1.3- m Vertical-Cavity Amplifier

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***Abstract*—We demonstrate the first 1.3-μm vertical-cavity optical amplifier. The amplifier was optically pumped and operated in reflection mode. Optimization of the top mirror reflectivity resulted in a 9.4-dB continuous wave fiber-to-fiber gain, a gain-bandwidth product of 220 GHz, and a saturation output power of −6.1 dBm, all at room temperature. By modulating the pump source, an extinction ratio of 27 dB in the output signal power was obtained.**

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

I. INTRODUCTION

VERTICAL-CAVITY amplifiers (VCA) in the 1.3-μm communication band are attractive components for applications in optical fiber networks, optical interconnects, parallel optical data processing, and optical switching. The advantages of VCA's over conventional edge-emitting devices are improved coupling efficiency to optical fiber, polarization insensitivity, and the potential to be integrated in high-density, two-dimensional array architectures.

Pulsed optically pumped VCA's have been demonstrated at 1550 nm [1]. Recently, electrical pumping of a reflection type VCA at 1.5 μm has demonstrated 18-dB continuous wave (CW) gain, a gain-bandwidth product of 25 GHz, and a saturation output power of −25 dBm at 218K [2]. In this work we demonstrate the first CW amplification at 1.3 μm for a VCA. Using optical pumping we have achieved a fiber-to-fiber gain of 9.4 dB, a gain-bandwidth product of 220 GHz, and a saturation output power of −6.1 dBm at room temperature.

II. DEVICE STRUCTURE AND EXPERIMENTAL SETUP

The VCA structure used in our experiments is shown in Fig. 1. The two undoped GaAs–$Al_{0.99}Ga_{0.01}As$ distributed Bragg reflector (DBR) mirrors were wafer fused to a 1.3-μm InP–InGaAsP active region consisting of three sets of 7-$InAs_{0.5}P_{0.5}$ quantum wells (QW) situated at the central peaks of the standing wave pattern in a $5/2\lambda$ cavity. Conditions for wafer fusion are reported elsewhere [3]. The bottom mirror had 25 periods giving a calculated bottom mirror reflectivity (R_b) of 0.998. The number of periods in the top mirror was varied in order to optimize the properties of the VCA. No patterning or lithography was performed on the sample except to facilitate wafer fusion.

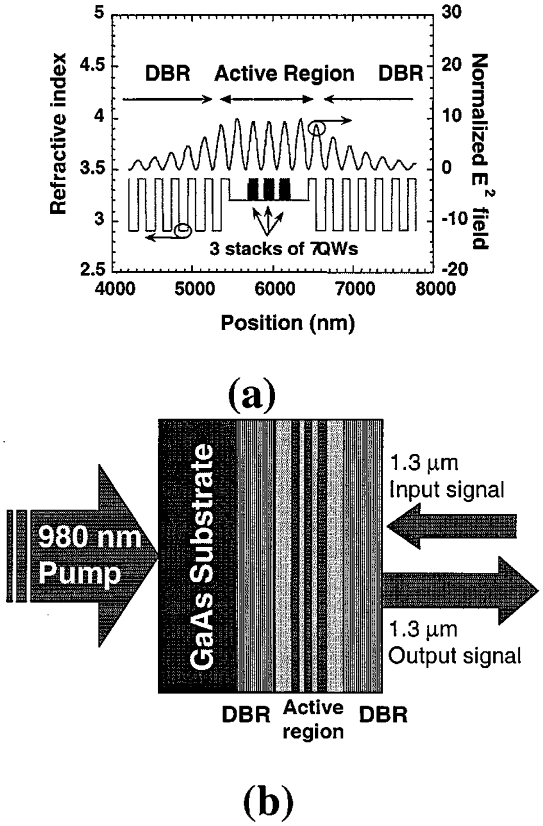

Fig. 1. Schematic of the VCA structure showing (a) refractive index and standing wave pattern, (b) pump and measurement configuration.

The VCA was operated in reflection mode and optically pumped through the GaAs substrate. A CW 980-nm diode laser was used as a pump source, and the pump beam was focused down to a spot size of 8 μm. The surface of the substrate was polished in order to minimize scattering of the pump light and, hence, maximize the amount of power reaching the active region.

A tunable 1.3-μm laser with a resolution of 0.01 nm was used as the signal source into the VCA, and a fiber and lens was used to couple the signal into and out of the VCA. The substrate of the VCA was anti reflection-coated at 1.3 μm to prevent light transmitted through the bottom mirror from being reflected back into the cavity. A circulator was used to separate the input and output signals, and an optical spectrum analyzer was used to monitor the spectrum of the signals. The total coupling loss, including loss in the circulator, was measured to be 4 dB.

III. RESULTS AND DISCUSSION

The gain was measured as a function of wavelength, input power, and pump power, as well as for different numbers of

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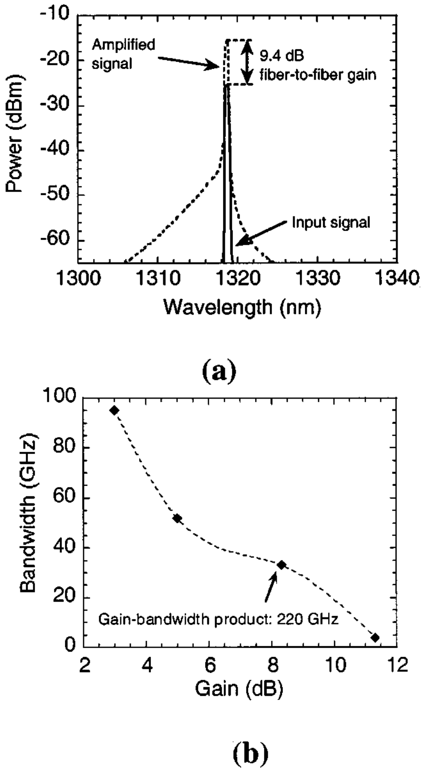

Fig. 2. (a) Spectra of input and output signals showing 9.4 dB fiber-to-fiber gain. The input power is -25 dBm and the pump power is 200 mW. (b) Gain-bandwidth as a function of fiber-to-fiber-gain. For a gain of 8.3 dB the bandwidth is 33 GHz (0.2 nm). This gives a gain-bandwidth product of 220 GHz. The input power is -25 dBm.

top mirror periods. To maximize the gain the number of top mirror periods was reduced to allow for a higher pump power without the occurrence of lasing. All results presented here were measured with 13 top mirror periods, which gives a calculated top mirror reflectivity, R_t, of 0.98.

Fig. 2(a) shows the spectra of the input signal from the tunable laser and the output signal from the VCA. The input signal is -25 dBm at 1318.8 nm, and the pump power is 200 mW. A fiber-to-fiber gain of 9.4 dB was measured.

Fig. 2(b) shows gain-bandwidth as a function of fiber-to-fiber gain. For a measured fiber-to-fiber gain of 8.3 dB, the bandwidth [full-width at half-maximum (FWHM)] is 33 GHz (0.2 nm). This gives a gain-bandwidth product of 220 GHz. The bandwidth decreased as the pump power and, hence, gain, was increased and lasing threshold was approached. Gain up to 13 dB was observed for a pump power of about 85% of threshold power, but that level is clearly to close to lasing, and the optical bandwidth was in the order of 4 GHz (0.02 nm). A wider gain-bandwidth can be obtained by decreased top mirror reflectivity [4].

Fig. 3(a) shows fiber-to-fiber gain as a function of input power. The pump power is 200 mW and the fiber-to-fiber gain is 6.4 dB in the unsaturated regime. The measured gain (dots) is flat to within ±0.5 dB up to -15 dBm of input power. The saturation input power (P_{sin}) corresponding to a 3-dB drop in gain is -9.5 dBm, giving a saturation output power (P_{sout}) of -6.1 dBm. The solid curve shows a fit based on rate equation analysis similar to [4]. Agreement with the measurements is found by using a 1.2-ns carrier lifetime and an apparent pump power absorption in the QW's of 480 cm^{-1}. This is a low value for absorption, which is expected, since losses are not taken into account. Significant losses, including scattering of pump light, as well as loss of carriers due to lateral diffusion in the QW's, are expected for external optical pumping and no carrier confinement. A comparison of the apparent absorption to an expected absorption near 5000 cm^{-1} indicates that the internal efficiency is in the order of 10%, which leaves room for improvement.

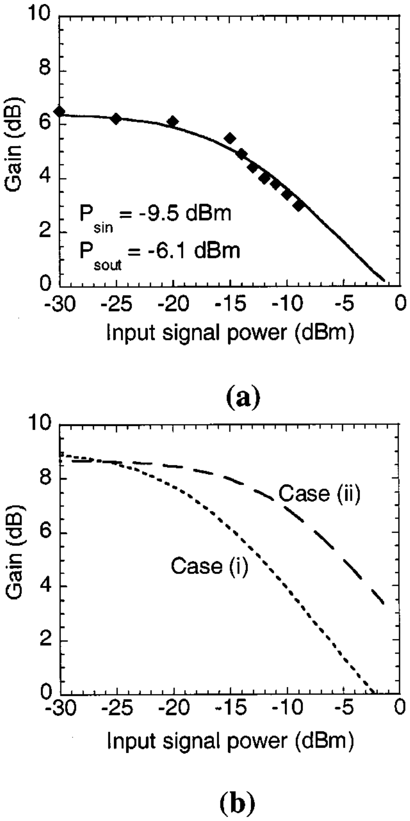

Fig. 3. (a) Gain as a function of input signal power for a pump power of 200-mW. The saturation powers correspond to a 3-dB gain drop. (b) Calculated gain versus input signal power. In case i) R_t is 0.985 and other parameters are the same as for the measurements [Fig. 3(a)]. In case ii) the absorption of pump power in the quantum wells is increased by 50% and R_t is 0.962.

Fig. 3(b) shows two calculated saturation curves for VCA's with different top mirror periods. For case i), $R_t = 0.985$ (14 mirror periods), the maximum gain is increased but Psout is decreased significantly. For case ii), $R_t = 0.963$ (11 mirror periods) and the pump power absorption in the QW's is increased by 50%. This gives the same maximum gain as in case i) as well as an increase in P_{sout}. This suggests that a more transmissive top mirror on our device (currently 13 periods, $R_t = 0.98$) may yield a higher maximum gain and a higher saturation output power if the pump power absorption can be increased by improving the internal efficiency.

The low top mirror reflectivity is compensated by a high single pass gain. To achieve this a large number of QW's is needed. In this type of structure, optical pumping is advantageous since it distributes the carriers more evenly among the wells as compared to electrical pumping. CW optical pumping

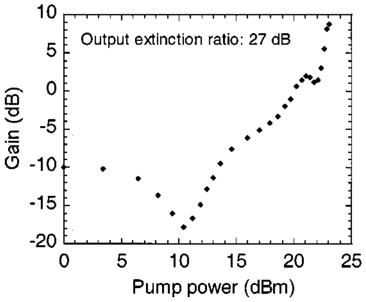

Fig. 4. Gain as a function of pump power, showing an extinction ratio of 27 dB. The input signal power is -25 dBm.

has already been successful in demonstrating high temperature operation in 1.3-μm [5] and 1.55-μm [6] VCSEL's. Integration of the pump laser [5] has demonstrated that optical pumping is a practical method to drive vertical cavity amplifiers.

Fig. 4 shows the gain as a function of pump power for an input signal of -25 dBm at 1317.5 nm. At zero pump power the output signal is pure reflection and the measured attenuation equals the loss in the system, which in this case is 10 dB. Since the collecting lens is focused on the active region and the reflected signal comes from the mirror surface, the lens is slightly out of focus, giving a higher loss than what was measured for the amplified signal. At a pump power of 10.5-dBm (11 mW) transparency is reached, allowing the signal to resonate in the cavity. Destructive interference occurs between the cavity mode and the signal reflected off the top mirror. This causes a dip in the output signal corresponding to -18-dB attenuation. As the pump power is increased, the top mirror reflection cannot cancel the amplified cavity mode and the device shows gain. A fiber-to-fiber gain of 9 dB was measured for 23 dBm (200 mW) of pump power. The shape of the curve is affected by the change in coupling efficiency as well as by the red-shift of the resonance cavity wavelength caused by the increased temperature. The red-shift as the pump power is increased from 11 to 23 dBm is 0.7 nm. The observed 27-dB change in output power for a 12.5-dB change in pump power suggests that modulation of the pump beam could be used to modulate the 1.3-μm signal, allowing the VCA to act as a switch [1], [7]. It has previously been demonstrated that high-speed direct modulation of 980-nm pump lasers can be performed [8].

For the present device the maximum amplifier gain is mainly limited by gain guiding and a low internal efficiency due to photon losses and lateral diffusion of carriers out of the active region. The next phase of this work will include etched posts and oxide apertures in the structure to provide index guiding as well as improved carrier confinement.

IV. CONCLUSION

A vertical cavity amplifier operating at 1.3 μm was demonstrated for the first time. We have measured 9.4-dB CW fiber-to-fiber gain, a gain-bandwidth product of 220 GHz, and -6.1-dBm saturation output power at room temperature. The extinction ratio of 27 dB obtained by modulating the pump power suggests that VCA's may make useful switches. Arrays of polarization independent amplifiers should be possible with this technology.

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