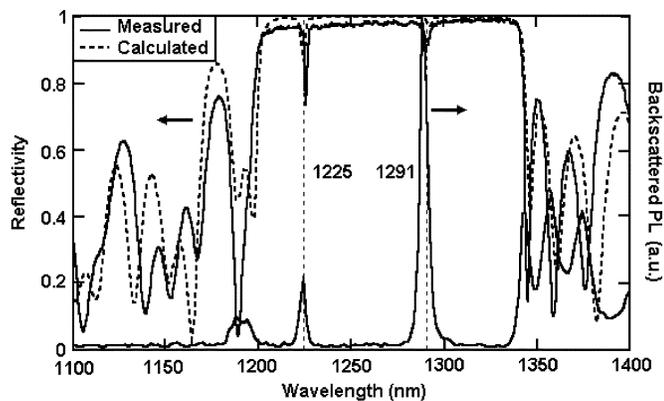


Fig. 1. Photoluminescence and reflectance spectra for the as-grown VCSOA structure.

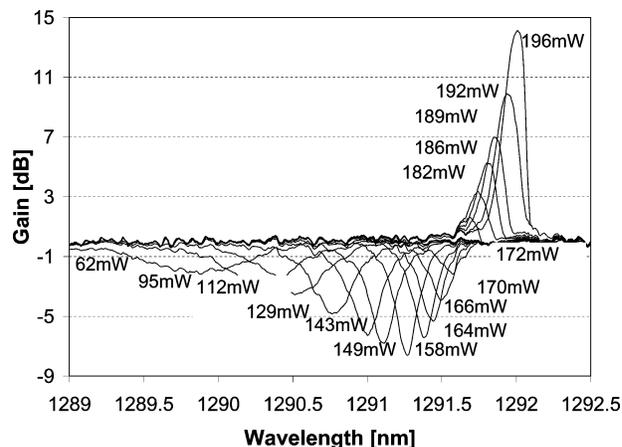


Fig. 3. Gain spectra versus pump power at 55 °C recorded using an SLD signal source.

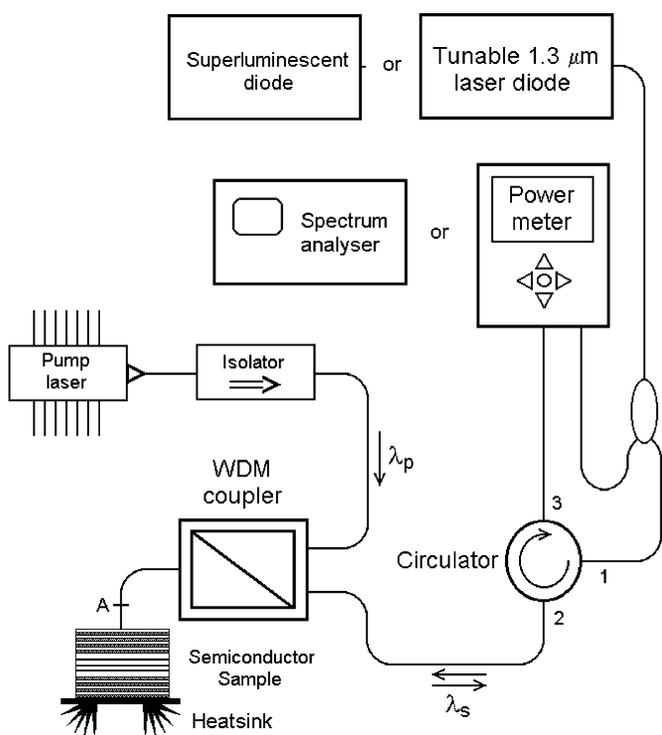


Fig. 2. Schematic diagram of VCSOA experimental setup.

allowed separation of the amplified signal from the input signal and pump light. Amplified signal light was detected using either an optical spectrum analyzer or an optical power meter, both of which were fully calibrated industry-standard instruments.

III. RESULTS AND ANALYSIS

System losses were measured to allow the extraction of the chip gain to enable direct comparison to other values in the literature. The optical losses incurred between the input port of the circulator and the APC connection of the patch cord, and between the APC connection of the patch cord and the output port of the circulator, were measured to be 2.8 and 2.3 dB, respectively.

Using the optical spectrum analyzer with an SLD output as a signal input, the gain versus the pump power characteristic was recorded as a function of sample temperature. (see Fig. 9) The SLD gives approximately -35 dBm of optical power across the

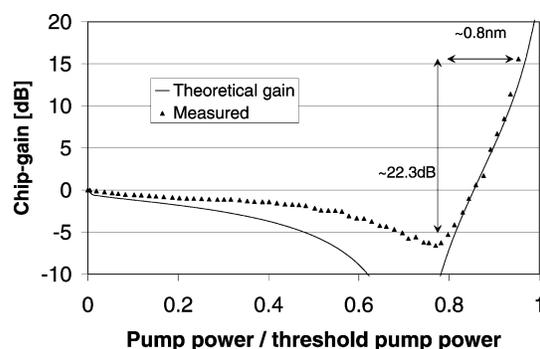


Fig. 4. Gain at resonance versus pump power taken at 55 °C.

wavelength range of interest. This is well below the saturation input power of the device. (see Fig. 7) These measurements, which will be discussed at length later in this paper, show that the optimum operating temperature of the device is ~ 55 °C. We begin by discussing our characterization of the VCSOA at this temperature.

Fig. 3 shows the VCSOA gain spectra for a set of different pump powers. The red shift of the cavity resonance is attributed to thermal effects in the microcavity induced by pump light absorption [9]. The variations in bandwidth and gain amplitude can be explained fully by the theory of [10] and are related to the (absorptive or emissive) state of the QWs in the active region.

The major changes in the gain of the device occur at the cavity resonance which varies with pump power and/or temperature. Fig. 4 shows the gain at resonance as a function of pump power at 55 °C.

The theoretical curve plotted in Fig. 4 is based on the following equations for reflection-mode amplifier gain G_R and incident pump power P_P [10]

$$G_R(N) = \frac{\left(\sqrt{R_f} - \sqrt{R_b} \exp\left(\xi g_0 \ln\left(\frac{N}{N_0}\right) L_a - \alpha_c L_c\right)\right)^2}{\left(1 - \sqrt{R_f R_b} \exp\left(\xi g_0 \ln\left(\frac{N}{N_0}\right) L_a - \alpha_c L_c\right)\right)^2} \quad (1)$$

$$P_P(N) = \frac{hcL_a A_p}{\lambda_p \eta_{abs}} (AN + BN^2 + CN^3). \quad (2)$$

Due to the low 1.3- μ m input signal power, carrier recombination due to stimulated emission has been neglected in (2).

TABLE I
PARAMETERS USED IN THEORETICAL CALCULATION OF VC SOA GAIN

Parameter	Meaning	Value
R_f	Front mirror reflectivity	99.1%
R_b	Bottom mirror reflectivity	99.5%
ξ	Gain enhancement factor	2
g_0	Gain parameter	3600 cm^{-1} [11]
N_0	Transparency carrier density	$1.9 \cdot 10^{18} \text{ cm}^{-3}$ [11]
L_a	Active layer thickness	42nm
L_c	Cavity length	$3.2 \mu\text{m}$
A_p	Pumped area	$154 \mu\text{m}^2$
λ_p	Pump wavelength	980nm
A	Monomolecular recombination coefficient	$11 \cdot 10^8 \text{ s}^{-1}$ [12]
B	Bimolecular recombination coefficient	$8.2 \cdot 10^{-11} \text{ cm}^3 \text{ s}^{-1}$ [12]
C	Auger recombination coefficient	$3.5 \cdot 10^{-29} \text{ cm}^6 \text{ s}^{-1}$ [12]
N	Carrier density	Determined via least squares fit to data
α_c	Internal loss coefficient	4 cm^{-1}
η_{abs}	Pump absorption efficiency	2.43%

The meanings and values of the parameters used in (1) and (2) are given in Table I. These values were determined from the experimental setup, the VC SOA structure, and from the literature [11], [12]. Only the internal loss coefficient and the pump absorption efficiency were allowed to vary and, via a least squares fit, were determined to be 4 cm^{-1} and 2.34%, respectively. These somewhat low values are consistent with the facts that the VC SOA structure is undoped and that in-well excitation is employed. It should be noted that the device parameters taken from the literature are the best available at the time of writing, however, they may not be fully accurate and, thus, act as fitting parameters to some extent.

The maximum achievable gain is limited by the laser-threshold gain of the device, which we estimate to be $\sim 18 \text{ dB}$ by extrapolation from our gain versus pump power data (the laser action pump threshold P_{th} equals 206 mW). Setting the pump power to 95% of P_{th} , i.e., 196 mW, allowed us to measure a chip gain value of 15.6 dB. Gain is achieved when the pump power exceeds 180 mW.

Detailed measurements of the VC SOA gain bandwidth and gain saturation were made using a tunable laser source (with a resolution of 0.001 nm) and a fiber-coupled optical power meter.

For an input signal power of -26 dBm and a peak gain of 10.4 dB corresponding to a pump power $\sim 94\%$ of P_{th} , the optical bandwidth (i.e., the full-width-half-maximum of the gain spectrum) was measured as 10.8 GHz as shown in Fig. 5. Our data were fitted using the following Fabry–Perot reflection mode amplifier gain (G_R) wavelength relationship [13]

$$G_R(\lambda) = \frac{(\sqrt{R_t} - \sqrt{R_b}g_s)^2 + 4\sqrt{R_t R_b}g_s \sin^2\left(2\pi nL\left(\frac{1}{\lambda} - \frac{1}{\lambda_c}\right)\right)}{(1 - \sqrt{R_t R_b}g_s)^2 + 4\sqrt{R_t R_b}g_s \sin^2\left(2\pi nL\left(\frac{1}{\lambda} - \frac{1}{\lambda_c}\right)\right)}. \quad (3)$$

A wider gain bandwidth could be achieved by removing mirror pairs from the top Bragg reflector, but this would require increased pump power to achieve the same peak gain values [10].

The difference between the maximum and minimum gain values [which occur 0.8 nm apart (see Fig. 4)], i.e., the extinction

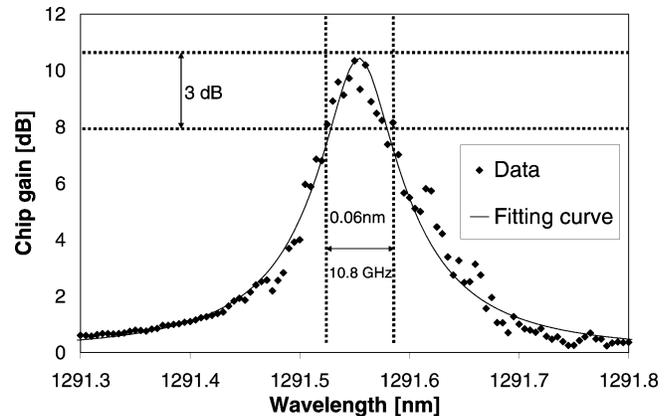


Fig. 5. Gain spectrum for $P_P = 0.958 P_{\text{th}}$, $P_S = -26 \text{ dBm}$, and $T = 55^\circ \text{C}$.

ratio of the VC SOA, is $\sim 22.3 \text{ dB}$, suggesting that such devices may have potential in wavelength-selective optical switching.

The values of the optical cavity length (which includes the depth penetrated into the distributed Bragg reflectors by the cavity mode) $nL = 10.7 \mu\text{m}$, the central emission wavelength $\lambda_c = 1291.55 \text{ nm}$, and the bottom mirror reflectivity $R_b = 0.995$, were all known from the design of the device; the single-pass gain g_s and the top mirror reflectivity R_t were determined to be 1.005 and 0.991, respectively, via a least squares fit. The fitted value of R_t is slightly lower than the value of 0.993 expected from our design, which may be indicative of surface roughness on the etched top mirror.

We then measured the optical gain bandwidth (Δf) as a function of peak gain (see Fig. 6). The data show good agreement with the theoretical curve which was generated using the following equation [10]:

$$\Delta f = \frac{c}{\pi nL} \cdot \arcsin \left[4\sqrt{R_t R_b}g_s \left(\frac{1}{(1 - \sqrt{R_t R_b}g_s)^2} - \frac{2}{(\sqrt{R_t} - \sqrt{R_b}g_s)^2} \right) \right]^{-1/2}. \quad (4)$$

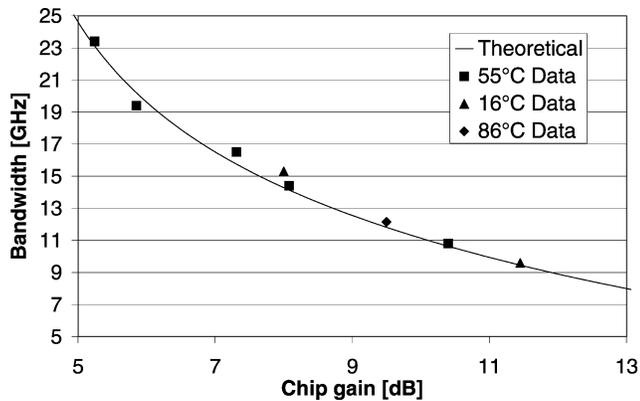
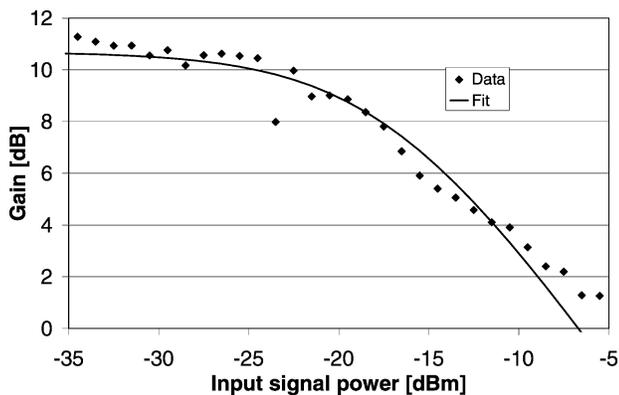


Fig. 6. 3-dB gain bandwidth versus chip gain.

Fig. 7. Gain versus input signal power; the 3-dB saturation output power is -9.3 dBm. $T = 55^\circ\text{C}$.

As can be seen from Fig. 6, the gain-bandwidth product is largely temperature independent over the range 16°C – 86°C . This means that temperature-induced wavelength tuning can be employed without significantly affecting the gain bandwidth of the device.

Fixing the signal wavelength at the cavity resonance at 55°C and a peak gain value of 11 dB (~ 1291.55 nm), the gain versus input power (gain saturation) characteristic of the device was measured. Fig. 7 shows these data together with a fitting curve generated from the following empirical equation relating the amplifier gain (G), input power ($P_{S,IN}$) and the saturation input power ($P_{S,IN,SAT}$):

$$G(P_{S,IN}) = \frac{G_{MAX}}{\left(1 + \frac{P_{S,IN}}{P_{S,IN,SAT}}\right)}. \quad (5)$$

For a small-signal gain of 11 dB, the 3-dB saturation output power was measured to be -9.6 dBm. Fig. 8 shows the output saturation power as a function of small-signal chip gain. The trend in the evolution of these data points is consistent with the theoretical analysis presented in [10].

The InP-based devices reported in [3] show higher gains, larger bandwidths, and better efficiencies (longer absorption lengths) than our devices, but the InP-based structures include a larger number of wells (21), and have lower top mirror reflectivity (0.975). Taking these structural differences into consideration along with the theory presented in [10], the amplification characteristics presented in this paper suggest that optimized GaInNAs-based VCISOAs should allow, at least,

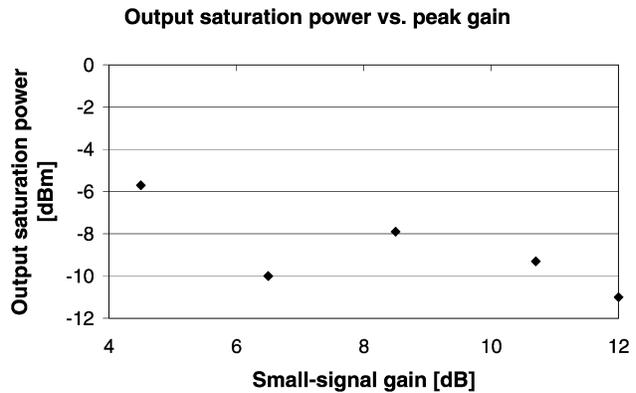
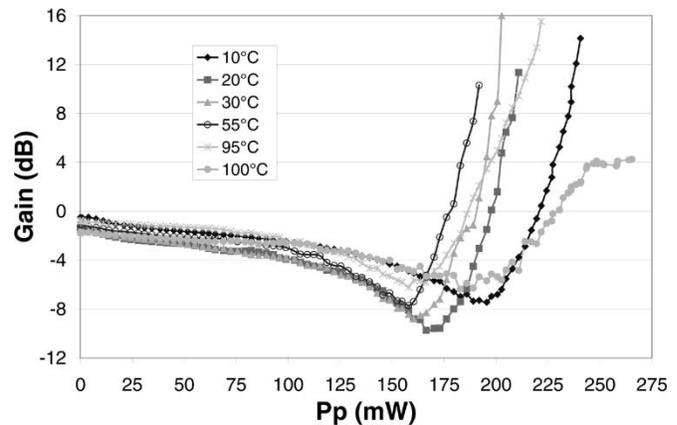
Fig. 8. Output saturation power versus small-signal gain. $T = 55^\circ\text{C}$.

Fig. 9. Fiber-to-fiber gain versus pump power for different temperatures.

similar performance to InP-based devices but with a simpler manufacturing.

IV. TEMPERATURE TUNING

Our measurement of the VCISOA's key amplifier characteristics was followed by an investigation of temperature-induced wavelength tuning of the device. Both the effective refractive index and the length of the cavity increase with temperature so that it was possible to thermally control the spectral position of the cavity resonance and, hence, the wavelength of the gain peak.

The chip gain (at resonance) was measured as a function of pump power for a number of different temperatures in the range 10°C – 100°C (see Fig. 9). With the exception of the 100°C curve, the gain versus pump power curves all share the same behavior, indicating that the device performance is limited to on-chip gain lower than the threshold gain of ~ 18 dB. At 100°C , however, the gain saturates to a value of 4 dB and threshold is never reached. Optimum efficiency is achieved at $\sim 55^\circ\text{C}$.

To gain a better understanding of how temperature affects the VCISOA performance, we first measured a set of temperature-dependent (120 K–300 K) backscattered photoluminescence (PL) to find the QW gain peak–cavity resonance offset. From these spectra, which were all modulated by the optical cavity (see Fig. 1), it was possible to estimate the position of the gain peak. Assuming that the gain spectrum is symmetrical and

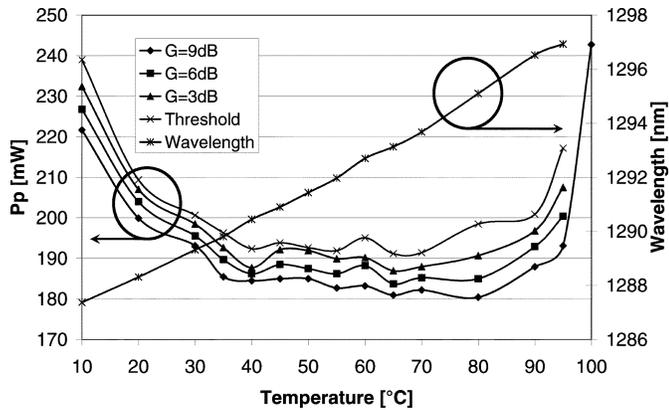


Fig. 10. Temperature dependence of the pump power required to reach fixed gain values and emission wavelength at threshold.

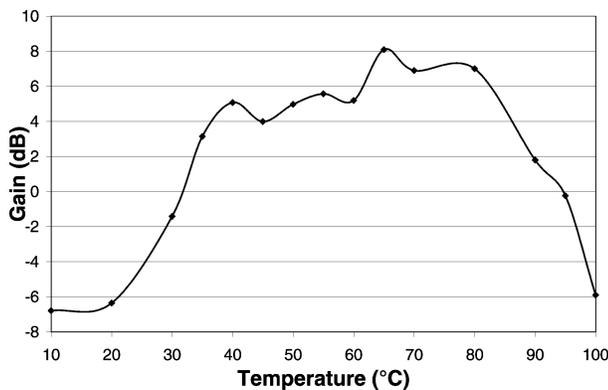


Fig. 11. VCSOA gain versus temperature under constant pump power (186 mW).

that the two resonances have identical strength, the gain peak is located halfway between the two cavity resonances when the PL intensity at both resonances is identical. This occurred at 189 K when the lower wavelength resonance was 1215 nm and the longer wavelength resonance was 1279 nm, giving an estimate of 1247 nm for the PL peak. By linear extrapolation, assuming redshifts of 0.33 nm/K for the GaInNAs QW [14] and 0.11 nm/K for the cavity resonance (see Fig. 10) it was estimated that the temperature at which the PL peak and the longer wavelength cavity resonance should be perfectly aligned and, hence, give optimum device performance should be approximately 60°C which is in very good agreement with the optimum experimental temperature mentioned above.

As a second part of our analysis, we monitored the pump power needed to achieve a given set of on-chip gain values. As represented in Fig. 10, all these curves follow the same trend. For temperatures between 40°C and 95°C, the pump power needed to reach a given gain value is nearly constant. The increase in the amount of pump power required to maintain a constant gain outside this window is due to a larger offset between the peak wavelength of the QW gain and the cavity resonance and also, at higher temperatures, to an increase in the non-radiative (Auger) recombination rate. In addition to pump requirements, we also recorded the change in the emission wavelength at threshold. As can be seen in Fig. 10, a linear variation with temperature with a rate of 0.11 nm/K has been measured

with no influence coming from the change in threshold pump power. This means that, with a favorable gain–cavity resonance offset, if the pump power can be sufficiently varied, our device can be operated with 9 dB of on-chip gain over a tuning range of 9.5 nm. Temperature-induced wavelength tuning has been demonstrated in InP-based VCISOAs with 10 dB of gain over 8 nm [1].

Another operational mode of the VCISOA could be to use it under constant pump power injection. As an example, we present in Fig. 11 the on-chip gain variations with temperature when the device is pumped with 186 mW. On-chip gain is provided as long as the temperature is set between 32°C and 95°C, but fiber-to-fiber gain ($G = 5.1$ dB) is achieved only for temperatures between 50°C and 85°C.

V. CONCLUSION

We have presented a full (CW) characterization of a 1300-nm monolithic GaInNAs–GaAs-based VCISOA, optically pumped at 980 nm in a fiber-coupled format. The device, produced by a single MBE growth, demonstrated gain values of up to 15.6 dB for 196 mW of pump power and a maximum extinction ratio of 22.3 dB. For an unsaturated chip gain of 10.4 dB, the optical bandwidth is 10.8 GHz. A 3-dB output saturation power of -9.6 dBm was measured for a small-signal gain of 11 dB. Taking into account structural differences, these characteristics are comparable to those reported for equivalent InP-based structures which require a more complicated fabrication process. With further optimization, including reducing the top mirror reflectivity and increasing the number of QWs in the active region, our results suggest GaInNAs-based VCISOAs can, at least, match InP-based devices while offering the major advantage of monolithic growth.

The key amplifier characteristics of the VCISOA follow basic Fabry–Perot amplifier predictions, verifying the design understanding for specifying and optimizing such devices. The performance of our device suggests that similar structures may be suitable for use in optical telecommunications as wavelength-selective preamplifiers and/or amplifying optical switches. There may also be potential for application of GaInNAs VCISOAs in optical interconnects. Finally, we have demonstrated temperature-induced wavelength tuning of our device with ~ 9 dB of chip gain over a range ~ 10 nm. This feature may be of use in wavelength-multiplexed systems.

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