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Optical gain in 1.3-µm electrically driven dilute nitride VCSOAs

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Abstract

We report the observation of room-temperature optical gain at 1.3 µm in electrically driven dilute nitride vertical cavity semiconductor optical amplifiers. The gain is calculated with respect to injected power for samples with and without a confinement aperture. At lower injected powers, a gain of almost 10 dB is observed in both samples. At injection powers over 5 nW, the gain is observed to decrease. For nearly all investigated power levels, the sample with confinement aperture gives slightly higher gain.

Keywords: Dilute nitride; Optical injection; Gain; Vertical cavity semiconductor optical amplifiers

Background

$In_xGa_{1-x}As_{1-y}N_y$ semiconductor alloy was first proposed by Kondow et al. in 1996 [1], and considerable research attention has been devoted to this alloy system due to its possible optoelectronic applications at an operating wavelength of 1.3 µm. With the addition of small amounts of nitrogen into the (In)GaAs lattice, a strong electron confinement and bandgap reduction are obtained. Furthermore, addition of N allows band engineering, allowing the device operating wavelength range to extend up to 1.6 µm [2]. An extensive set of different devices based on this alloy has been fabricated and demonstrated [3]. Examples of these devices are vertical cavity surface-emitting lasers (VCSELs) [4-6], vertical external cavity surface-emitting lasers [7,8], solar cells [8,9], edge-emitting lasers [10], photodetectors [11], semiconductor optical amplifiers (SOAs) [12], and vertical cavity semiconductor optical amplifiers (VCSOAs) [13,14].

VCSOAs can be seen as the natural evolution of SOAs, which, owing to their fast response, reduced size, and low-threshold nonlinear behavior, are popular in applications such as optical routing, signal regeneration, and wavelength shifting. Within these fields, VCSOAs have been used as optical preamplifiers, switches, and interconnects [15-17]. Their geometry provides numerous advantages over the edge-emitting counterpart SOAs, including low noise figure, circular emission, polarization insensitivity, possibility to build high-density two-dimensional arrays of devices that are easy to test on wafer, and low-power consumption that is instrumental for high-density photonic integrated circuits. Generally speaking, a VCSOA is a modified version of a VCSEL that is driven below lasing threshold. The first experimental study of an $In_xGa_{1-x}As_{1-y}N_y$/GaAs-based VCSOA was reported in 2002 [18], with a theoretical analysis published in 2004 [19]. Several studies on optically pumped $In_xGa_{1-x}As_{1-y}N_y$ VCSOAs have been published [14,20-23], while electrically driven VCSOAs have been demonstrated only in 'Hellish' configuration [24]. The present contribution builds on these technological developments to focus on an electrically driven multifunction standard VCSOA device operating in the 1.3-µm wavelength window.

Methods

The amplification properties of $In_xGa_{1-x}As_{1-y}N_y$ VCSOAs were studied using a 1,265- to 1,345-nm tunable laser (TL; TLM-8700-H-O, Newport Corporation, Irvine, CA, USA), whose output was sent to the sample using the setup shown in Figure 1a. The TL signal was split via a 10/90

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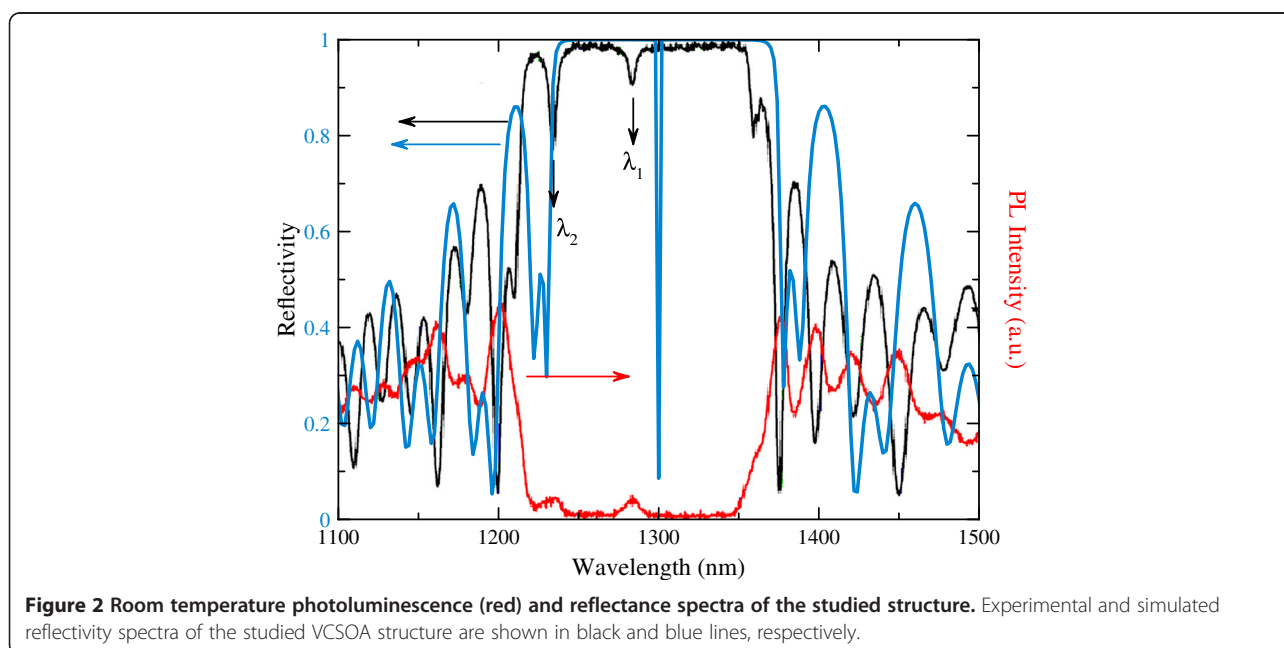Full list of author information is available at the end of the article

Figure 1 Experimental setup (a) and the layer structure of the investigated samples (b).
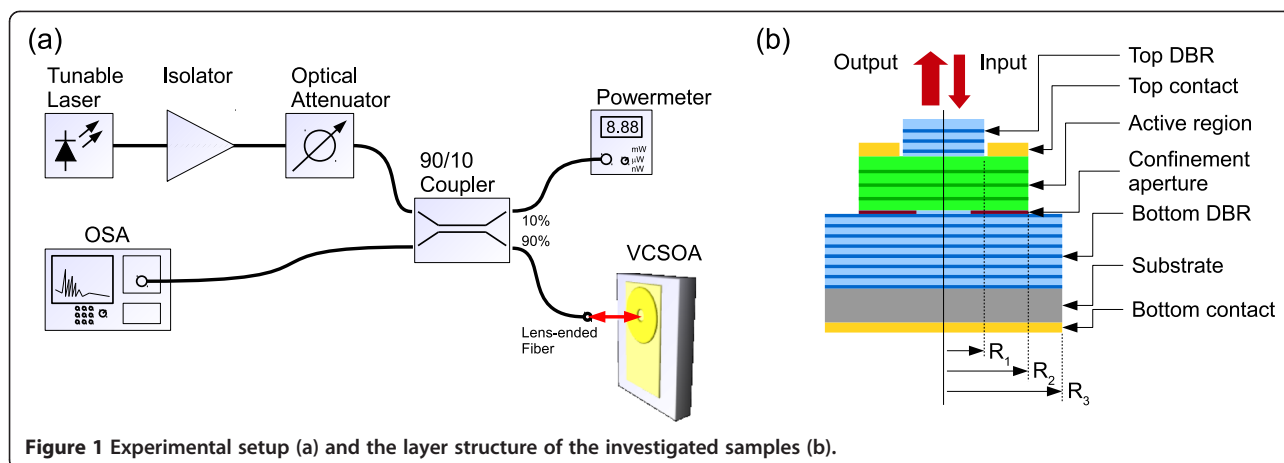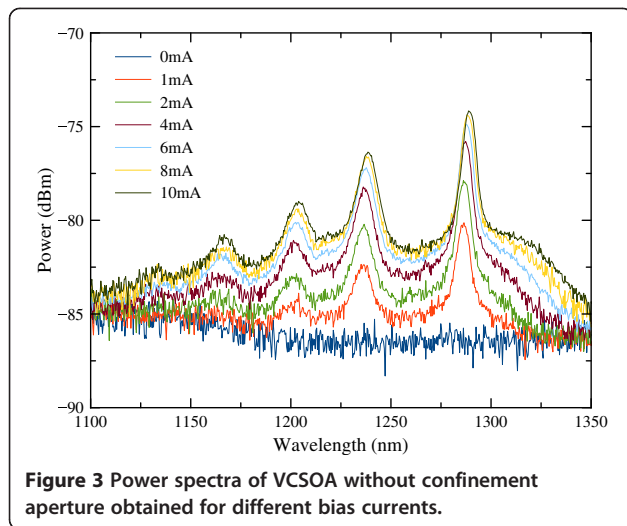
coupler to a power meter and to the sample, respectively. Back reflections were avoided using an optical isolator while the TL power was changed from 0 to 7 mW using an optical attenuator. A lens-ended fiber (SMF-28 fiber, conical lens with cone angle of 80° to 90° and radius of 6.0 ±1.0 μm) was used to focus the TL light to the sample surface as well as to collect its reflected/emitted/amplified light, which was then directed to an optical spectrum analyzer (OSA). The VCSOA was electrically DC biased up to 10 mA and stabilized in temperature at 20°C via a Peltier cooler.

The investigated VCSOA structure with a 3.5λ cavity is shown in Figure 1b. The structures were grown by a solid source molecular beam epitaxy reactor with a radio frequency plasma source for incorporating nitrogen. The growth was carried on an n-type GaAs(100) substrate, and the bottom and top distributed Bragg reflectors (DBRs) were doped with silicon (n-type) and beryllium (p-type), respectively. The two DBRs comprised 21 and 24 pairs of $Al_xGa_{1-x}As/GaAs$ layers for the top and bottom DBR, respectively. The Al concentrations were $x = 0.8$ and 0.98 in the top and bottom DBRs, respectively. The confinement aperture, which is required for better carrier and light confinement, was defined in the uppermost layer of the bottom DBR. The active region contains three stacks of three 7-nm-thick $In_{0.35}Ga_{0.65}As_{0.975}N_{0.025}$ quantum wells separated by 20-nm thick GaAs spacers. A set of several VCSOA

Figure 2 Room temperature photoluminescence (red) and reflectance spectra of the studied structure. Experimental and simulated reflectivity spectra of the studied VCSOA structure are shown in black and blue lines, respectively.

Figure 3 Power spectra of VCSOA without confinement aperture obtained for different bias currents.

samples was fabricated, having different dimensions of the top DBR mirror radius (R_1), confinement aperture radius (R_2), and bottom DBR radius (R_3) for cases with and without the confinement aperture. In this paper, we compare the results obtained for two samples with and without confinement aperture, with $R_1 = 5$ μm, $R_2 = 25$ μm, and $R_3 = 50$ μm.

Results and discussion

Room-temperature reflectivity and photoluminescence (PL) measurements were performed on the as-grown sample, and the results are shown in Figure 2. Simulated

reflection is also shown in the figure. Two resonances λ_{R1} and λ_{R2} are observed within the DBR stop band as a result of the relatively long cavity length [25]. The principle resonance, which is designed for 1.3-μm operation, is observed at $\lambda_{R1} = 1,282$ nm, while the other unwanted resonance at lower wavelength is observed at $\lambda_{R2} = 1,235$ nm. Figure 3 shows the VCSOA amplified spontaneous emission (ASE) spectra obtained with no optical injection at different applied bias currents of 0 to 10 mA for the sample without confinement aperture. The highest ASE power peak appears at 1,288 nm and is blue-shifted with respect to that of the lasing cavity mode wavelength [26,27]. The other modes are also consistent with the PL spectra. Figure 3 shows that with increasing the bias current, the amplitude of each mode increases and also slightly shifts towards higher wavelengths. This shift is associated with local temperature increase in the device. A similar result was observed in the VCSOA with the confinement aperture.

Since no significant change in the spectrum amplitude above 7 mA was observed, we investigated the devices up to this current value. ASE power spectra taken at 7 and 0 mA (ASE_0) are used to extract the spectrum $ASE - ASE_0$, which is the spectrum where the background noise is minimized. To find the amplified optical signal (AOS), we injected light sweeping the TL wavelength (λ_{inj}) from 1,266 to 1,310 nm with a 7-mA current bias. Figure 4 shows results for injection at $\lambda_{inj} = 1,279$ nm only. We could not investigate the second resonance peak λ_{R2} because of the wavelength limit of the TL. In
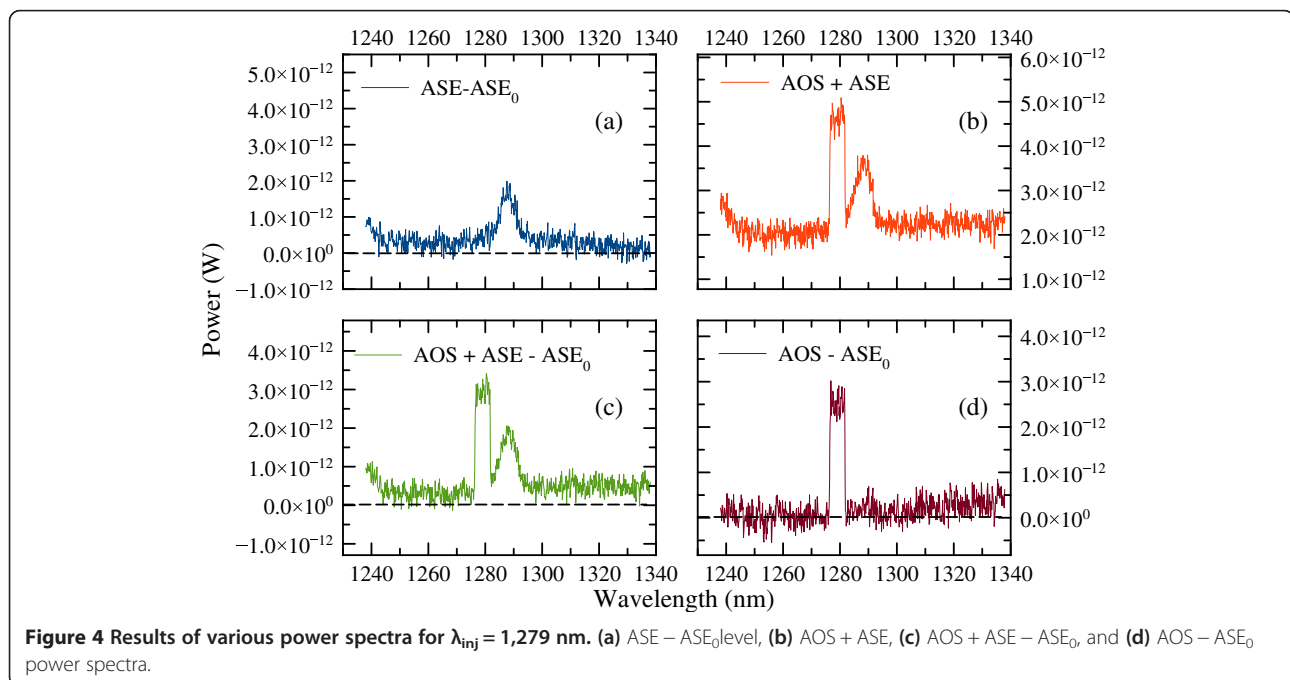

Figure 4 Results of various power spectra for $\lambda_{inj} = 1,279$ nm. (a) $ASE - ASE_0$ level, **(b)** AOS + ASE, **(c)** AOS + ASE − ASE$_0$, and **(d)** AOS − ASE$_0$ power spectra.

Figure 4a,b,c,d, the results for ASE – ASE_0, AOS + ASE, AOS + ASE – ASE_0, and finally AOS – ASE_0 spectra are shown, respectively.

As the gain is small, the amplified signal cannot be easily discerned in Figure 4d. Hence, the gain was calculated using the simple relation
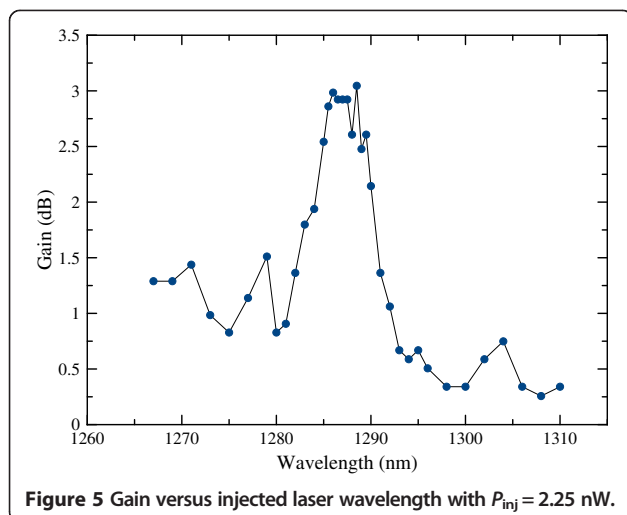
$$\text{Gain} = \frac{\text{AOS} + \text{ASE-ASE}_0}{\text{AOS-ASE}_0} \qquad (1)$$

for each wavelength after obtaining AOS and ASE data. Results are shown as a function of the injected wavelength in Figure 5 for a specific laser power (P_{inj}) of 2.25 nW. A maximum gain of 3 dB with a very broad peak is observed at the maximum ASE wavelength of 1,288.5 nm. In the study, measured signal levels are very near to limits of the OSA; therefore, larger bandwidth wavelength values are used, which can be the reason of the broadness of the gain peak.
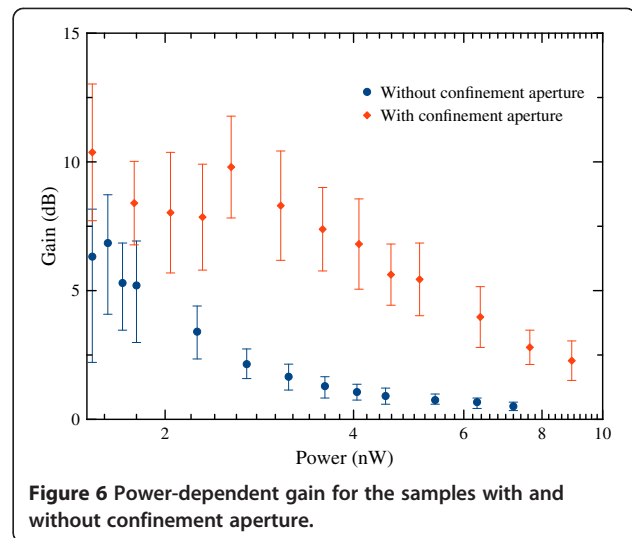
Having verified that the gain peak corresponds to the ASE peak wavelength, we investigated the P_{inj} dependence by varying it from 1.5 nW to a few milliwatts for the single wavelength of 1,288.5 nm. Results are presented for both samples with and without confinement aperture in Figure 6 for power values below 10 nW. For injected laser powers over 5 nW, the gain falls rapidly. At the lowest injected power, the sample with confinement aperture exhibits 10 dB of gain, which is observed near the maximum ASE wavelength. For the investigated injected power range, the sample with the confinement aperture showed a higher gain because of the better carrier and light confinement in the VCSOA.

Conclusions

In this paper, we report the observation of gain in an electrically driven dilute nitride VCSOA device operated

Figure 6 Power-dependent gain for the samples with and without confinement aperture.

at 1.3-μm in reflection mode. Two different types of samples with and without confinement aperture are investigated. The ASE power peak is found to be at 1,288.5 nm with additional modes, which are caused by the length of the cavity. Optical gain is found to occur at low optical injection values. Above 5 nW of optical injection, the gain is found to fall rapidly. The maximum observed optical gain is observed at 1,288.5 nm at room temperature. The maximum observed optical gain at 7-mA current at room temperature is around 10 and 6 dB for samples with and without confinement aperture, respectively. It is important to mention that despite the small gain, the device is very promising because it requires very small currents compared with in-plane SOAs.

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Figure 5 Gain versus injected laser wavelength with P_{inj} = 2.25 nW.

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