Long-Wavelength Vertical-Cavity Lasers and Amplifiers

Adil Karim, Student Member, IEEE, Staffan Björlin, Joachim Piprek, Senior Member, IEEE, and John E. Bowers, Fellow, IEEE

Invited Paper

Abstract—We report on advances in vertical-cavity surface-emitting lasers (VCSELs) and vertical-cavity semiconductor optical amplifiers (VCSOAs) operating at 1.3 and 1.55 μm. These devices have the potential to dramatically reduce manufacturing costs compared to traditional in-plane devices, while allowing for the possibility of producing integrated modules and arrays on wafer. A number of different technologies have been proposed and demonstrated for these devices. In this paper, we discuss the different materials systems used for distributed Bragg reflectors (DBRs) and active regions. Recent designs and results are summarized. Wafer bonded VCSELs and VCSOAs are examined in detail.

Index Terms—Distributed Bragg reflectors, Fabry–Perot resonators, laser amplifiers, optical pumping, optical resonators, semiconductor lasers, semiconductor optical amplifiers, surface-emitting lasers, vertical-cavity lasers, wafer bonding.

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting lasers (VCSELs) have been studied extensively for use in fiber-optic networks and as optical interconnects. The VCSEL offers many potential advantages when compared to the traditional in-plane laser. The most recognized advantage of the VCSEL is compatibility with low-cost wafer scale fabrication and testing methods. High-volume, low-cost manufacturing is of vital importance for the next generation of active optical devices. The VCSEL offers several other attractive characteristics that make it well suited for use in fiber-optic systems. These include a circularly shaped output beam for high coupling efficiency, high modulation bandwidths at low current levels, single mode operation, low power consumption and the potential for producing integrated modules and arrays on wafer.

Rapid progress in VCSEL development over the last decade has allowed 850- and 980-nm devices to be deployed in optical networks. The use of ion implantation for current confinement [1] has permitted the manufacture of highly efficient planar devices. The selective oxidation of AlGaAs alloys [2] has enabled major advances in threshold current and wallplug efficiency. In short-haul applications such as Fiber Channel and Gigabit Ethernet, the efficiency and high speed at low power of 850–980 nm VCSELs have made them the light source of choice. However, for longer reach applications, long wavelength (1.3–1.6 μm) laser diodes are required in order to operate with low loss and dispersion. Multimode 1300-nm VCSELs are of interest for potential use in short distance links. Single-mode VCSELs at 1300 and 1550 nm are widely anticipated as low-cost light sources in telecommunication networks. Ten Gigabit Ethernet standards are expected to focus on low-cost high-performance laser diodes such as long-wavelength VCSELs. Lower voltage operation should also be possible due to the narrower bandgap of long-wavelength materials.

Vertical cavity semiconductor optical amplifiers (VCSOAs) in the 1.3-μm band are also anticipated as components in optical networks. Advantages over conventional semiconductor optical amplifiers (SOAs) include improved fiber coupling efficiency, polarization insensitivity, and suitability for integration in high-density array architectures. Additional applications include switching and wavelength conversion. Long wavelength VCSELs and VCSOAs are similar in concept. The material and design sections in this paper may be applied to both types of devices.

Despite the obvious commercial incentives, long-wavelength VCSELs have been slower to develop than their short-wavelength counterparts. The main limitation has been unsatisfactory high-temperature operation. Maximum operating temperatures of 70 °C–85 °C are specified for sources in fiber-optic networks. Inherent material qualities of InP–InGaAsP such as low characteristic temperatures, high Auger recombination rates, and high intervalence band absorption have slowed the rate of progress [3]. The lack of a robust aperturing technique on InP similar to the lateral oxidation of AlGaAs on GaAs has limited the operating efficiency. Distributed Bragg reflectors (DBRs) with high thermal conductivity, high reflectivity, and in the case of current injection through the DBR, high electrical conductivity have proven difficult to fabricate on InP. A number of novel designs have been developed to overcome the limitations of the traditional InGaAsP material system. These include AlInGaAs active regions on InP [4], GaInNAs active region on GaAs [5], metamorphic GaAs mirrors grown on InP [6], multiple active regions [7], and antimonide DBRs [8]. The best high-temperature results to date have been achieved using wafer bonded GaAs–AlGaAs mirrors in both electrically pumped [9] and integrated optically pumped designs [10]. In this paper, we explore...
the progress made in long-wavelength VCSEL development. Distributed Bragg reflectors for long-wavelength devices are presented in Section II. Section III examines the development of active regions for long-wavelength VCSELS. Device structures and results are summarized in Section IV. Results from wafer bonded vertical-cavity lasers are presented in Section V. Design, operating conditions, and measurements for VCSEOS are contained in Section VI. In Section VII, we conclude and discuss the future of long-wavelength VCSELS.

II. DISTRIBUTED BRAGG REFLECTORS (DBRs)

The principal obstacle in long-wavelength VCSEL development has been the lack of high-quality DBRs that can be integrated with InP-based active regions. The performance demands for long-wavelength VCSELS are particularly stringent. High reflectivity, high thermal conductivity, and possibly high electrical conductivity must be included in the mirror design. These considerations must be balanced in order to optimize VCSEL performance.

Due to the short gain length of the cavity, VCSEL mirrors must have high reflectivities. The required reflectivities, usually greater than 99%, are obtained by alternating quarter wavelength layers of high and low refractive-index materials. These mirror stacks are known as distributed Bragg reflectors, or DBRs. The peak reflectivity of a DBR is given by [11]

\[ R = \left( \frac{1 - q \alpha p^{n-1}}{1 + q \alpha p^{n-1}} \right)^2 \left( 1 - \frac{q \alpha \lambda}{n_H (1 - p^2)} \right) \]

where \( q \), \( \alpha \), and \( p \) are refractive index ratios that characterize the incident, mirror, and exit media and have values less than 1. Factor \( q \) is the ratio of incident medium and first DBR section refractive indexes. Factor \( \alpha \) is the ratio of exit medium and final DBR section refractive indexes. Factor \( p \) is the ratio of low and high index mirror period refractive indexes. The number of mirror layers (not periods) is given by \( n \). \( n_H \) is the refractive index of the high-index DBR material. The free-space center wavelength is denoted by \( \lambda \) and \( \alpha \) is the effective absorption loss in the mirror. This absorption may be due to scattering in amorphous layers or absorption in semiconductor material. The maximum reflectivity of a DBR is limited by index contrast and absorption loss in the mirror. Fig. 1 compares peak reflectivity versus number of DBR periods for four different 1550-nm VCSEL mirrors.

The four mirror systems shown are \( \alpha \)-Si–SiO\(_2\), GaAs–AlAs, AlGaAsSb–AlAsSb, and InGaAsP–InP. The \( \alpha \)-Si–SiO\(_2\) DBR reaches peak reflectivity with a small number of mirror periods, but this value is limited by absorption in the deposited amorphous layers. Typical absorption coefficients for \( \alpha \)-Si are \( \alpha \approx 100 \text{ cm}^{-1} \) at 1550 nm and \( \alpha \approx 1000 \text{ cm}^{-1} \) at 1300 nm [12]. Dielectric mirrors require more complicated current injection schemes, limiting their usefulness. In addition, fabrication of a VCSEL with a deposited bottom DBR is a difficult process that involves substrate holing. Thermal conductivity is also an issue, as will be discussed later.

The epitaxially grown DBRs require a higher number of mirror periods to reach saturation, but are capable of reaching higher peak reflectivities than dielectric DBRs due to lower material absorption. The InGaAsP–InP system is the most commonly grown on InP, but is limited by low index contrast. Long growths are required to reach reasonable reflectivity levels. The AlGaAsSb–AlAsSb system has been studied recently for DBR applications on InP [8], [13]. This system features higher index contrast than InGaAsP–InP DBRs. GaAs–AlAs DBRs have slightly higher contrast than AlGaAsSb–AlAsSb DBRs, but have a significantly higher thermal conductivity. There is a 3.7% lattice mismatch between GaAs and InP, so GaAs–AlAs DBRs must be wafer bonded to [14], [15] or metamorphically grown on [16] InP-based active regions.

The thermal properties of DBRs are of considerable importance. The DBRs comprise the bulk of the VCSEL and must be able to effectively dissipate heat from resistive and lasing processes. This is particularly crucial for long-wavelength VCSELS due to the low characteristic temperatures of InP active regions. Dielectric mirrors typically exhibit low thermal conductivities, though materials such as MgO and Al\(_2\)O\(_3\) have been introduced with improved results [17]. The thermal conductivity of epitaxially grown mirrors depends greatly on alloy composition. Ternary and quaternary alloys have substantially lower thermal conductivities than binary mirrors, due to alloy scattering [18]. Interface scattering reduces thermal conductivity for all DBRs. Table I summarizes optical and thermal data for 1550-nm VCSEL DBRs. The values for \( n_H \)
and \( n_3 \) refer to the refractive indices of the first and second mirror materials listed in each row. The thermal conductivities of these materials are given by \( k_3 \) and \( k_3 \) in W/cm-K. The next column shows \( N \), the number of mirror periods required for 99% reflectivity for each DBR combination. The thermal resistance of a 99% reflective DBR with an area of 1000 \( \mu \text{m}^2 \) is given in the final column and denoted by \( R_{\text{th}} \) in K/W. The thermal resistance of a particular mirror stack is calculated by dividing the required mirror length by the area given above and the effective thermal conductivity of the mirror material. The exact thermal resistance of a VCSEL is determined by device geometry and operating conditions.

GaAs–AlAs and \( \alpha \text{-Si–Al}_2\text{O}_3 \) DBRs have the lowest thermal resistance of the 1550-nm DBRs described above. Unfortunately, neither of these mirrors can be grown on InP using traditional epitaxial methods. The mature growth fabrication technology, high optical quality, and low thermal resistance of GaAs–AlAs DBRs have spurred development in wafer fusion or metamorphic growth of these DBRs on InP-based active regions. Lateral oxidation of these GaAs–AlAs DBRs for current and mode confinement can dramatically improve performance compared to unapertured devices. The short wavelength success and long wavelength promise of GaAs-based DBRs have also encouraged the search for long wavelength active region materials such as GaAsSb [19] and InGaAsN [20] that can be grown on GaAs substrates.

Current supply through semiconductor DBRs is generally the simplest and most uniform method for injecting carriers into the VCSEL active region. However, doping semiconductor mirrors for current transport also increases the optical loss of the mirror, which limits the peak reflectivity. A careful balance must be struck between high reflectivity and low electrical resistance. The voltage across a semiconductor DBR is determined by the resistance of each mirror period and the potential difference across each of the large number of heterojunction barriers. The resistance of p-type DBRs is much greater than comparable n-type DBRs due to lower hole mobility and large valence band offsets. The resistance of both p- and n-type DBRs have been reduced by choosing appropriate interface grading and doping schemes for flat-band structures [21]. The doping levels must be chosen carefully, taking into account the free carrier absorption losses introduced at the design wavelength, particularly in p-type material. In p-type GaAs, the absorption coefficient dependence on hole concentration at 1550 nm is approximately linear and given by \( dx/dp = 29 \times 10^{18} \text{cm}^2 \), where \( p \) is the hole concentration in cm\(^{-3}\) [22]. The loss dependence in n-type GaAs is much smaller, with \( dx/dn = 5 \times 10^{18} \text{cm}^2 \), where \( n \) is the electron concentration in cm\(^{-3}\). Interface grading and doping schemes have met with considerable success in high wavelength VCSEL DBRs at lower doping levels than in short-wavelength devices. In order to avoid losses in p-type material, several groups have explored tunnel junction structures. These structures typically use n-type DBRs and a highly doped \( n^++/p^++ \) tunnel junction near the active region to convert electrons into holes [23], [24]. Intracavity contacts have also been explored. However, the lack of a robust apertureting technique on InP may limit efficiency and manufacturability.

The realization of high-performance long-wavelength VCSEL DBRs is a continuing goal. Unlike GaAs-based VCSELs where GaAs–AlGaAs DBRs are the standard, InP-based long-wavelength VCSELs being studied today use several different mirror materials. These DBR materials can be epitaxially grown, wafer bonded, or deposited. Due to the low single pass gain in long-wavelength VCSELs, these mirrors must have a near-optimal combination of high reflectivity, high thermal conductivity, and high electrical conductivity. Devices with wafer bonded GaAs–AlGaAs mirrors have shown the best performance to date, particularly at elevated temperatures. These devices feature oxide apertures that have enabled high-performance short-wavelength VCSELs. Rapid progress is being made in the development of InP-based devices with epitaxial mirrors, such as AlGaAsSb–AlAsSb. Research continues in a number of different directions, with several robust and manufacturable DBR fabrication techniques having already been demonstrated.

III. Active Regions

The requirements for long-wavelength VCSEL active regions are more demanding than for their in-plane counterparts. Vertical cavity devices typically have shorter gain regions and higher thermal resistances than edge-emitting lasers. These problems become even more pronounced at the elevated operating temperatures of 70 °C–85 °C specified for sources in fiber-optic networks. High-temperature operation of lasers with InP-based active regions has been more difficult to obtain than with short-wavelength GaAs-based active regions. However, recent developments in active region materials and design have facilitated a number of reports of 1.3- and 1.55-\( \mu \text{m} \) vertical-cavity lasers operating above room temperature. These active regions can be broadly classified into those grown on InP and on GaAs.

A. InP Active Regions

The InP-InGaAsP system is the most commonly used for emission in the 1.3–1.55-\( \mu \text{m} \) range. Edge-emitting lasers fabricated from these lasers have been studied extensively and are commonly used in fiber-optic networks. However, the InP system suffers from lower characteristic temperatures compared to GaAs lasers. At 1.3 and 1.55 \( \mu \text{m} \), laser performance is impaired by high Auger recombination rates, intervalence band absorption (IVBA), carrier leakage, free carrier absorption, and poor thermal conductivity [3]. Long-wavelength lasers in telecommunication networks are typically packaged with a thermoelectric cooler in order to mitigate the inherent temperature sensitivity of the device. However, in order for long-wavelength VCSELs to maintain a cost advantage over their in-plane counterparts, it is desirable that they be able to operate uncooled over the specified temperature range.

Progress in InP-based edge emitters has carried over into the VCSEL world. Early long-wavelength VCSEL active regions consisted of bulk InGaAsP [25], with an inevitable migration toward quantum-well devices [26]. The higher differential gain and lower carrier density required for transparency [27] in strained quantum-well active regions have provided the margin necessary to achieve continuous-wave (CW) operation at elevated temperatures. Due to the high gain requirements of VCSELs, it is desirable to use a large number of quantum wells. Advanced strain compensation techniques have been
developed in order to grow thicker strained active regions without introducing undesirable misfit dislocations. The highest reported operating temperature for an electrically pumped long-wavelength VCSEL of 85 °C was achieved using a strain compensated InGaAsP–InP active region [9].

An alternative to InGaAsP is AllnGaAs lattice-matched to InP. Active regions containing AllnGaAs should offer improved high temperature performance compared to InGaAsP. The conduction band offset for AllnGaAs, $\Delta E_c = 0.72 \Delta E_g$, is much greater than the offset for InGaAsP alloys, $\Delta E_c = 0.35 \Delta E_g$ [28, 29]. This should lead to improved electron confinement, increased hole transport, and enhanced differential gain, particularly at elevated temperatures. AllInGaAs active regions have been used to demonstrate CW operation of long-wavelength VCSELs at temperatures up to 40 °C [4] and separately with submilliampere thresholds [30]. Multiple AllnGaAs active regions have been used to increase differential efficiency, reducing the DBR performance requirements [7]. The lifetime of devices with Al-containing active regions may be an area of concern, although long lifetimes have recently been reported for edge-emitting devices [31].

B. GaAs Active Regions

The mature epitaxial and fabrication techniques developed for short-wavelength VCSELs on GaAs have inspired a number of efforts to develop long-wavelength active regions on GaAs. CW operation of a 1.3-μm VCSEL with a GaInNAs active region up to 55 °C was reported [32]. The GaInNAs system on GaAs has drawn attention in recent years for its potential in long-wavelength VCSEL applications as well as for improved high-temperature performance in edge emitters [33]. Although this materials system holds a great deal of promise, there are a number of issues that must be addressed in order to develop practical devices. A type II band lineup may limit lasing efficiency in GaInNAs devices. Nitrogen incorporation is made difficult by a miscibility gap that may limit operation at wavelengths much longer than 1.3 μm, although the possibility of extending the emission wavelength to 1.55 μm does exist. In addition, threshold current densities rise dramatically as the emission wavelength is increased beyond 1.2 μm. GaAsSb active regions on GaAs have also been explored for long-wavelength VCSEL applications [34] with room temperature CW operation at 1.23 μm reported [35]. Novel concepts such as quantum-dot active regions have been explored for extended wavelength emission on GaAs with 1.3-μm in-plane lasers and shorter wavelength VCSELs demonstrated to date [36, 37]. Quantum-dot active regions are attractive due to improved carrier confinement and the potential for efficiently scaling to smaller devices. The large demand for 1.3-μm VCSELs should continue to drive research on GaInNAs, GaAsSb, and quantum dot active regions, with the short-term goal of developing commercial devices.

IV. DEVICE DESIGN

The choice of active region and mirror materials represent only a handful of the considerations that must be taken into account when designing a long-wavelength VCSEL. Each mirror may be deposited, wafer bonded, or epitaxially grown. Epitaxially grown mirrors can be either lattice-matched or metamorphic. Current and mode confinement can be achieved with oxide apertures, ion implantation, or buried heterostructures. Current injection can be accomplished with a traditional p-n structure or with tunnel junctions to reduce p-type absorption losses. Intracavity contacts may also be used to reduce optical losses, but may result in unfavorable spatial distribution of carriers in the absence of current confinement. Optical pumping can be provided by a short-wavelength VCSEL wafer bonded to a long-wavelength cavity [10]. A summary of recent long-wavelength VCSEL results is shown in Table II.

It can be seen from Table II that a number of different approaches are being pursued in the development of long-wavelength VCSELs. The best high-temperature results to date have been achieved using InP–InGaAsP active regions and wafer-bonded GaAs–AlGaAs DBRs, both in optically pumped and electrically pumped configurations. Fig. 2 shows progress in maximum operating temperatures for long-wavelength VCSELs in recent years. The next section focuses on the design and performance of electrically pumped long-wavelength VCSELs with two wafer-bonded mirrors. In Section VI, we present results for an optically pumped vertical-cavity semiconductor optical amplifier (VCSOA). The material and design issues discussed above are equally relevant for amplifier design, although specific mirror reflectivities, doping levels, and the number of quantum wells vary significantly between optimized VCSELs and VCSOAs.

V. WAFER-BONDED LONG-WAVELENGTH VCLS

Wafer-bonded devices were the first electrically pumped long-wavelength VCSELs to operate continuous wave at room temperature [38]. In addition, wafer-bonded devices were the first to operate with submilliampere threshold currents [39]. Continued advances, including the introduction of oxide apertures, have enabled operation at elevated temperatures [40, 41]. The high thermal conductivity of GaAs–AlGaAs DBRs has made wafer fusion a potentially attractive means of fabricating long-wavelength VCSELs that meet commercial performance requirements. In this section, we report 85 °C CW operation of a 1528-nm VCSEL with an InP–InGaAsP active region and wafer-bonded GaAs–AlGaAs mirrors. A superlattice barrier was used to reduce defect density in the bonded active region.

The high pressure and temperature of wafer bonding can cause a reduction in the photoluminescence of multiple-quantum-well (MQW) structures. Dopant and point defect diffusion during the bonding process both contribute to this reduction in luminescence. In addition, defect migration from the bonding interface can generate nonradiative recombination centers in the bonded MQW region [42]. A superlattice defect-blocking layer has been introduced near the fused junction in order to mitigate the bonding effects. The luminescence of fused InGaAsP MQW structures has been preserved and even enhanced by the addition of this superlattice layer [43]. Dopants and defects that would ordinarily aggregate at the strained well–barrier interfaces migrate to the highly strained...
GaAs–InP interface during the bonding process. The increase in post-bonding luminescence can be attributed to blocking of defects migrating from the fused junction by the superlattice.

Vertical cavity lasers utilizing this superlattice barrier on the p-InP side of the p-InP–p–GaAs fused junction were fabricated. The superlattice consisted of four periods of p-type InP–InGaAsP with a 15-nm period. The device structure is shown in Fig. 3. The improved high-temperature operation is due in part to the presence of the superlattice barrier, which should improve gain at both room temperature and above compared to fused active regions without a superlattice barrier. It should be noted that high-temperature CW operation was achieved despite the introduction of the highly resistive superlattice layer and a high diode turn-on voltage which is due to poor contact formation. 35 devices that passed current were tested to determine their maximum operating temperature. All devices passing current on the wafer had maximum CW operating temperatures above 65 °C. A histogram of these results is shown in Fig. 6.

The top mirror was a 25.5 period p-type parabolically graded GaAs–Al_{0.9}Ga_{0.1}As DBR, with an oxide aperture for mode and current confinement. Device sizes fabricated were 7–13 μm, as determined by the oxide aperture. The active region contained six strained quantum wells. The 31-period GaAs–AlAs bottom mirror was undoped. The p-contact was on the top DBR, while the n-contact was on the n-cladding of the active region. Devices were tested in a p-up configuration with no special heat sinking. The room temperature cavity mode was at 1528 nm, while the gain peak was at 1542 nm. Despite the unfavorable mode-gain offset and high threshold voltage, continuous wave operation was achieved at temperatures as high as 85 °C. Room-temperature output power and voltage characteristics are

---

**TABLE II**

**SUMMARY OF LONG-WAVELENGTH VCSEL STRUCTURES AND RESULTS**

<table>
<thead>
<tr>
<th>Group</th>
<th>* (μm)</th>
<th>Active Region</th>
<th>Mirrors</th>
<th>Design</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of California, Santa Barbara</td>
<td>1.55</td>
<td>InGaAsP</td>
<td>Bonded</td>
<td>Oxide aperture</td>
<td>85°C CW, 0.65 mW output at 20°C, I_0=0.8 mA [31]</td>
</tr>
<tr>
<td>Gore Photonics</td>
<td>1.3</td>
<td>InGaAsP</td>
<td>Bonded</td>
<td>Optically pumped</td>
<td>80°C CW, 2.8 mW output at 20°C, I_0=5.0 mA [30]</td>
</tr>
<tr>
<td>Walter Schottky Institute</td>
<td>1.55</td>
<td>AlInGaAs</td>
<td>AlInGaAs/InAlAs, a-Si/MgF_2</td>
<td>Tunnel junction</td>
<td>40°C CW, 1.6 mW output at 20°C, I_0=0.85 mA [10]</td>
</tr>
<tr>
<td>Sandia National Laboratories</td>
<td>1.3</td>
<td>GaInNAs</td>
<td>GaAs/AlGaAs</td>
<td>Oxide aperture</td>
<td>55°C CW, 60 μW output at 20°C, I_0=1.5 mA [65]</td>
</tr>
<tr>
<td>Alcatel</td>
<td>1.55</td>
<td>InGaAsP</td>
<td>Metamorphic GaAs/AlGaAs, InGaAsP/InP</td>
<td>Tunnel junction, ion implant</td>
<td>45°C CW, 1 mW output at 20°C, I_0=13 mA [9]</td>
</tr>
<tr>
<td>University of California, Santa Barbara</td>
<td>1.55</td>
<td>AlInGaAs</td>
<td>AlGaAsSb/AlGaAs</td>
<td>Tunnel junction</td>
<td>Room temperature electrically pulsed [6]</td>
</tr>
<tr>
<td>UT Austin</td>
<td>1.15</td>
<td>InGaAs quantum dots</td>
<td>GaAs/AlGaAs, MgF/ZnSe</td>
<td>Oxide aperture</td>
<td>CW I_0=0.5 mA at 25°C [68]</td>
</tr>
</tbody>
</table>

---

**Fig. 2.** Progress in maximum operating temperatures of long-wavelength VCSELs.

**Fig. 3.** Wafer-bonded, top-emitting VCSEL device structure.
shown in Fig. 4. A family of $L-I$ curves for CW operation from 10 °C to 85 °C is shown in Fig. 5.

The maximum output power at 20 °C was 0.65 mW. Threshold currents as low as 1.0 mA were measured for 7-μm devices. Further improvements are expected for devices with reduced turn-on voltage and series resistance. Bonded devices have consistently shown an excess voltage drop of 1 V across the GaAs–InP p-p interface at current densities required for lasing. No such drop exists at the n-n junction. Alternative approaches include intracavity contacts, tunnel junction injection, or optical pumping. Next-generation devices should benefit from a more favorable mode-gain offset, along with improved current and carrier confinement.

VI. VERTICAL CAVITY SEMICONDUCTOR OPTICAL AMPLIFIERS (VCSOAs)

Low-cost, long-wavelength amplifiers are needed for a variety of applications in long haul, access, and central office applications. Semiconductor optical amplifiers (SOAs) are an alternative to fiber amplifiers and have been an area of intense research for many years. Conventional in-plane devices suffer from poor coupling efficiency to optical fiber, are typically sensitive to signal polarization, and are not yet priced competitively with fiber amplifiers. A vertical-cavity laser operated below threshold functions as a Fabry–Perot amplifier. These amplifiers share the same fabrication advantages as VCSELs. In addition, the transverse geometry provides insensitivity to polarization of the input signal, and low insertion loss yields a low noise figure. VCSOAs are attractive for a wide range of applications. They provide a low-cost alternative to fiber amplifiers for small network and fiber to the home (FTTH) applications. They are also attractive for optical processing such as switching [44], modulation [45], and wavelength conversion. VCSOAs have recently been presented operating at telecommunications wavelengths. A gain of 18 dB was reported for an electrically pumped VCSOA operating at 1.55 μm, measured at 217 K for an input signal of −45 dBm [46]. This VCSOA had a low saturation power and coupling losses are not included in the quoted gain. Fiber-to-fiber gain of 9.4 dB and a saturation output power of −6.1 dBm have been reported for an optically pumped VCSOA at 1.3 μm [47]. The optical bandwidth is naturally low for VCSOAs. Values from 0.03 to 3 nm have been measured. Narrow bandwidth provides a filter effect, but wider bandwidths are desired for low-precision input signals. A coupled cavity scheme has been proposed to increase the optical bandwidth [48]. High single-pass gain and reduced feedback are desired for VCSOAs. For a given pump power or drive current, higher mirror reflectivity results in higher amplifier gain. However, for high mirror reflectivities, maximum amplifier gain is limited by lasing threshold and a reduced mirror reflectivity allows for stronger pumping. For lower mirror reflectivities, amplifier gain is limited by the maximum achievable single pass gain. A MQW active region is required and stacked MQW active regions are desirable to provide high single-pass gain. The mirror reflectivity should be sufficiently low so that the available cavity gain can be fully utilized without the onset of...
Fig. 7. Design curves for VCSOA operated in reflection mode. By picking a target gain–bandwidth product, the required top mirror reflectivity can be extracted for the desired gain as can saturation power and pump current density.

lasing. The amplifier may be operated in either transmission or reflection mode, with separate design considerations required for each.

The optical bandwidth of the VCSOA, which is equivalent to the linewidth of the Fabry–Perot mode, increases with reduced pump level, $P/P_{th}$, where $P$ is the pump power and $P_{th}$ is the pump power required for lasing. The pump level can be decreased by reducing the pump power or the mirror reflectivity. High amplifier gain and wide optical bandwidth can be obtained simultaneously (high gain–bandwidth product) if the mirror reflectivity is reduced. The optical bandwidth is also affected by the cavity length. Cavity length and mirror reflectivity can thus be varied in order to tailor the optical bandwidth for different applications. Gain saturation occurs at higher input signal powers as the QWs are depleted of carriers. The saturation output power benefits from low mirror reflectivity. Extensive work has been done on predicting properties of VCSOAs [49], [50]. These trends are summarized in Fig. 7 for a reflection-mode amplifier. The gain–bandwidth product was calculated using a Fabry–Perot approach. The model used in the saturation power calculations is based on rate equation analysis. The bottom mirror reflectivity used in the calculations was 0.999. By picking a target gain–bandwidth product, the required top mirror reflectivity can be extracted for the desired gain as can saturation power and pump current density. Stars indicate results from the experiments discussed in this paper.

This set of design curves indicates potential for improved performance, including a gain–bandwidth product on the order of 1 THz with a gain of 20 dB and output saturation powers of up to +15 dBm. These improvements would require reduced top mirror reflectivity and increased pump power compared to the experimental results reported here. The large number of quantum wells required for high single-pass gain are difficult to pump evenly using electrical injection. Uniform distribution of carriers among the quantum wells is critical to device performance. Optical pumping has been used to evenly generate carriers in the wells. This allows for an undoped structure, reducing optical losses. Optical pumping has proven to be an efficient and commercially viable way to pump vertical-cavity structures [51], [52]. Integrated optical pumping is a key technology for the next generation of highly efficient low-cost VCSOAs.

A number of different VCSOA design schemes have been reported. Long-wavelength VCSOAs have been presented that employ wafer bonding, epitaxially grown DBRs, as well as dielectric DBRs. Oxide apertures [53] and proton implantation [54] for mode and current confinement were recently implemented into the design of 980-nm VCSOAs. Insulating InP regrowth for mode and current confinement has been used in the fabrication of long-wavelength VCSOAs [46].

The structure used in our experiments is shown in Fig. 8. Two undoped GaAs–Al$_{0.25}$Ga$_{0.75}$As DBRs were wafer bonded to a 1.3-μm MQW InP–InGaAsP active region. The active region consisted of three sets of seven compressively strained InAs$_{0.3}$P$_{0.7}$ QWs. The bottom mirror had 25 periods, while the number of periods in the top mirror was varied to optimize performance. No patterning or lithography was performed on the sample except to facilitate wafer fusion. The VCSOA was operated in reflection mode and optically pumped through the GaAs substrate by a 980-nm diode laser. A tunable 1.3-μm laser was used as an input-signal source. A circulator was used to separate input and output signals.

Fig. 9 shows fiber-to-fiber gain as a function of wavelength for a VCSOA with 12 top mirror periods ($R = 0.973$) and a $-20$-dBm input signal. The maximum gain measured was 11.3 dB. The full-width at half-maximum (FWHM) bandwidth is 100 GHz (0.6 nm), indicating that the VCSOA may be useful as an amplifying filter in wavelength division multiplexing (WDM) systems. Peak gain of up to 13 dB was observed.

Fiber-to-fiber gain as a function of input power is shown in Fig. 10 for 12 top mirror periods ($R = 0.973$). The pump power is 120 mW and the fiber-to-fiber gain is 10.2 dB in the unsaturated regime. The measured gain is flat to within ±0.5 dB up to −15-dBm input power. The saturation input power corresponding to a 3-dB drop in gain is −10.7 dBm, for a saturation output power of −3.5 dBm. The points indicate measured data, while the line is a curve fit based on the relation $G = G_0(1 + P/P_{sat})^{-1}$ where $G_0$ is the unsaturated gain and $P_{sat}$ is a fitting parameter.
Fig. 9. Fiber-to-fiber gain versus wavelength. Optical bandwidth of 0.6 nm (100 GHz) was measured at FWHM.

Fig. 10. Fiber-to-fiber gain versus input signal power. Saturation output power of –3.5 dBm was measured. This is the output power corresponding to a 3-dB drop in amplifier gain.

The modulating performance of the VCSOA was also investigated. At a pump power of 4 mW, there is nearly complete destructive interference between the reflected signal and cavity mode. As the pump power is increased, the device begins to show gain since the reflected signal no longer cancels the amplified cavity mode. Pump intensity modulation of 13 dB results in a 46-dB change in signal output power between amplified and cancelled states. These results are shown in Fig. 11. This suggests that the VCSOA may be of interest for switching applications. Switching with gain is advantageous since it affords the opportunity to compensate for coupling losses during signal distribution. In addition, the narrow VCSOA bandwidth prevents amplified spontaneous emission buildup in cascaded systems. High-speed direct modulation of 980-nm pump lasers has been previously demonstrated [55].

The amplifier presented here is limited by gain guiding and low internal efficiency. Photon losses and lateral diffusion of carriers out of the active region must be reduced. The design of mirrors and active region is not yet optimized. Future work will include improved mode and carrier confinement in the form of etched posts and oxide apertures.

Advances in fiber amplifier design have dramatically reduced costs for long-haul optical transmission and allowed system designers to extend the reach and capacity of point-to-point fiber links. However, the high cost of fiber amplifiers has limited adoption in short reach and metropolitan applications. Progress in 1.3-μm fiber amplifiers has trailed that of 1.55-μm amplifiers. VCSOAs operating at 1.3 μm are of interest for a number of applications. The low cost makes them attractive for mass production and network applications such as broadcast signal distribution, LANs and FTTH where fiber amplifier costs are prohibitive. VCSOAs offer increased functionality in applications such as modulation, switching, and wavelength conversion. Future development of these devices will benefit greatly from research done on long-wavelength VCSELs over the past decade.

VII. CONCLUSION

The last few years have seen tremendous progress in the field of long-wavelength vertical-cavity lasers. Techniques such as wafer bonding and metamorphic growth have been used to integrate dissimilar materials. Novel active region materials have been introduced with the hopes of improving high-temperature performance. The ultimate goal is a robust, manufacturable process to make low cost VCSEL arrays. Applications such as LANs, metropolitan area networks (MANs), and FTTH demand low-cost, high-performance sources. The rapid adoption of short-wavelength VCSELs for commercial applications indicates the market opportunity available for long-wavelength VCSELs capable of higher bit rates over greater distances. Inexpensive amplifiers and switches will be necessary to regenerate and route signals as optical networks expand their reach. Long-wavelength vertical-cavity devices
may be the low-cost components that enable this next generation of fiber-optic networks.

REFERENCES


KARIM et al.: LONG-WAVELENGTH VERTICAL-CAVITY LASERS AND AMPLIFIERS 1253


Adil Karim (S’97) received the B.S. degree in applied physics from the California Institute of Technology, Pasadena, in 1996 and the M.S. degree in optics from the University of Rochester, Rochester, NY, in 1997. He is currently pursuing the Ph.D. degree in electrical engineering at the University of California, Santa Barbara.

His research interests include long-wavelength vertical-cavity lasers and wavelength division multiplexing.

Staffan Björn received the M.S. degree in engineering physics from the Royal Institute of Technology, Stockholm, Sweden, in 2000. He is currently pursuing the Ph.D. degree in electrical engineering at the University of California, Santa Barbara.

His research interests include design and characterization of vertical-cavity semiconductor optical amplifiers and vertical-cavity lasers.

Joachim Piprek (SM’98) received the Ph.D. degree in solid-state physics from Humboldt University, Berlin, Germany in 1986. He worked in industry and academia on design and analysis of optoelectronic devices. He currently is an Adjunct Associate Professor at the University of California, Santa Barbara. His research interests include vertical-cavity lasers, novel semiconductor materials, and advanced computer simulation.

John E. Bowers (S’78–M’81–SM’85–F’93) received the M.S. and Ph.D. degrees in applied physics from Stanford University, Stanford, CA.

He is the Director of the Multidisciplinary Optical Switching Technology Center (MOST) and a Professor in the Department of Electrical Engineering, University of California, Santa Barbara. He is a Member of the Optoelectronics Technology Center and the NSF Science and Technology Center on Quantized Electronic Structures. His research interests are primarily concerned with high-frequency optoelectronic devices and physics. He has worked for AT&T Bell Laboratories and Honeywell before joining UCSB. He has published five book chapters, over 200 journal papers, over 200 conference papers, and has received 12 patents. Dr. Bowers is a fellow of the American Physical Society, a recipient of the IEEE LEOS William Streifer Award, and is Vice President for Conferences of IEEE LEOS. He is a recipient of Sigma Xi’s Thomas F. Andrew prize and the NSF Presidential Young Investigator Award and NSF Graduate Fellowship.