Wavelength selection in MEMS tunable vertical-cavity SOAs

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Abstract: We analyze the tuning characteristics of MEMS tunable vertical-cavity semiconductor optical amplifiers. Completed devices exhibit 10 dB device gain over an 11 nm tuning range.

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1. Introduction

Long-wavelength vertical-cavity semiconductor optical amplifiers (VCSOAs) are attractive as a low-cost alternative to erbium doped fiber amplifiers (EDFAs) and conventional in-plane SOAs for use in fiber optic communication systems. The vertical-cavity geometry of VCSOAs allows for the fabrication of 2-D arrays of amplifiers, and permits on-chip testing. In this way, VCSOAs may be fabricated with high yield and low cost. As shown previously, the high finesse Fabry-Pérot (FP) cavity of VCSOAs results in a narrow gain bandwidth [1]. This inherent filtering effect is advantageous, as it eliminates out-of-band noise and provides channel selection in multi-wavelength systems. The narrow gain-spectrum eliminates the need for an optical filter after the amplifier, thereby further reducing cost [2]. Furthermore, the circular symmetric geometry of the vertical cavity results in high coupling efficiency to optical fiber. These properties make VCSOAs especially promising for optical preamplification of high-bitrate receivers. At high bit rates (10Gb/s, 40Gb/s, and higher), avalanche photodetectors are limited by their gain-bandwidth product, and in this regime optical preamplification is advantageous. However, in low-cost systems, uncooled sources are typically used, and the signal wavelength can vary over a fairly wide range. If the signal wavelength deviates only slightly from the peak gain wavelength of the VCSOA, distortion of the signal may result. It is therefore of great interest to make tunable VCSOAs that can cover a wider wavelength range and be precisely adjusted to match the wavelength of the signal.

Temperature tuning of long-wavelength VCSOAs has previously been investigated [3], but a more promising method is microelectromechanical (MEMS) tuning. In this case mechanical alteration of the resonant wavelength gives rise to tuning ranges greater than those that can be achieved by refractive index modulation. The use of MEMS tuning is a popular mechanism for wavelength selection in vertical-cavity devices, including vertical-cavity surface-emitting lasers [4-6], resonant-cavity light emitting diodes [7], asymmetric Fabry-Pérot modulators [8], and vertical-cavity filters [9]. By integrating a MEMS based tuning element with a VCSOA, it is possible to control the FP cavity mode by mechanically altering the position of a suspended distributed Bragg reflector (DBR).

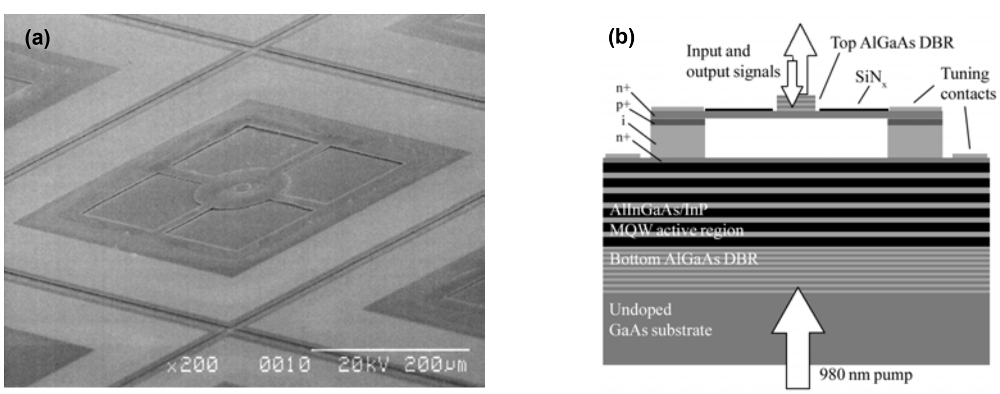

Fig. 1 (a) Electron micrograph of a released MT-VCSOA device. (b) Cross-sectional schematic of the MT-VCSOA structure

Two options exist for mechanical wavelength tuning, including direct cavity length modulation, which requires an anti-reflection coating within the cavity, and phase tuning of a DBR structure containing a tunable air gap (coupled-cavity design). Although easier to implement, phase tuning leads to non-linear tuning effects over the wavelength range of the device. In this design, the presence of the fixed semiconductor-air interface leads to varying top mirror reflectivity, due to interactions between the fixed phase reflection of the interface and the reflected phase from the suspended mirror structure. Other issues that must be taken into account include changes in optical overlap with the active region and the active material gain spectrum over the device tuning range. This work explores the wavelength tuning characteristics of long-wavelength MEMS tunable VCSOAs (MT-VCSOAs) fabricated using GaAs-based micromachining techniques in conjunction with GaAs to InP wafer bonding.

2. MT-VCSOA Design

Fig. 1 shows an electron micrograph as well as a cross-sectional schematic of the MT-VCSOA. The device utilizes an InP-based active region bonded to two AlGaAs DBR mirrors. The active region contains fives sets of five compressively strained AlInGaAs quantum wells (QWs) placed at the peaks of the standing optical wave in a 5/2-λ cavity. The peak gain of the active region is designed to be at 1545 nm at room temperature. The bottom mirror consists of 30-periods of MBE grown $GaAs/Al_{0.98}Ga_{0.02}As$ with a calculated reflectivity of 0.999. The top DBR consists of 4 periods of $GaAs/Al_{0.98}Ga_{0.02}As$ on top of a 3/4-λ n^+ GaAs layer, a 5/4-λ (optical thickness in air) $Al_{0.98}Ga_{0.02}As$ sacrificial etch layer and a 1/4-λ n^+ GaAs layer directly above the active region. This structure forms a 5.5 period DBR including the air gap as a low index layer. The top mirror design allows for maximum reflectivity, as well as increased optical overlap with the QWs, at the expense of reduced tuning due to the aforementioned coupled-cavity effects. The MT-VCSOA is designed to be pumped optically, and to operate in reflection mode.

As shown in the schematic, the GaAs membrane and the 1/4-λ GaAs layer closest to the active region are doped n+. The material directly below the membrane support structure is comprised of 200 nm of p+ $Al_{0.98}Ga_{0.02}As$, followed by 1750 nm of intrinsic $Al_{0.98}Ga_{0.02}As$. A reverse bias across this n^+/p^+/intrinsic/n^+ diode creates an electrostatic force that displaces the suspended membrane down towards the substrate, reducing the air gap thickness and phase shifting the upper DBR structure, resulting in a blue-shift of the resonance wavelength. The diode is designed to have a reverse breakdown voltage of 60 V.

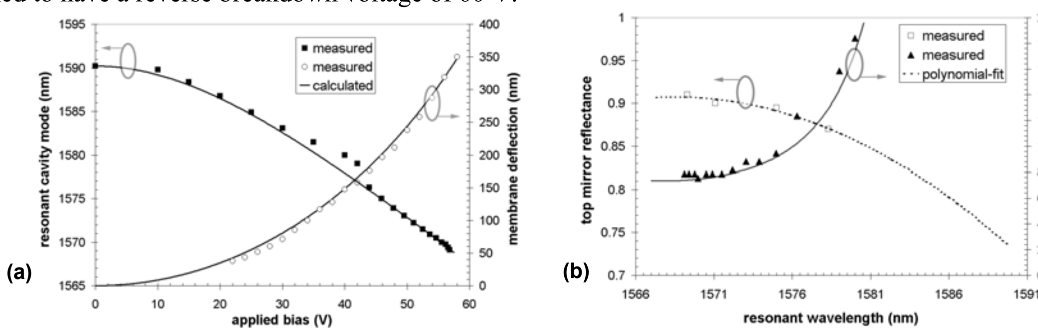

Fig. 2 (a) Tuning characteristics of the MT-VCSOA, including resonant wavelength and membrane deformation with applied bias. (b) Required pump power for constant 10 dB gain, and top mirror reflectance as a function of wavelength.

3. Device testing and results

Following processing, the air-gap thickness is measured using a white light interferometer. In this case the devices show a much larger air-gap than the ideal 5/4-λ 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. The dynamic deflection of the released membrane is measured using a laser Doppler vibrometer. As shown in Fig. 2, the membrane is displaced by as much as 340 nm with a reverse bias of 57 V (breakdown voltage of the diode). As expected, the deflection shows a parabolic dependence with the applied voltage and the experimental data matches closely with the values generated by a one-dimensional electromechanical model similar to that described in [10]. Using the measured deflection data, the resonance wavelength of the device can be calculated. As shown in Fig. 2, the resonant cavity mode blue-shifts from 1590 nm to 1569 nm with a tuning bias of 57 V (340 nm displacement). The measured resonance wavelength 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.

For optical testing, an external cavity tunable laser diode is used as a signal source, while the input signal power is controlled by a variable optical attenuator. The signal is coupled into and out of the top of the device through a fiber focuser. A circulator is used to separate the two signals and we use an optical spectrum analyzer to monitor the output signal. A 980 nm laser, which is coupled in through the bottom DBR by another fiber focuser, serves as the optical pump. The coupling loss through the setup is measured to be about 7 dB. Two alternatives exist for characterizing the amplifier properties of the MT-VCSOA, including constant gain and constant pump power operation. In the first case, the optical pump power is varied to achieve a constant value of 10 dB device gain (3 dB fiber-to-fiber) over the tuning range. The results of this experiment can be seen in Fig. 2. Because of the competing phases from the multiple air-semiconductor interfaces the reflectivity of the phase tunable DBR increases as the device wavelength is blue shifted (increasing tuning bias). Over the tuning range the top DBR reflectance varies from 85.7% at the initial cavity mode, to 90.7% near the breakdown voltage of the diode. Because of the non-ideal deformation of the support structure, the initial air gap results in an optical thickness near a multiple of 1/2-λ. 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, resulting in reduced reflectivity values. As the device is tuned, the decreasing air gap thickness begins to approach an odd multiple of 1/4-λ, and the reflected waves begin to add in phase.

Included in Fig. 2 is the theoretical and experimental pump power required for 10 dB device gain. The required pump power is estimated by combining the reflection mode FP gain equation with the carrier rate equation assuming below saturation conditions. These relationships have been shown to be very effective for modeling the properties of VCSOAs [1-3]. As seen 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 a tuning range of 11 nm. A maximum device gain of 17 dB is measured at 1570 nm. As the cavity mode is tuned closer to the QW gain peak, less pump power is needed to reach the same gain. In addition to the reduced mirror reflectivity, the roll-off in material gain and the non-ideal optical overlap of with the active region give rise to the high pump power required at long wavelengths.

In the second case we analyze the constant pump power (80 mW) characteristics of the MT-VCSOA over the tuning range, as shown in Fig. 3. As the device is tuned to shorter wavelengths the optical bandwidth decreases, reaching a minimum value of 46.3 GHz at 1568 nm. This decrease in bandwidth is attributed to the increased top mirror reflectance at higher tuning bias values. Also shown is the peak gain of the MT-VCSOA over the device tuning range. In this case the estimated maximum gain is 14.3 dB at 1568 nm with 80 mW of pump power. The peak of the device gain curve is dictated by the active material gain spectrum and the top mirror reflectivity as a function of wavelength. Included in Fig. 3 is the MT-VCSOA gain spectrum at various tuning voltages and pump power values. The solid lines are calculated curve fits based on the FP equations as described in [1] and [3]. This plot verifies the decrease in optical bandwidth at shorter wavelengths.

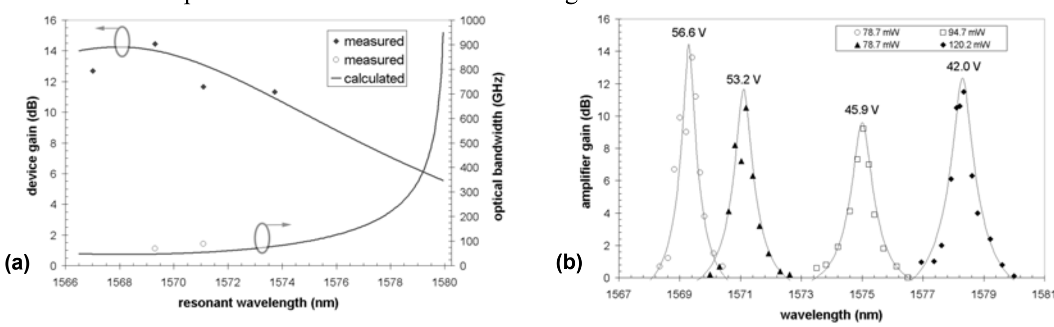

Fig. 3 (a) Peak device gain and optical bandwidth of the MT-VCSOA over the device tuning range. (b) Gain spectrum of the MT-VCSOA at various tuning bias values.

4. Summary

The wavelength tuning characteristics of a microelectromechanical tunable vertical-cavity semiconductor optical amplifier have been investigated. The device is fabricated using a combination of GaAs to InP wafer bonding and GaAs-based micromachining techniques. Completed devices have resulted in a minimum of 10 dB of amplifier gain (3 dB fiber-to-fiber) over 11 nm of tuning, with a peak amplifier gain of 17 dB at 1570 nm.

5. References

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