Vertical-Cavity Amplifying Modulator at 1.3 μm

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***Abstract*—The modulation/switching properties of a vertical-cavity semiconductor optical amplifier operating at 1.3 μm wavelength are investigated. The device was optically pumped and operated in reflection mode. A 150-mV (100 mA) modulation of the drive to the pump source produced a 7-dB modulation of the pump power, which produced a 35-dB modulation in the output signal. The maximum extinction ratio was 35 dB, and limited by device heating. Frequency response measurements revealed a modulation bandwidth of 1.8 GHz when the amplifier was saturated. This enabled 2.5-Gb/s modulation of a −10 dBm input signal with 5.5-dB fiber-to-fiber gain.**

***Index Terms*—Laser amplifiers, modulation, optical modulation, optical pumping, optical switches, semiconductor optical amplifiers.**

I. Introduction

SEMICONDUCTOR optical amplifiers (SOAs) are interesting devices for modulation applications due to their large extinction ratio and fast gain dynamics that enables nanosecond switching time, which is needed for optical packet switching. The amplifier gain compensates for losses associated with coupling or division of a signal, producing loss-less components. In-plane SOAs have been studied extensively for modulation [1],[2] and switching [3]–[5]. Vertical-cavity semiconductor optical amplifiers (VCSOAs) have a number of advantages over in-plane SOAs, such as polarization independence, high coupling efficiency to optical fiber (facilitating a low noise figure), and low-power consumption due to a small active volume. The typically narrow gain bandwidth of VCSOAs suppresses accumulation of amplified spontaneous emission (ASE), which can be a limiting factor when SOA switches are cascaded [5]. In addition, the vertical-cavity design allows for on-wafer testing and fabrication of two-dimensional arrays. Operating these devices in reflection mode is desirable since it reduces difficult and costly fiber alignment. Alternatively, transmission mode operation makes it easier to achieve the large extinction ratio required for switching applications. Vertical-cavity modulators based on electroabsorption (without gain) have previously been demonstrated [6]. A vertical-cavity amplifying switch operated in reflection mode at 1.5 μm, demonstrated a 14-dB extinction ratio and a switching time of 20 ps [7]. This letter investigates the maximum obtainable extinction ratio and the small-signal modulation bandwidth for a wafer-bonded optically pumped reflection-mode VCSOA operating at 1.3 μm.

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II. Theory

Modulating the pump power/drive current to a SOA modulates the gain, and thereby, the output signal power. For operation in transmission mode, the incoming signal is absorbed when the SOA is turned off resulting in very large extinction ratios; 71 dB is reported in [3]. For operation in reflection mode, a large extinction ratio is more difficult to achieve. The output signal variation with pump power in a VCSOA is governed by the single-pass gain and the reflectivity of the mirrors. This can be modeled using the Fabry–Pérot approach, where the output signal is given by the sum off all fields exiting the amplifier cavity [8]. The amplifier gain for a reflection mode VCSOA is given by

$$G_r = \frac{\left(\sqrt{R_t} - \sqrt{R_b} g_s\right)^2 + 4\sqrt{R_t R_b} g_s \sin^2 \varphi}{\left(1 - \sqrt{R_t R_b} g_s\right)^2 + 4\sqrt{R_t R_b} g_s \sin^2 \varphi} \quad (1)$$

where

- R_t top mirror reflectivity;
- R_b bottom mirror reflectivity;
- g_s single pass gain;
- φ single pass phase detuning relative the resonance frequency.

The field exiting the cavity is 180° out of phase with respect to the field reflected off the front facet of the VCSOA, resulting in destructive interference. At a single-pass gain corresponding to $g_s = \sqrt{R_t}/\sqrt{R_b}$, the fields are of the same magnitude and complete cancellation of the output signal occurs. Using this level as off-state makes it possible for significantly larger extinction ratios, than if the VCSOA was completely turned off in the off-state.

Amplification, as well as cancellation of the signal, occurs only within the linewidth of the Fabry–Pérot mode. Variations in the cavity resonance frequency have to be smaller than the Fabry–Pérot linewidth in order to maintain the signal within the optical bandwidth of the device. The cavity resonance frequency of a VCSOA is sensitive to both temperature and carrier density variations. For high modulation speed, thermal effects will not modulate the cavity resonance frequency. For switching, however, the VCSOA might be in the on-state for several seconds and device heating can be detrimental. Care has to be taken to operate the VCSOA in a regime, where the generated heat can be efficiently dissipated in order to achieve reliable performance. Optical pumping is, in this case, advantageous since

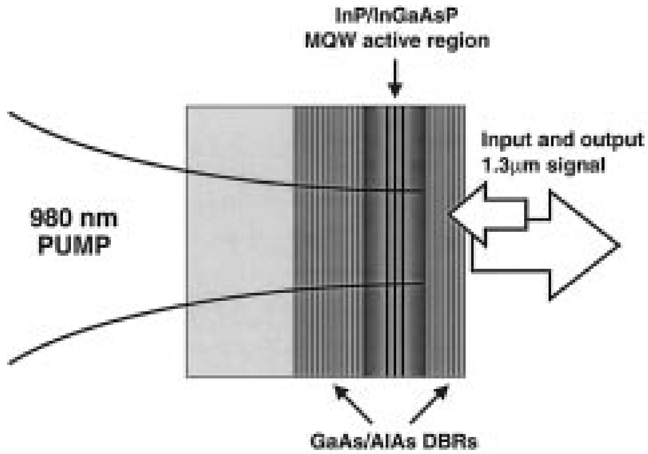

Fig. 1. Schematic of reflection mode VCSOA, showing direction of pump beam and signal.

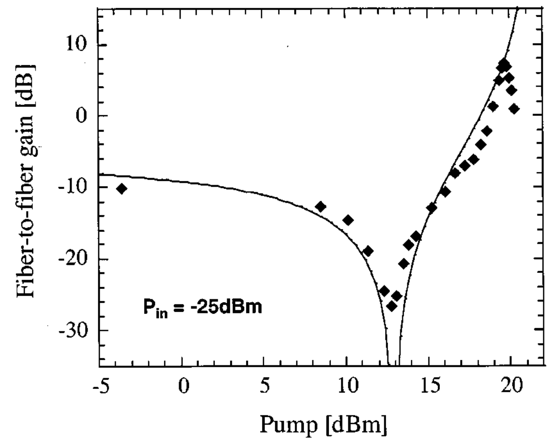

Fig. 2. Output signal power versus pump power for −25 dBm of input signal power. A 35-dB extinction ratio is measured.

joule heating is eliminated and device heating thereby minimized.

The modulation bandwidth of a SOA is limited by how fast the carrier density can be modulated. For low-input signal power, the limiting factor is the slow spontaneous recombination of carriers, which is typically on the order of several nanoseconds. At higher input powers, the faster stimulated recombination dominates over other recombination processes, thereby shortening the carrier lifetime, which enables higher modulation speed. In-plane SOAs have demonstrated modulation bandwidths up to 1.8 GHz [2].

III. Experiments

A schematic of the VCSOA used in this work is shown in Fig. 1. The device consists of an InP–InGaAsP active region wafer bonded to two GaAs–$Al_{0.9}Ga_{0.1}As$ distributed Bragg reflector (DBR) mirrors, forming a 5/2 λ cavity. The active region has three sets of seven compressively strained $InAs_{0.5}P_{0.5}$ quantum wells surrounded by strain compensating barriers. The bottom and top mirror have 25 and 13.5 periods, yielding calculated reflectivities of 0.999 and 0.955, respectively. The device was optically pumped through the substrate and bottom mirror using a 980-nm laser diode. The device is a gain-guided planar structure; the diameter of the active region, which is defined by the diameter of the pump beam is 7 μm. Free-space optics were used to focus the pump beam onto the backside of the device. The sample was mounted vertically in order to facilitate alignment of pump and signal beams. This configuration yields poor heat sinking; we will later show that the maximum extinction ratio achieved was limited by device heating. An external cavity 1.3-μm tunable laser was used as signal source. The signal was coupled into and out of the VCSOA through the top DBR using a fiber and a lens. The input and output signals were separated by means of an optical circulator, which also blocked any pump light that entered the fiber. An optical spectrum analyzer was used to monitor the output spectrum from the VCSOA. A HP lightwave component analyzer was used to modulate the pump laser in order to determine the frequency response of the VCSOA. Pump lasers, such as the one used in this work, have previously demonstrated modulation bandwidths in excess of 3 GHz [9].

Fig. 2 shows fiber-to-fiber gain versus pump power for −25 dBm input signal power at 1291.5 nm. This signal power is well below saturation of the VCSOA. The dots are measurements and the line is a curve fit based on (1). For low pump powers (<10 dBm), any light entering the cavity is absorbed and the measured output signal is the reflection off the top mirror. About 10-dB attenuation due to coupling loss was measured in this regime. At 13 dBm (20 mW) of pump power the cavity mode and the initial reflection cancel out. At this point, the theoretical curve approaches negative infinity. The measured signal attenuation is 27 dB. Infinite attenuation of the output signal is not possible in practice, since the finite gain level produces some ASE. As the pump power is increased further, amplification of the signal is observed, eventually producing 8-dB fiber-to-fiber gain for 20 dBm (93 mW) of pump power. 150-mV (100 mA) modulation of the drive current was needed to produce this 7-dB modulation of the pump power. An output signal extinction ratio of 35 dB for 150-mV modulation is demonstrated, yielding a modulation efficiency of 233 dB/V. For higher pump power, heating causes a red shift in the cavity resonance frequency away from the signal frequency, and the observed output power decreases. Output spectra from the VCSOA at maximum and minimum output signal powers are shown in Fig. 3. The spectra correspond to 22 and 93 mW of pump power, respectively. The fiber coupled ASE, 3 dBm below the signal level, marks the minimum output power that can be achieved in the off-state. No extinction ratio degradation was observed as the input signal power was increased and the VCSOA saturated; 35-dB extinction ratio was measured up to −10 dBm of input signal power.

The temperature sensitivity is analyzed in Fig. 4. Three curves of the gain spectra are shown, corresponding to the dip, the peak, and rollover in Fig. 2. The dots are measurements and the lines are curve fits based on (1). The gain bandwidth for the case of 8-dB fiber-to-fiber gain (93-mW pump power) is 0.25 nm. The red shift as the pump power is increased from 22 to 93 mW is less than 0.1 nm, so the signal stays well within the bandwidth. As the pump power is increased further, heating of the active region increases dramatically resulting in a significant red shift

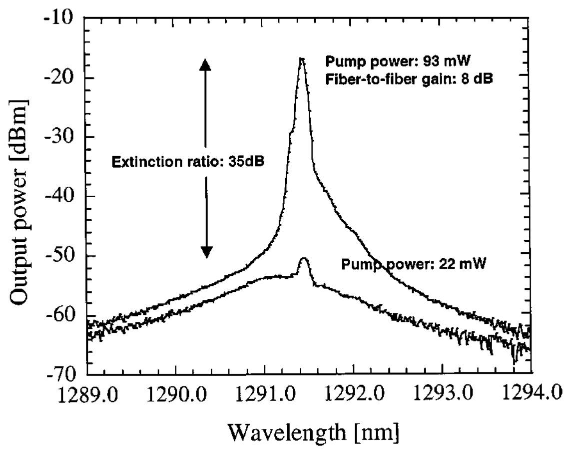

Fig. 3. Output spectra from the VCSOA for -25 dBm of input signal power and 22 and 93 mW of pump power.

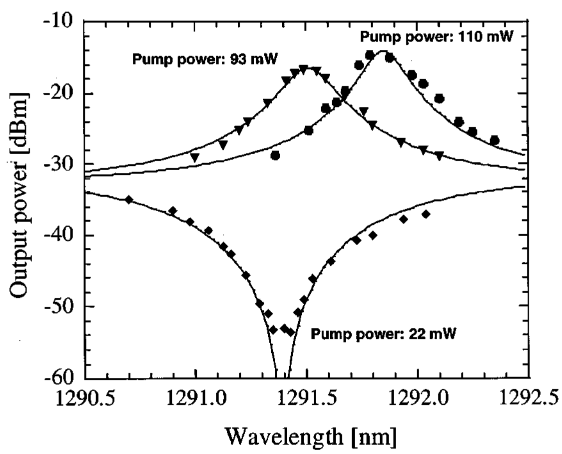

Fig. 4. Spectral dependence of gain for three different pump powers and an input signal of -25 dBm. Red shift due to increased heating at higher pump powers limits the extinction ratio.

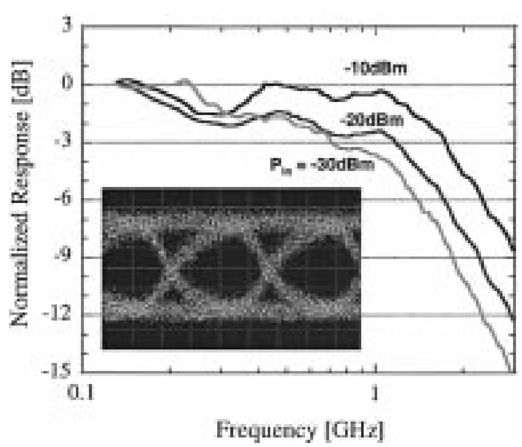

Fig. 5. Frequency response of VCSOA. A 3-dB bandwidth of 1.8 GHz is measured when the VCSOA is saturated. Inset shows 2.5-Gb/s modulation with 5.5-dB fiber-to-fiber gain for -10 dBm of input signal power.

of the cavity resonance frequency. Fiber-to-fiber gain in excess of 10 dB was observed for pump powers of about 120 mW. The severe heating makes modulation up to this level impossible.

Fig. 5 shows small signal frequency response of the VCSOA for different input signal powers. For input signal powers of -20 and -30 dBm, which is well below saturation, 10 dB of fiber-to-fiber gain was measured. For these cases, the 3-dB modulation bandwidths were 0.8 and 1.1 GHz, respectively. As the input signal power was increased to -10 dBm, the gain medium was saturated and the fiber-to-fiber gain dropped to 5.5 dB. In this regime, stimulated emission dominates carrier recombination allowing for faster modulation. A 3-dB bandwidth of 1.8 GHz was measured. The frequency response of the device allowed for 2.5-Gb/s modulation in the saturated regime. The eye diagram in Fig. 5 shows 2.5-Gb/s modulation of a -10 dBm input signal with 5.5-dB fiber-to-fiber gain. This modulation bandwidth suggests that a switch based on these VCSOAs would have subnanosecond switching time, which is needed for packet switching.

IV. Conclusion

The modulation properties of an optically pumped reflection mode VCSOA were investigated. A modulation efficiency of 233 dB/V was obtained. An extinction ratio of 35 dB was achieved, with the on-state corresponding to 8-dB fiber-to-fiber gain. The maximum extinction ratio was limited by device heating and can be improved with better heat sinking. The small signal modulation response of the VCSOA was also measured. A modulation bandwidth of 1.8 GHz was measured when the VCSOA was saturated. This enables 2.5-Gb/s transmission with 5.5-dB gain, or switching with subnanosecond switching time.

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