Invited Paper

Tunable vertical-cavity SOAs: a unique combination of tunable filtering and optical gain

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ABSTRACT
In this paper the design and performance of novel micromechanically-tunable vertical-cavity semiconductor optical amplifiers (VCSOAs) are presented. Theoretical design issues include overviews of the signal gain, wavelength tuning characteristics, saturation properties, and noise figure of these unique devices. Using general Fabry-Pérot relationships it is possible to model both the wavelength tuning characteristics and the peak signal gain of tunable VCSOAs, while amplifier rate equations are used to describe the saturation and noise properties. It is found that these devices follow many of the same design trends as fixed-wavelength VCSOAs. However, with tunable devices, the tuning mechanism is found to result in varying amplifier properties over the wavelength span of the device. Experimental results for three generations of devices are given. The culmination of this work is a new bottom-emitting design in which the optical cavity is inverted and the MEMS-tuning structure serves as the high-reflectivity back mirror. By suppressing the variation in mirror reflectance with tuning, this configuration exhibits a two-fold increase in the effective tuning range as compared with our initial devices—with a minimum of 5 dB fiber-to-fiber gain (12 dB on-chip gain) over a wavelength span of roughly 21 nm, from 1557.36 nm to 1536.43 nm. Furthermore, these devices exhibit saturation, bandwidth and noise properties similar to state-of-the-art fixed-wavelength VCSOAs, including a fiber-coupled saturation output power of -1.36 dBm and an average gain bandwidth and noise figure of 65.2 GHz and 7.48 dB.

Keywords: Fabry–Pérot resonators, laser amplifiers, MEMS, semiconductor optical amplifiers, surface-emitting lasers, vertical-cavity devices, wafer bonding.

1. INTRODUCTION
Vertical-cavity semiconductor optical amplifiers (VCSOAs) are an attractive alternative to existing amplifier technologies for use in fiber-optic communication systems such as metro-area networks and fiber to the home. In such applications, VCSOAs exhibit a number of advantages including a high coupling efficiency to optical fiber, polarization insensitive gain, decreased power consumption, the potential to fabricate 2-D arrays, and the ability to perform on-wafer testing. Additionally, by altering the composition of the active material, amplification may be achieved at nearly any desired wavelength, in contrast with the limited wavelength range of fiber amplifiers. Due to the filtering properties of the high finesse Fabry-Pérot (FP) cavity, VCSOAs exhibit a narrow gain bandwidth, typically limiting operation to the amplification of a single channel. This inherent filtering effect is advantageous, as it eliminates out-of-band noise and provides channel selection in multi-wavelength systems. Moreover, the narrow gain bandwidth eliminates the need for an optical filter after the amplifier making VCSOAs ideal as preamplifiers in receiver modules [1]. Recently, both optically and electrically-pumped long-wavelength VCSOAs have been demonstrated which operate in the telecom-relevant long-wavelength range from 1.3 to 1.5 µm [2]-[5]. However, for many applications, a narrow-band amplifier with a fixed center wavelength is of limited use. In CWDM systems for instance, the specifications for the transmitter wavelength is somewhat loose and all components in the system must tolerate variations in the signal wavelength due to temperature fluctuations. Additionally, tunable filters and ultimately tunable receivers are very attractive for channel selection in broadcast-and-select systems; the use of a tunable VCSOA in this case allows for simultaneous filtering and optical gain, with the added flexibility of a variable center wavelength. It is therefore of great interest to make tunable VCSOAs that can cover a wide wavelength range and at the same time be precisely adjusted to the desired wavelength.

Previously, temperature tuning of long-wavelength VCSOAs has been investigated [6], [7]. Unfortunately, temperature tuning is hampered by a slow time response and a limited wavelength range. A more promising approach is microelectromechanical (MEMS) tuning. In this case, mechanical alteration of the effective FP mode gives rise to tuning ranges greater than those that can be achieved by refractive index modulation. In contrast with temperature variation, MEMS-based tuning is capable of a rapid and low power response. Although little previous work has focused
specifically on MEMS-tunable VCSOAs (MT-VCSOAs), a number of research groups have developed a variety of other tunable vertical-cavity devices including vertical-cavity surface-emitting lasers [8]-[12], resonant-cavity light emitting diodes [13], asymmetric Fabry-Pérot modulators [14], and vertical-cavity filters [15]. Recently, both electrically and optically pumped vertical-cavity surface-emitting lasers (VCSELs) with >30 nm single-mode tuning ranges have been demonstrated [8], [9]. The majority of these structures have utilized electrostatic tuning, although thermal tuning is also frequently used [8]. As an extension of fixed-wavelength VCSOAs, we have developed the first widely tunable VCSOAs through the use of an integrated electrostatic actuator [16], [17]. Similar to previous generations of fixed-wavelength VCSOAs [2], MT-VCSOAs operate in reflection mode and are optically pumped. The major difference in the tunable devices is the incorporation of a micromachined membrane structure, which is suspended above an air gap within the top DBR. These devices utilize an integrated electrostatic actuator to vary the thickness of the air gap, resulting in a variation in the effective cavity length and continuous tuning of the resonant cavity mode.

Continuing the tradition of long-wavelength VCSOA research at UCSB, the MEMS-tunable amplifier project started in 2003 and led to the demonstration of the first micromechanically-tunable VCSOA in 2004 [16]. Including this initial demonstration, three generations of MT-VCSOAs have been developed. The second generation of devices employed an improved mechanical structure and was used to fully characterize this new class of devices [17]. Recently a third generation of devices has been completed. This design makes use of an improved optical cavity design, resulting in a significant increase in the effective tuning range, while exhibiting state-of-the-art gain, bandwidth, saturation and noise properties [18]. In this paper we will review the progress of MT-VCSOA research at UCSB. In Section 2, an overview of the general design issues and theoretical models for tunable vertical-cavity amplifiers is presented. The device structure and fabrication process is discussed in Section 3. In Section 4 we present the experimental testing procedure and present an overview of the results from three generations of MT-VCSOAs.

2. DESIGN OF MEMS-TUNABLE VCSOAS

In its simplest form the VCSOA is an SOA based on VCSEL technology. As with the VCSEL and the in-plane laser diode, the vertical-cavity geometry of VCSOAs gives rise to major differences in amplifier properties when compared to in-plane Fabry-Pérot SOAs (FP-SOAs).

2.1 General Design Issues

Due to the vertical-cavity geometry, the optical field in a VCSOA passes perpendicularly through the material layers, greatly reducing the active material length that the mode overlaps with. This reduced interaction length results in a significant reduction in the achievable single-pass gain. With in-plane SOAs, the active material length may be on the order of hundreds of micrometers, whereas in a VCSOA the combined thickness of the MQW layers may be on the order of hundreds of nanometers. The reduction in single-pass gain requires a corresponding increase in feedback necessary to achieve a desired gain level. As with VCSELs, this feedback is achieved by incorporating highly reflective distributed Bragg reflectors (DBRs) to form a FP cavity. The resulting feedback from the resonant cavity structure constrains the gain bandwidth to the linewidth of the FP mode, which is typically on the order of a nanometer or less.

The most significant difference when comparing VCSOAs and VCSELs lies in the reduced mirror reflectivities used in the resonant cavity structure, as well as the increased number of quantum wells necessary to achieve a high single-pass gain. In order to minimize the required threshold current in VCSELs strong feedback is desired. With VCSOAs on the other hand, reduced feedback is advantageous as it allows for high gain without the onset of lasing. VCSOAs therefore require a longer total active region length and lower mirror reflectivities than VCSELs. Low mirror reflectance allows for operation at higher carrier density and thus higher single-pass gain, resulting in a wider gain bandwidth, higher saturation power, and a reduced noise figure [19]-[21]. It is important to recognize that there is a limit to the lowest mirror reflectance that may be used; if the reflectance is too low the mirror losses will result in insufficient signal gain. With VCOSAs there exists an optimum design with an intermediate reflectance that allows for operation at high carrier density while at the same time avoiding exceeding lasing threshold.

The need for increased single-pass gain requires the incorporation of a large number of QWs in the FP resonant cavity. With VCSOAs a stacked multi-quantum-well (MQW) active region is used to increase the total active material length in the inherently short optical cavity. The large number of QWs typically used in VCSOAs makes it difficult to achieve a uniform carrier distribution throughout the active material with electrical injection. Optical pumping is an attractive way
to pump VCSOAs for a number of reasons. Optical pumping generates carriers in the QWs without the need for transporting the carrier through the structure. This results in a very uniform carrier distribution throughout the large number of QWs. It also allows the entire structure to be undoped, which simplifies growth and processing, and minimizes optical losses.

The basic structure of a VCSOA consists of an active region enclosed by two mirrors. The device can be optimized for operation in either reflection mode or transmission mode, as shown schematically in Fig. 1. In reflection mode, the VCSOA is designed to have one high reflectivity mirror (~100%), and the signal enters and exits from the same side of the device through a slightly transmissive mirror. In this configuration a bottom mirror reflectivity close to unity is desired and the top mirror reflectivity can be modified to vary the properties of the VCSOA. In transmission mode operation both mirrors are slightly transmissive and the signal is injected on one side of the device and collected on the other. Ultimately, the choice of the mode of operation, either reflection mode or transmission mode, will depend on the intended application. For the work presented here all devices are designed for reflection mode operation.

![Fig. 1](image)

**Fig. 1** Schematic of the operating modes of VCSOAs, including transmission mode (left) and reflection mode (right).

### 2.2 Signal Gain of FP-SOAs

A convenient approach for modeling VCSOAs is to replace the DBRs by hard mirrors of the same reflectance and use an effective cavity length, which includes the penetration of the optical field into the DBRs [22]. With this method we can utilize the well-known FP relationships to describe signal gain and wavelength tuning characteristics of MT-VCSOAs. Because the FP equations contain only a small number of unknowns, it is possible to generate a relatively general description of the device properties. The FP approach is carried out by considering an incoming optical field and summing all of the field components exiting the cavity. To obtain the power gain, the fields are squared and the total output power is divided by the input power. Using this technique, it is possible to model the gain spectrum of a VCSOA for both reflection mode \((G_r)\) and transmission mode \((G_t)\) operation [23]:

\[
G_r = \frac{(\sqrt{R_t} - \sqrt{R_b} g_s)^2 + 4\sqrt{R_t} R_b g_s \sin^2 \phi_s}{(1 - \sqrt{R_t} R_b g_s)^2 + 4\sqrt{R_t} R_b g_s \sin^2 \phi_s}
\]

\[
G_t = \frac{(1 - R_t)(1 - R_b) g_s}{(1 - \sqrt{R_t} R_b g_s)^2 + 4\sqrt{R_t} R_b g_s \sin^2 \phi_s}
\]

\[
\phi_s = 2\pi n c L_e \left( \frac{1}{\lambda} - \frac{1}{\lambda_R} \right)
\]

Here, \(R_t\) is the top mirror reflectance, \(R_b\) is the bottom mirror reflectance, \(g_s\) is the single-pass gain, and \(\phi_s\) is the single-pass phase detuning. The phase in (3) gives the deviation of the signal wavelength \(\lambda\) from the resonant wavelength of the cavity \(\lambda_R\), with the effective index of the optical cavity \(n_e\) and the total cavity length \(L_e\). When the signal wavelength is identical to the FP resonance, \(\phi_s = 0\) in (3), and (1) and (2) can be used to calculate the peak gain. It is important to note that in each case the amplifier must operate under the condition of \(g_s^2 R_t R_b < 1\) to avoid exceeding lasing threshold. With vertical-cavity devices standing wave effects must be considered. In this case gain enhancement results from the placement of the active material layers at the peaks of the optical standing wave. The majority of VCSOA active regions utilize some sort of periodic gain structure in order to maximize the achievable single-pass gain. Typical long-wavelength active materials include InGaAsP and AlInGaAs lattice matched to InP, although recently 1.3-µm VCSOAs utilizing GaInNAs QWs lattice matched to GaAs have been demonstrated [5], [24].

### 2.3 Tunable Cavity Design

In addition to standing wave effects, the short cavity length of the VCSOA leads to an inherently large axial mode spacing. Because of this fact, continuous, mode-hop-free tuning is achievable over a relatively wide wavelength span. To realize wavelength tuning of the device, we use a MEMS-based optical cavity design similar to that used in tunable
VCSELs, RCLEDs and photodetectors. These devices contain a variable thickness air gap within the resonant cavity structure that allows for changes in the effective cavity length. With MEMS tunable vertical-cavity devices, there exists a number of distinct optical cavity structures. Here, we will focus on the design used for our MT-VCSOAs, namely the semiconductor coupled cavity design (SCC-design). Additional tunable cavity designs may be found in [25], [17]. For the following all lengths are given as optical thicknesses.

![Fig. 2 (a) Schematic of the semiconductor coupled cavity design. The mirror reference planes have been defined so that the DBR begins with a high index layer (black line). Additionally, the mirrors are designed to give a $\pi$ phase shift at $\lambda_c$, which is defined as the wavelength at which the air gap is of the ideal thickness and the DBRs meet the Bragg condition, and $m$ and $k$ are integers. The circulating arrows indicate the position of maximum intensity of the optical standing wave. (b) Three-dimensional schematic of the MT-VCSOA, highlighting the four-leg design of the suspended DBR structure. With an applied voltage the membrane is attracted towards the substrate, reducing the air-gap thickness and blue shifting the VCSOA resonant cavity mode.

The SCC-design utilizes a semiconductor cavity containing the active material of length a multiple of $\lambda_c/2$, along with an air gap of thickness near an odd multiple $\lambda_c/4$. In this design the air gap acts as a low index layer of the top DBR as seen in Fig. 2(a). The large index step afforded by the air gap allows for enhanced reflectance of the tunable mirror structure, as well as maximum overlap of the optical field with the active region. With the SCC-design, the increased optical overlap is achieved at the expense of a decreased wavelength tuning efficiency, resulting in a reduced wavelength shift for a given change in air-gap thickness. In a tunable vertical-cavity amplifier, the tradeoff of a decreased tuning range for an increased optical overlap is preferred, as it is necessary to achieve the highest possible single-pass gain in these devices. With the SCC-design, the coupling between the passive air cavity and semiconductor cavity containing the active material leads to complications in the tuning mechanism. These complications include changes in the tunable mirror reflectance and confinement factor with tuning, which may result in variations in the peak gain, bandwidth, saturation and noise figure over the wavelength tuning range of the amplifier.

To achieve wavelength tuning of the VCSOA cavity mode it is necessary to construct a mechanical system to physically alter the thickness of the air gap. The most efficient realization of such a structure involves the use of an integrated micromechanical actuator. Using a MEMS-based tuning element, various actuator designs are possible—the most commonly used being electrostatic and thermal actuators. A schematic of the four-leg design of the MT-VCSOA is included in Fig. 2(b) above. For a low power, high speed tuning response the most effective actuator design is the integrated electrostatic actuator. In its simplest form the electrostatic actuator can be seen as a pair of parallel capacitor plates separated by an air gap of a specified thickness, in which one or more of the plates is freely suspended. Because the suspended structure serves as the top mirror for the device, the thickness of the membrane and air gap will be predetermined by the optical design of the DBR. Nevertheless, additional processing steps may be used to modify the thickness of the mechanical suspensions (legs), allowing increased freedom in design of the mechanical structure [26].

With an applied bias, the Coulomb force is exerted on the plates due to the charge separation present. If one, or both, of the plates is free to move, then the electrostatic force results in a change in the air-gap thickness, leading to a variation in the effective cavity length of the VCSOA. The displacement of the electrostatic actuator is highly non-linear, due to the changing force with displacement. Due to this inherent non-linearity, the electrostatic actuator will exhibit only a limited range of valid solutions. As a rule of thumb, for displacements less than 1/3 of the initial air-gap thickness, there exists a stable equilibrium position for the actuator. Beyond this distance, the electrostatic force overwhelms the restoring force and leads to pull-in of the actuator. At this point the membrane will be forced into physical contact with the opposite electrode, resulting in a permanent fusing of the pair due to the effects of stiction, or damage due to
capacitive discharge if there are no insulating materials separating the electrodes. A detailed description of the theoretical modeling and characteristics of our electrostatic actuator design is presented in [17], [27].

With the SCC-design, the variation in thickness of the air gap allows for wavelength tuning by modifying the effective cavity length of the device. Continuing with the FP modeling approach, the tunable mirror structure can be described using the standard relationships for a FP interferometer. The effective reflectance may then be written as [28]:

\[
R_{\text{eff}} = \frac{R_c + R_m - 2\sqrt{R_c R_m \cos(\phi_g)}}{1 + R_c R_m - 2\sqrt{R_c R_m \cos(\phi_g)}}
\]  

(4)

where \(R_m\) is the power reflectance of the membrane DBR, \(R_c\) is the reflectance of the interface between the semiconductor cavity and the air gap, \(\phi_g\) is the round trip phase in the air gap = \(2\beta_g L_g + 2(\beta \rho - \gamma_m) L_m\), \(\beta_g = 2\pi \lambda / \lambda_m\) = \(2\pi \lambda / L_m\), \(L_m\) is the penetration depth into the membrane DBR, and \(L_m\) is the thickness of the air gap. Similarly, the reflected phase is given by the relation [25]:

\[
\phi_{\text{eff}} = \tan^{-1} \left( \frac{\sqrt{R_c (1 + R_c) - R_m (1 + R_m) \cos(\phi_g)}}{R_c (1 + R_c) - R_m (1 + R_m) \sin(\phi_g)} \right).
\]  

(5)

From (4), we see that the reflectance of the tunable mirror structure varies with the round trip phase in the air gap. Most notably, with the SCC-design the effective reflectance will be reduced with tuning due to phase interference from multiple reflections within the air-cavity structure.

The wavelength tuning characteristics of the SCC-design are derived by treating the air-gap-DBR structure as a mirror with a tunable phase shift. The resonant wavelength of the optical cavity occurs when the round trip phase of the semiconductor cavity and the DBRs (including the contribution of the air gap in the tunable mirror) is equal to an integer multiple of \(2\pi\). For small changes in \(L_m\) centered on the ideal air-gap thickness, the shift in wavelength of the resonant cavity mode corresponding to a given change in air-gap thickness is given by [25]:

\[
\frac{\Delta\lambda}{\lambda_m} = \frac{\gamma_{\phi} \Delta L_m}{L_m + L_c + \gamma_{\phi} (L_m + L_c)}
\]  

(6)

with the phase coupling factor \(\gamma_{\phi} = \frac{d\phi_{\text{eff}}}{d\phi_g}\). The denominator in (6) describes the total cavity length of the device, including the penetration depth into the bottom DBR \(L_c\), the length of the semiconductor cavity \(L_m\), and the effective length of the tunable mirror structure, which is the sum of the air-gap thickness \(L_m\) and the penetration depth into the membrane DBR \(L_m\), scaled by \(\gamma_{\phi}\). From (6), we find that the wavelength shift of SCC-design is directly proportional to the phase coupling factor, thus for a given change in air-gap thickness a device with a large \(\gamma_{\phi}\) will exhibit a larger wavelength tuning rate. The response of \(R_{\text{eff}}, \phi_{\text{eff}},\) and \(\gamma_{\phi}\) as a function of the thickness of the air gap, is shown in Fig. 3.

In this plot it has been assumed that \(R_c = 0.32,\) and \(R_m = 0.95.\) With these values \(\gamma_{\phi}\) exhibits a minimum value of about 0.28 when the air-gap thickness is equal to an odd multiple of \(\lambda_m / 4.\) In this case, any change in the air-gap thickness will result in a change in the effective cavity length equal to roughly 0.28 times the change in air-gap thickness, scaled by the total cavity length. Within this linear tuning regime, the small value of the phase coupling factor reduces the effects of tilt or additional loss that may be caused by non-uniformity of the membrane DBR, by reducing the total penetration depth of the optical field into the tunable mirror structure. For large membrane displacements, the phase coupling factor increases dramatically, reaching a maximum value of 3.61 at integer multiples of \(\lambda_m / 2.\)

With the MT-VCSOA, the decrease in air-gap thickness upon actuation leads to a reduction in the effective cavity length and a blue shift in the peak gain wavelength. For the SCC-design, the competing phases from the multiple reflections present in the air-cavity structure lead to a varying phase coupling factor (Fig. 3) and a non-linear wavelength shift with respect to the change in air-gap thickness, as in Fig. 4. This non-linearity is further exaggerated by the non-linear voltage deflection characteristics of the electrostatic actuator. Using (6) it is possible to compare the maximum tuning range around the center wavelength of the cavity for a variety of air-gap thicknesses, given the limited travel of the electrostatic actuator [29]. Assuming that the displacement is limited to roughly 1/3 of the initial air-gap thickness and centered at \(\lambda_m\), the approximate wavelength shift for is found to be 6.4 nm for a \(\lambda_m / 4\) air gap, 24.2 nm for a 3\(\lambda_m / 4\) air gap, and 53.1 nm for a 5\(\lambda_m / 4\) air gap. Here the maximum estimated wavelength tuning range is highlighted as the shaded area of the figure. By increasing the air-gap thickness the total wavelength tuning range may be extended. However with an increasing air-gap thickness the required tuning voltage will also increase due to a decrease in the
applied force. Furthermore, given a longer cavity length, the FP mode spacing is reduced, decreasing the single-mode tuning range.

Fig. 3 Effective mirror reflectance, reflected phase, and phase coupling factor of the SCC-design as a function of the thickness of the air gap, with $R_c = 0.32$ and $R_m = 0.95$.

Fig. 4 Resonant wavelength as a function of the air-gap thickness. The varying phase coupling factor in (6) results in a highly non-linear tuning response.

2.4 Signal Gain of MT-VCSOAs

Using the relationships presented above it is possible to derive expressions describing the effects of the tunable mirror structure on the peak gain of the VCSOA. Combining (1) for the peak reflection gain (with $\phi_s = 0$), with the relationships describing the reflectance of the tunable mirror structure (4), the peak signal gain of a reflection mode SCC-design tunable VCSOA may be written:

$$G = \left( \frac{R_{\text{eff}} - g_s}{1 - R_{\text{eff}} g_s} \right).$$  

(7)

Here we have assumed that the device contains a highly reflective fixed mirror ($R_b = 1$) and a slightly transmissive membrane DBR ($R_m < 1$). This expression shows that the peak gain is dependent on the effective reflectance of the tunable mirror structure, which is a function of the membrane reflectance, the cavity-air interface reflectance, and the round trip phase of the air gap. Another option for the SCC-design reflection mode tunable VCSOA would be to use the tunable mirror structure as the highly reflective mirror and use the fixed substrate DBR as the transmissive mirror. In the limit of $R_m = 1$ in (4), $R_{\text{eff}} \to 1$ regardless of the phase of the air gap, and the expression for the peak gain becomes:

$$G = \left( \frac{R - g_s}{1 - R g_s} \right).$$  

(8)

with $R_t$ defined as the power reflectance of the transmissive mirror in this case. Thus, by using the MEMS tuning structure as the high reflectivity mirror in the reflection mode SCC-design tunable VCSOA, the peak gain relationship becomes independent of both the reflectance of the cavity-air interface and the round trip phase of the air gap. In this configuration the MEMS tuning element may be described as a Gires-Tournoi interferometer, essentially a FP interferometer with a unity back reflector.

2.5 Saturation and Noise Properties

At high input signal powers, or at operation near threshold, the large photon density present in the resonant cavity will lead to carrier depletion and saturation of the gain medium. A common approach to modeling the saturation properties of VCSOAs involves the use of steady-state rate equations for carriers and photons [19]-[21]. Compared with the well-known relationships used to analyze lasers, the rate equations for FP amplifiers include an additional term for the input signal and a modified mirror loss term—with VCSOAs the mirror loss is a function of the both mirror reflectance as well as the amplifier gain [30]. Using the procedure outlined in [20], the steady-state forms of the amplifier rate equations may be used to determine the saturation characteristics of the MT-VCSOA [17]. For high saturation output power it is desirable to maintain a large carrier density to photon density ratio as the signal power is increased. This can be achieved by increasing the active volume (large pump/signal spot sizes), reducing the cavity photon density (through increased mirror loss), and increasing the carrier density in the active region (high pump power).
The noise figure (NF) of an optical amplifier describes the signal-to-noise ratio (SNR) degradation that occurs as a signal passes through the device. In general, the amplification of an optical signal adds undesired power fluctuations due to the inherent randomness of the optical processes involved. The output amplified spontaneous emission (ASE), and hence the signal-spontaneous beat noise is greatly affected by the mirror reflectivity. Considering signal-spontaneous beat noise to be dominant [21], [31], the noise factor, $F$, defined as input SNR over output SNR (the noise figure is defined as $NF = 10\log(F)$ and expressed in decibels), is given by $F = 2n_{sp}(G-1)/G$, which for high signal gain ($G>>1$) reduces to $F = 2n_{sp}$. Here, $n_{sp}$ is the population inversion parameter and $\chi$ is the excess noise coefficient, which describes signal-spontaneous beat noise enhancement due to finite mirror reflectivity. $\chi$ takes a value of one for zero reflectivity and values higher than one for finite mirror reflectivities. An excess coefficient of one can be obtained for VCOSAs if the mirror reflectivities are chosen properly [31]. For a reflection mode device, $\chi$ depends only on the bottom mirror reflectivity and for values of $R_b$ greater than 0.999, $\chi \approx 1$. The population inversion parameter $n_{sp}$ equals unity for complete inversion and increases for incomplete inversion. Thus, it is desirable to operate at high carrier densities in order to minimize $n_{sp}$. Unfortunately, high carrier densities may lead to lasing; it is therefore important to reduce the mirror reflectance in order to allow for full inversion without reaching the point of self-sustaining oscillation, while still maintaining sufficient reflectance to achieve the desired level of signal gain. Note that the important parameter when regarding noise in any amplifier application is the fiber-to-fiber noise figure. In this instance the superior coupling efficiency of VCOSAs, as compared to in-plane SOAs, becomes a clear advantage.

3. FABRICATED DEVICES

In total three generations of MT-VCSOAs have been developed. The initial devices represent the first demonstration of a purpose built tunable VCOSA. The second generation of devices has been developed in order to improve the limitations in the mechanical structure of the initial devices, such as the high required tuning voltage and limited wavelength tuning range. The final generation of devices focuses on changes to the optical design of the MT-VCSOA in order to increase the effective tuning range and realize more consistent amplifier properties with tuning. All MT-VCSOAs developed in the course of this work operate in reflection mode and are optically pumped. Additionally, these devices utilize an InP-based stacked MQW active region that is bonded to two GaAs/AlGaAs DBRs via a direct wafer bonding procedure [32]. Using wafer bonding it is possible to combine the high gain, long-wavelength InP-based active material, with the excellent thermal properties and high index contrast of GaAs-based DBRs. The use of optical pumping allows for the generation of a uniform carrier distribution given the large number of QWs.

![Cross-sectional schematic of the material structure for Generations 1 & 2 (left) and Generation 3 (right). All devices operate in reflection mode and are pumped with a 980 nm laser; wavelength tuning is achieved with the SCC tunable cavity design.](image)

3.1 Material Structure

The first and second generations of devices utilize a high reflectivity bottom mirror and the signal input/output occurs through the transmissive MEMS-tunable DBR, as in Fig. 5. The major changes between the initial devices and the second generation comprise updates to the mechanical design of the electrostatic actuator and in this case both utilize an identical epi-material structure. In these devices the active region contains five sets of five compressively strained AlInGaAs QWs (25 in total) placed at the peaks of the standing optical wave in a $5\lambda_c/2$ cavity, with the peak gain designed to be at 1545 nm at room temperature. The bottom mirror is a 30-period GaAs/Al$_{0.98}$Ga$_{0.02}$As DBR with a calculated reflectance of 0.999, while the top DBR consists of either 4 or 5 periods of GaAs/Al$_{0.98}$Ga$_{0.02}$As on top of a
3\(\lambda_c/4\) n\(^+\) GaAs layer, a 5\(\lambda_c/4\) (optical thickness in air) Al\(_{0.98}\)Ga\(_{0.02}\)As sacrificial etch layer and a \(\lambda_c/4\) n\(^+\) GaAs layer directly above the active region.

As grown, the AlGaAs top mirror wafer contains a 5 period DBR on the GaAs membrane layer; during the fabrication procedure one period is removed using a wet chemical etching process to create the 4 period devices. Selective removal of the AlGaAs sacrificial layer results in the formation of the 5\(\lambda_c/4\) air gap, which acts as the first low index layer in the top DBR. The combination of the semiconductor active region and the top mirror containing the air gap form the SCC-design tunable cavity. The peak reflectance of this structure is calculated to be 0.968 for 4 periods on top of the GaAs structural layer, and 0.976 for 5-periods, including the contributions of the air gap as a low index layer. During the fabrication procedure a thin layer of tensile-stressed (260 MPa) SiN\(_x\) is deposited on top of the membrane and legs. This film creates a slight tensile stress in the structure to ensure the flatness of the free-standing membrane.

The details of the electrostatic actuator design are covered in [17], [27]. The basic structure consists of a n\(^+\)/p\(^+\)/i/n\(^+\) diode. Here the GaAs membrane layer and the \(\lambda_c/4\) GaAs layer closest to the active region are doped n\(^+\). The sacrificial AlGaAs film is comprised of 200 nm of p\(^+\) AlGaAs, followed by 1750 nm of intrinsic AlGaAs. A reverse bias across the structure results in a Coulomb force that displaces the membrane towards the substrate, reducing the air-gap thickness and blue-shifting the resonant cavity mode. It is important to note that with this actuator, it is only possible to reduce the air gap, thus it is only possible to blue shift the resonant wavelength. With the doping scheme described here, the tuning diode is designed to have a reverse breakdown voltage of 60 V.

In the third generation of devices the optical cavity has been inverted—in this design the MEMS tunable mirror structure is used as the high reflectivity mirror and the fixed substrate DBR is used for signal input/output. These devices incorporate an updated active region design. In this iteration the InP-based stacked MQW active region contains four sets of seven 0.85% compressively strained AlInGaAs quantum wells (28 in total) placed at the top four peaks of the standing optical wave in a 5\(\lambda_c/2\) cavity. The last standing-wave peak overlaps with a 276-nm thick InP heat spreading layer. The addition of the binary heat spreading layer is important as the active region incorporates absorbing -0.55% tensile strained AlInGaAs barriers. Again the PL peak is designed to be at 1540 nm at room temperature.

The resonant cavity design in the third generation of devices (Fig. 5) has been updated in order to minimize changes in the mirror properties with tuning. For Generation 3, the transmissive bottom DBR consists of 14 periods of GaAs/Al\(_{0.92}\)Ga\(_{0.08}\)As, with a maximum theoretical power reflectance of approximately 0.94. To reduce stray reflections from the substrate to air interface we use a \(\lambda_c/4\) SiO\(_x\) anti-reflection coating (ARC) with a measured power reflectance of 0.014 within the wavelength span of the MT-VCSOA. From the top down the high reflectivity MEMS-tunable mirror structure consists of 15 periods of GaAs/Al\(_{0.92}\)Ga\(_{0.08}\)As, a 3\(\lambda_c/4\) n\(^+\) GaAs membrane layer, an approximately 5\(\lambda_c/4\) (optical thickness in air) Al\(_{0.85}\)Ga\(_{0.15}\)As sacrificial etch layer and a \(\lambda_c/4\) n\(^+\) GaAs layer directly above the active region. The maximum power reflectance of the top mirror is calculated to be 0.996, including the contribution of the air gap and the loss from the doped layers that make up the electrostatic actuator.
For the patterned portions of the Generation 3 devices, including the DBR pillar and sacrificial layer, we use a reduced Al content to slow the oxidation rate and improve the reliability. This is especially important for the nearly 2-µm thick sacrificial AlGaAs layer, where oxidation in ambient will lead to cracking of the support material beneath the GaAs membrane. The doping scheme for the electrostatic actuator structure remains unchanged from the previous devices, however, the Al composition of the sacrificial etch material (making up the p⁺ and intrinsic layers in the diode) has been reduced from 98% in Generations 1 and 2, to 85% for the Generation 3 devices.

The basic fabrication procedure for MT-VCSOAs may be found in [16]-[18]. Basically, these devices are fabricated using a combination of direct wafer bonding and AlGaAs-based micromachining. Micrographs of a completed Generation 1 device are presented in Fig. 6.

4. EXPERIMENTAL RESULTS

To facilitate the mechanical analysis of the MEMS tuning structure, the initial air-gap thickness is measured using a vertical-scanning interferometer, and the quasi-static and dynamic displacement of the membrane structure is characterized using a laser Doppler vibrometer [27]. For optical testing, an external-cavity tunable laser diode operating near 1550 nm is used as a signal source and the input signal power is controlled to be -35 dBm by a variable optical attenuator. As MT-VCSOAs operate in reflection mode, the signal is coupled into and out of the transmissive mirror and a circulator is necessary to separate the amplified output. For the top-emitting structures (Generations 1 and 2) a long-wavelength fiber focuser is used for signal input/output through the top mirror and a second fiber focuser is used to couple the 980 nm pump through the bottom DBR. For the bottom-emitting Generation 3 devices a single long-wavelength fiber focuser is used for both the signal and pump injection. After multiplexing with a WDM coupler, both the 980-nm pump and long-wavelength signal are coupled through the bottom of the sample with a single 1550-nm fiber focuser. Due to the wavelength dependent focal length of the lens, there is a narrow range of stage positions where the pump spot size is slightly larger than that of the signal [18].

All measurements are made with the fiber coupled amplified output signal on a calibrated optical spectrum analyzer (OSA) at a resolution bandwidth of 0.1 nm. The coupling loss through the setup is measured to be approximately 7 dB, including back-coupling of the output into the focuser (5.8 dB) and the round trip through the WDM coupler and circulator (1.2 dB). The OSA is used to record the characteristics of the VCSOA as a function of pump and signal power, tuning bias, and wavelength. By recording the individual gain spectra over the device tuning range, and fitting the data with (1), the variation in peak gain, top mirror reflectance, and single-pass gain may be determined as a function of the resonant wavelength MT-VCSOA. With these devices the tuning range is recorded by noting the wavelength of the ASE peak as a function of the bias applied to the electrostatic actuator.

4.1 Generation 1

The typical wavelength tuning response for the first generation of MT-VCSOAs can be seen in Fig. 7. In this device the membrane is displaced by 340 nm with a reverse bias of 57 V. As expected, the deflection shows a parabolic dependence with the applied voltage and the experimental data matches well with the values generated by a simple one-dimensional electromechanical model. The 340-nm displacement results in a continuous blue-shift of the resonant cavity mode from 1590 nm to 1569 nm. With direct measurements of the membrane displacement, the resonance wavelength of the device can be calculated using (6). Here the tuning response follows the theoretical values extremely well; the points of largest error exhibit a red-shift in wavelength due to heating from the high pump power, which is not taken into account in the model. The high required tuning voltages result from a non-ideal initial air-gap thickness. Here, the increase in the air-gap thickness results from stress related deformation of the mechanical support structure. Measurements reveal a much larger air gap than the ideal 5λc/4 design of 1950 nm. The actual air-gap thickness measured for the device presented here is 3911 nm, due to stress related deformation of the undercut support structure.

Fig. 8 presents the theoretical and experimental pump power required for 10 dB device gain (3 dB fiber-to-fiber), as well as the extracted mirror reflectance as a function of the resonant wavelength of the optical cavity. The reflectance data is generated by fitting the individual gain spectrum curves for each tuning bias, while the required pump power is estimated by combining the carrier rate equation with the peak gain relationship presented in (7). As shown in the plot, the MT-VCSOA must be tuned from 1590 nm to 1580 nm before 10 dB of device gain is observed. Device gain larger than 10 dB is measured for wavelengths between 1580 nm and 1569 nm, yielding an effective tuning range of 11 nm. A maximum device gain of 17 dB is measured at 1570 nm.
Over the tuning range the calculated top DBR reflectance varies from 86.8% at the initial cavity mode, to 97.6% near the breakdown voltage of the diode (measured to be 57 V). Because of the non-ideal membrane deflection, the initial air gap results in an optical thickness near a multiple of $\lambda_c/2$. At this point the reflection from the first air-semiconductor interface and the reflection from the bottom of the membrane are nearly out of phase. As the device is tuned, the decreasing air-gap thickness begins to approach an odd multiple of $\lambda_c/4$, and the reflected waves begin to add in phase, leading to a rapid increase in reflectance of the top mirror structure. Additionally, as the cavity mode is tuned closer to the active material gain peak less pump power is needed to reach the same gain level.

Fig. 9 shows the MT-VCSOA gain spectrum at various tuning voltages and pump powers, with an input signal power of -35 dBm. The solid lines are calculated curve fits based on (1). By varying the applied bias on the electrostatic actuator, the narrow gain spectrum of the VCSOA may be swept over the wavelength tuning range of the device. For these devices we record a minimum bandwidth of 32.6 GHz at 1569.3 nm. In this case the decrease in bandwidth at shorter wavelengths is due to the increased top mirror reflectance as shown in Fig. 8. Conversely, at longer wavelengths the reduced top mirror reflectance results in a broadening of the amplifier gain spectrum.

4.2 Generation 2

The best performance parameters measured with the first generation of MT-VCSOAs was at least 10 dB of device gain (3 dB fiber-to-fiber) over a tuning range of 11 nm, as well as a peak signal gain of 17 dB (10 dB fiber-to-fiber) at 1570 nm. Although these devices were successful in demonstrating the concept of a tunable VCSOA, the mechanical design exhibited a number of limitations including excessively high tuning voltages and poor device lifetimes. To overcome these limitations a second generation of MT-VCSOAs was developed utilizing a revised mechanical structure. The updated mechanical structure greatly reduces the required tuning voltage, increases the wavelength tuning range, and markedly improves the reliability of the devices.
Fig. 10 SEM image of the updated tunable VCSOA mechanical design. Here a low-temperature SiO$_2$ film has been patterned by liftoff to reduce excessive undercutting of the sacrificial material below the support structure.

For the revised mechanical design an additional liftoff step is added prior to release in order to constrain the free edges of the mechanical support structure and avoid excessive undercutting of the sacrificial material below the supports [33]. For the liftoff procedure a low temperature (100° C) SiO$_2$ layer is deposited using inductively-coupled plasma enhanced chemical vapor deposition, as demonstrated in Fig. 10. Additional changes include a radiused support structure, in order to reduce the effects of stress concentration, and an enlarged DBR pillar to increase the rigidity of the membrane.

Fig. 11 Resonant cavity mode shift and membrane displacement as a function of the applied tuning bias.

With the updated mechanical structure, the total membrane displacement is improved, while at the same time, the required operating voltage is largely reduced, as compared with the first generation of devices [16]. As seen in Fig. 11, we record a total displacement of 455 nm with the application of 29 V to the tuning diode. These results are typical for the updated mechanical structure. With this actuator design, the application of 25 V results in a membrane displacement of approximately 250 nm and a corresponding ASE wavelength shift of 53.8 nm, as shown in Fig. 11. The large decrease in the required tuning voltage is attributed to the better control over the air-gap thickness found with the new actuator design. With the previous generation of devices the deformation of the support structure caused the air gap to nearly double in thickness [16]. By constraining the support structure against out of plane deformation, the initial plate separation is now better controlled, leading to a large reduction in the required tuning voltage for the revised mechanical structure, as well as a significant increase in the overall wavelength tuning range.

Although the updated mechanical design is capable of very large total wavelength spans, the effective tuning range remains unchanged from the best results of Generation 1. From measurements of the amplifier gain spectrum (Fig. 12) it is apparent that the peak gain decreases markedly with tuning. Upon further investigation it was found that the largely varying mirror properties over the wavelength span of the device were responsible for the limited effective tuning range. With VCSOAs the mirror reflectance is crucial in determining the characteristics of the amplifier, including the gain, bandwidth, saturation, and noise figure [19]-[21], [17]. With MT-VCSOAs the use of the coupled cavity tuning structure may result in largely varying mirror reflectance as a function of the round trip phase of the air gap, as can be seen in (4). With the SCC-design the varying reflectance is caused by the changing magnitude of interference from the multiple reflections within the air gap. With an ideal air-gap thickness near $\lambda_c/4$ the multiple reflections add in phase,
leading to a peak in the effective reflectance. Upon tuning, the air-gap thickness is varied, and begins to approach a multiple of $\lambda_c/2$, eventually reaching a position where the reflection from the suspended DBR and semiconductor-air gap interface are 180° out of phase, resulting in a minimum in the effective mirror reflectance. From the perspective of the semiconductor cavity, the destructive interference leads to a reduced effective mirror reflectance as the air-gap thickness is deviated from its ideal value.

Combining (4) and (6), it is possible to plot the effective reflectance of the SCC-design air-gap-DBR structure as a function of the resonant wavelength of the VCSOA, as shown in Fig. 13. In this plot we have used $R_s = 0.32$ and theoretical curves are generated for a number of membrane reflectance values. Here we are assuming that the center wavelength of the tunable mirror structure is the same for all devices. Because the experimental data was recorded for different samples, slight non-uniformities in the epitaxial growth procedure may shift the ideal value of $\lambda_c$. Along with the theoretical curves we have included the data collected by curve fitting the gain spectra using (1) for samples with 4 and 5 period DBR pillars. For lower membrane reflectance values the roll-off in mirror reflectance with tuning becomes quite severe. With the 4-period DBR pillar reflectance changes of nearly 10% are possible over the tuning range. Also included in Fig. 13 is the variation in mirror reflectance for a typical SCC-design tunable VCSEL with a peak effective reflectance of 0.997 for the tunable mirror structure [26]. Over the same wavelength range $R_{\text{eff}}$ reduces only slightly to 0.995. Compared with the mirror requirements in a VCSEL, the lower reflectivities necessary with the VCSOA lead to a much larger change in mirror reflectance as the air gap is varied from its ideal thickness. In this case the variation in reflectance will greatly diminish the wavelength span over which acceptable amplification may be achieved.

4.3 Generation 3

Although the updated mechanical design developed for the second generation of devices was capable of rather larger ASE wavelength shifts and required only modest tuning voltages, the effective tuning range of these devices was still limited to approximately 10 nm. Following an in-depth analysis of the properties of the resonant cavity [17] it was found that the main limitation to the effective tuning range of these top-emitting structures is the roll-off in the tunable mirror reflectance with variations in the air-gap thickness. In these devices the variation in mirror properties with tuning is exaggerated by the low reflectance required for the transmissive mirror structure. To overcome this limitation we proposed that the optical cavity be inverted and the MEMS-tunable DBR structure be used as the high reflectivity mirror, while the fixed substrate DBR be used as the transmissive mirror for signal input/output [17]. In this light we present a third generation of MT-VCSOAs utilizing a revised optical cavity design that greatly increases the effective tuning range and exhibits more constant amplifier properties with tuning. For the bottom-emitting devices of Generation 3 the major modifications to the fabrication procedure include the addition of an evaporated SiO$_x$ quarter-wave transformer as an ARC, a revised wet etch for the selective removal of the Al$_{0.85}$Ga$_{0.15}$As sacrificial layer, and a reduction of the actuator film stress.

Fig. 14 presents the gain spectra of a bottom-emitting MT-VCSOA for an optical pump power of 83 mW and a stage temperature of 15 ºC. As seen in the figure, the device is capable of at least 5 dB fiber-to-fiber gain (12 dB on-chip gain) over a 21 nm wavelength span, with a maximum applied voltage of 10.5 V. The pull-in instability of the
An electrostatic actuator is found to be the limit of the overall wavelength tuning range. We record a peak fiber-to-fiber gain value of 11.2 dB (18.2 dB on-chip gain) at 1548.00 nm. By fitting the individual gain spectra with the standard relationship for a reflection-mode Fabry-Pérot amplifier (1), we can extract the mirror reflectance values as well as the single-pass gain as a function of the resonant wavelength of the VCSOA [17]. Note that with increased pump power, the device could not be brought to lasing threshold. From theoretical fitting of the gain spectra we find that the average single-pass gain is 3.5% over the tuning range at an optimal pump power of 83 mW. Combining this with the extracted mirror reflectance, the device is operating at an average of 97.8% of the single-pass gain required to reach threshold.

![Gain spectra over a >20 nm range at 15 °C for a constant pump power of 83 mW and a maximum tuning bias of 10.5 V.](image)

In addition to the wide effective tuning range, the Generation 3 devices also exhibit excellent amplifier characteristics. From Fig. 15 we measure a maximum fiber-coupled saturation output power of -1.36 dBm at 1554.69 nm, with an unsaturated fiber-to-gain of 9.17 dB (16.17 dB on-chip gain). This value is comparable to the record high saturation output power of 0.5 dBm measured for our fixed-wavelength devices [34] and is attributed to the low reflectivity of the transmissive mirror and the relatively large spot sizes used in the test setup. From Fig. 15, the average gain bandwidth of the device is 65.2 GHz over the 21-nm tuning range. Optical measurements of the amplifier noise [31] reveal a fiber-coupled noise figure of 7.48 dB for an average fiber-to-fiber gain of 8.95 dB. These properties are similar to state-of-the-art fixed-wavelength VCSOAs, confirming that the tuning mechanism does not sacrifice overall device performance. The calculated curves are based on the theoretical models developed in [17].

![Saturation output power and gain bandwidth as a function of resonant wavelength at 15 °C for a pump power of 83 mW.](image)

![Comparison of the peak fiber-to-fiber gain at a constant pump power for top- and bottom-emitting MT-VCSOAs. Here we define the wavelength of peak gain as the center wavelength of the optical cavity.](image)

Previously, the best peak gain performance measured for our MT-VCSOAs was at least 3 dB fiber-to-fiber gain (10 dB on-chip gain) over 11 nm using a top-emitting configuration with a transmissive tunable DBR [16]. These devices required large variations in pump power to maintain a constant signal gain, due to the significant variation in reflectance (>10%) with tuning—arising from the destructive interference of the multiple reflections within the passive air cavity [17]. By inverting the optical cavity and using the MEMS-tuning structure as the high reflectivity mirror we see a
significant increase in the width of the peak gain envelope, as in Fig. 16, due to the more constant mirror properties with tuning, as predicted in [17]. For the bottom-emitting devices, the tunable mirror reflectance varies from a maximum value of 0.993 to a minimum of 0.986, a difference of only 0.7% over the 21-nm tuning range.

CONCLUSIONS
Vertical-cavity semiconductor optical amplifiers (VCSOAs) have numerous potential applications in fiber-optic communication systems including use as preamplifiers, optical switches, and modulators. As small form-factor 2-D arrays, VCSOAs are a low-cost alternative to existing amplifier technologies. The inherent filtering effect of the high-finesse Fabry-Pérot cavity eliminates the need for an optical filter after the amplifier, making VCSOAs ideal as preamplifiers in high bit-rate receivers. For application in reconfigurable optical networks it is of interest to develop tunable VCSOAs that can cover a wide wavelength range and be precisely adjusted to match the wavelength of the desired input signal. Furthermore, because VCSOAs are capable of simultaneous amplification and spectral filtering, the addition of tunability allows for the creation of wavelength agile filters with the added benefit of optical gain.

As an extension of fixed-wavelength devices, we have developed the first widely-tunable VCSOAs through the integration of a MEMS-based electrostatic actuator. In contrast with temperature tuning, the micromechanical actuator used in our MT-VCSOAs is capable of rapid, low power and wide wavelength tuning. During the course of this work three generations of MT-VCSOAs were developed. Building upon the knowledge gained from previous structures the final generation of devices exhibit state-of-the-art long-wavelength VCSOA properties, along with the added flexibility of wide wavelength tuning. For these devices a new bottom-emitting design was developed in which the optical cavity is inverted and the MEMS-tuning structure serves as the high-reflectivity back mirror. By suppressing the variation in mirror reflectance with tuning, this configuration exhibits a two-fold increase in the effective tuning range as compared with our initial devices—with a minimum of 5 dB fiber-to-fiber gain (12 dB on-chip gain) over a wavelength span of roughly 21 nm, from 1557.36 nm to 1536.43 nm. Additionally, we record saturation, bandwidth and noise properties similar to state-of-the-art fixed-wavelength VCSOAs, including a fiber-coupled saturation output power of -1.36 dBm and an average gain bandwidth and noise figure of 65.2 GHz and 7.48 dB respectively. Through the use of an improved electrostatic actuator design, the maximum required tuning voltage has been reduced to 10.5 V, a five-fold reduction compared with the first generation of MT-VCSOAs.

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