

Observation of bistability in a Vertical-Cavity Semiconductor Optical Amplifier (VCSOA)

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Abstract: We report, the first time to our knowledge, an observation of optical bistability in a Vertical-Cavity Semiconductor Optical Amplifier (VCSOA) operated in reflection mode. Counterclockwise hysteresis loops are obtained over a range of initial phase detuning and bias currents. One hysteresis loop is observed experimentally with an input power as low as 2 μW when the device is biased at 98% of its lasing threshold. We also numerically simulate the optical bistability and obtain good agreement with our experimental observations. Bistable VCSOAs significantly advances the prospect of dense 2-D array of low switching-intensity all-optical logic and memory elements.

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OCIS codes: (190.1450) Bistability; (250.5980) Semiconductor optical amplifiers

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1. Introduction

Optical bistability in semiconductor optical amplifiers (SOAs) has been studied extensively in view of the potential applications in optical logic and all-optical signal processing [1,2]. Optical bistability refers to the situation in which two stable optical output states are associated with a single input state, depending on the switching history. The first observation of optical bistability in a SOA was reported in 1983 [3]. Since then, optical bistability in SOAs has been reported at all communication wavelengths with switching power ranging from several to hundreds of microwatts [4,5]. Researchers seeking to utilize the low input switching energy and the presence of optical gain have demonstrated optical logic and optical memory functions based on the optical bistability in SOAs [6].

So far, all experiments reported in the literature have been conducted with in-plane SOAs, in which the light input/output direction is parallel to the substrate. With in-plane devices, the possibility of the large-scale integration is limited. In order to overcome this shortcoming, Adams *et al.* have proposed the investigation of optical bistability in vertical-cavity semiconductor optical amplifiers (VCSOAs), because arrays of VCSOAs are inherently easy to produce [7]. Furthermore, they have speculated that proposed VCSOAs would show the advantage of more tolerance on initial phase detuning due to their short cavity length.

In the past few years, VCSOAs have drawn increasing research attention [8,9]. As compared to in-plane SOAs, they exhibit several advantages including higher coupling efficiency to optical fibers and lower noise figure due to their circular geometry and small dimensions, respectively. Previously, we have reported optical gain of 16 dB in a non-optimized 850 nm VCSOA [10]. In this paper, we report the first observation of the optical bistability in a VCSOA operated in reflection mode (input signal enters and exits from the same side of the device.) The results show that the optical hysteresis loop can be obtained with input power as low as 2 μ W when the device is biased close to its lasing threshold. Furthermore, the experimental observations are in good agreement with the numerical simulations based on an existing theory and device parameters [1,7]. The dependence of the optical bistability on bias current, initial phase detuning and input power are also investigated briefly.

2. Theory

The physical mechanism of the optical bistability in a SOA mainly rises from the dependence of refractive index on carrier concentration for wavelengths close to the forbidden band-gap [1,11]. Since the optical input can deplete the carrier concentration through stimulated emission, the length of the optical path of the cavity is a function of input intensity. Based on these mechanisms, the SOA shows the behavior of a negative nonlinear medium: when an optical input detuned to the long-wavelength side of the cavity resonance is fed into the amplifier, the resulting carrier depletion due to the increased internal intensity shifts the cavity resonance towards the input wavelength. This in return enhances the internal intensity, leading to a positive feedback loop.

The most commonly used model describing the optical bistability in SOAs was proposed by Adams in the 1980's [1,7,12]. In this model, the expression of single-pass phase delay ϕ has been modified to include the impact of the change in the material refractive index on the effective cavity length due to the external photon input. For a SOA in steady state, ϕ and net gain coefficient g can be given by

$$\phi = \frac{2\pi L}{\lambda} + \frac{g_0 L b}{2} \left(\frac{I_{av}}{I_s + I_{av}} \right) \quad (1)$$

$$g = \frac{\Gamma g_0 I_s}{I_s + I_{av}} - \alpha \quad (2)$$

where L is the cavity length and λ is input wavelength. Γ , g_0 , b , α are the confinement factor, unsaturated net gain per unit length, the linewidth enhancement factor and the effective loss coefficient, respectively. The saturation intensity I_s and the intracavity average intensity I_{av} are defined as follows

$$I_s = \frac{E}{\Gamma \alpha \tau} \quad (3)$$

$$I_{av} = \frac{(1 - R_1)(1 + R_2 e^{g_0 L})(e^{g_0 L} - 1)}{[(1 - \sqrt{R_1 R_2} e^{g_0 L})^2 + 4\sqrt{R_1 R_2} e^{g_0 L} \sin^2 \phi] g_0 L} \frac{P_{in}}{P_x} \quad (4)$$

where E is the photon energy and τ is the electron lifetime. R_1 and R_2 are the reflectivities of the front and back cavity mirrors, respectively. P_x is the scaling parameter used to convert input power P_{in} to the input intensity. Equations (1) and (2) define net gain for a Fabry-Perot cavity as a function of the average optical field strength in the cavity and the single-pass phase change, or detuning. The detuning (Eq. 1) is of the same form as the traditional equations to describe gain saturation, and the magnitude of the shift is proportional to the material gain ($g_0 L$) and linewidth enhancement factor (b). The saturation intensity (I_s) damps the response of the system when the input is high. Then, the output power of an amplifier in reflection mode (signal enters and exits the device from the same side) can be shown to have the form of

$$P_R = \frac{[(\sqrt{R_1} - \sqrt{R_2} e^{g_0 L})^2 + 4\sqrt{R_1 R_2} e^{g_0 L} \sin^2 \phi] g_0 L}{(1 - R_1)(1 + R_2 e^{g_0 L})(e^{g_0 L} - 1)} I_{av} P_y \quad (5)$$

A separate scaling parameter, P_y , is used here to account for coupling loss. For zero loss, P_x and P_y would be equal. Based on Eq. (1)-(5), the input-output characteristics of optical bistability in a SOA can be calculated.

3. Experimental results

Optical bistability in a VCISOA has been observed with the experimental setup shown schematically in Fig. 1. A tunable external-cavity semiconductor laser (center wavelength 850nm) was used as the input light source. The initial phase detuning of the input was adjusted by changing the source wavelength through the rotation of a grating in the laser. The spatial filter cleaned up the spatial profile of the input beam to increase the coupling efficiency. Input and output light power were measured by two Si photodetectors. For a VCISOA biased at a given current, a primary polarization direction exists along which the amplifier gain is the maximum. The polarizer is used to align the input light to that polarization. The input power is controlled with a variable attenuator. A laser diode objective lens with >97% transmission at 850nm provided a high coupling efficiency of the input light into the VCISOA. An optical isolator inserted in the optical path prevented reflected light from the amplifier reaching the source laser and giving rise to spurious results.

The amplifier is an 850nm GaAs vertical-cavity semiconductor optical amplifier, which is composed of two high-reflectivity distributed Bragg reflector (DBR) mirrors to form a high finesse Fabry-Perot cavity. The top and bottom DBR mirrors consist of 22 and 30.5 pairs of quarter-wavelength thick high and low refractive index materials, respectively. Ion implantation was employed in the device to create crystalline damage around the active region. The resultant insulating material provides electrical confinement. The lasing threshold current of the VCISOA was about 5.6 mA at 297 K. Since the device substrate is not transparent at 850nm, the VCISOA was operated in reflection mode. The device is mounted in

a temperature controlled holder with a precision of 0.01°C , in order to minimize thermal fluctuation.

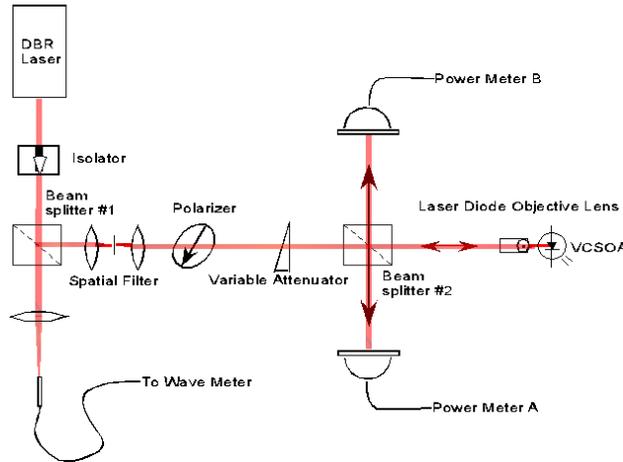


Fig. 1. Experimental setup

The optical transfer function (output power vs. input power) is shown in Fig. 2. From left to right, the initial phase detuning values are $-4 \times 10^{-4} \pi$, $-4.8 \times 10^{-4} \pi$ and $-5.7 \times 10^{-4} \pi$, respectively. The device was biased at 95% of its threshold when those curves were measured. Notice that all hysteresis loops obtained experimentally are counterclockwise. As depicted in Fig. 2, when the detuning is increased, the optical power required to achieve optical bistability is higher and the hysteresis becomes wider. A bistable switching occurs with the input power of about $4 \mu\text{W}$ as the initial phase detuning was set to be $-4.8 \times 10^{-4} \pi$.

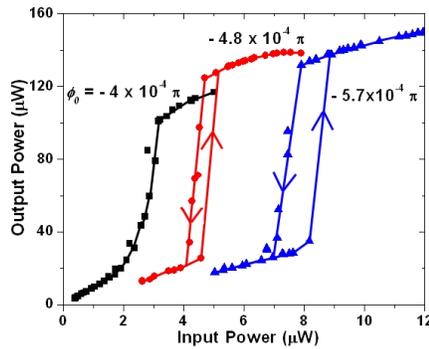


Fig. 2. Optical I/O: hysteresis loops with $I_{\text{Bias}} = 0.95 I_{\text{Th}}$. The initial phase detuning values are $-4 \times 10^{-4} \pi$ for squares, $-4.8 \times 10^{-4} \pi$ for dots and $-5.7 \times 10^{-4} \pi$ for triangles

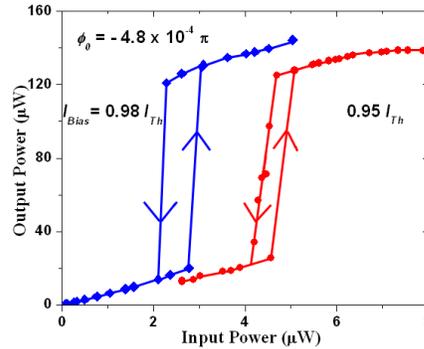


Fig. 3. Optical I/O: hysteresis loops measured at different bias currents with the same initial phase detuning: $I_{\text{Bias}} = 0.98 I_{\text{Th}}$ for diamonds and $I_{\text{Bias}} = 0.95 I_{\text{Th}}$ for dots

Optical bistability in a device biased at different bias currents was also investigated. Two curves shown in Fig. 3 have the same initial detuning but different bias currents: one is biased at 95% of its lasing threshold and the other at 98%. As the bias current is increased, the nonlinearity caused by the interaction between input light and gain medium becomes stronger. And thus with the same detuning, the optical bistability occurs at lower input power when the bias current is higher. Experimentally, the input power in order to achieve optical switching is reduced from $4 \mu\text{W}$ to $2 \mu\text{W}$ as bias current is raised from 95% to 98%.

Optical switching power observed here is an order of magnitude lower than previously reported in in-plane devices. Sharfin and Dagenais report a switching power of $3 \mu\text{W}$, but this

is a calculated result. The coupling efficiency of their device is only 2%, so 150 μ W was actually used [6]. Similarly, Pan and Dagenais report input powers of several μ W, but only after correcting for a 7.3 dB (\sim 5X) coupling loss [13]. Similar corrections can be found in other literature [5,12]. By contrast, our results are not adjusted for coupling loss to the device, but the total optical power delivered to the laser diode objective lens is given. This improvement is likely due, in part, to better coupling efficiency, but another major contributor should be the very high mirror reflectivities. The low mirror loss means that the optical intensity inside the cavity at a given input level will be larger in a VC SOA than for most FPSOAs. Consequently, the strength of the nonlinear interaction is enhanced, contributing to the low switching threshold. In addition, notice from Fig. 2 and Fig. 3 that the switching transitions observed are less abrupt as expected from theoretical calculations. In practice, the input signal has a certain width in frequency. When the VC SOA resonance is pulled towards the input signal, partial overlap in frequency may happen first, resulting in a gradual transition.

The initial wavelength detuning for the curves shown in Fig. 2 and Fig. 3 are less than 0.05nm. The relation between the detuning in term of wavelength and in term of phase ϕ is governed by Eq. (1). Both the theoretical curve (solid line) and the measured data (dots) of optical gain vs. wavelength detuning in a VC SOA are plotted in Fig. 4. The theoretical curve is drawn based on expression (5). The plots show that 3-dB gain spectrum bandwidth of the device is about 0.04nm. Further detuning causes the gain, and thus the internal intensity, to drop dramatically and ceases the nonlinear interaction in the device. Therefore, in contrast to the supposition in Ref. [7], our measurements did not show better tolerance on detuning in a VC SOA than a FPSOA, because the high reflectivity mirrors restrict the gain bandwidth. However, a 3-dB gain bandwidth of 0.6nm has been demonstrated in a VC SOA with lower reflectivity mirrors, which should exhibit better tolerance [14].

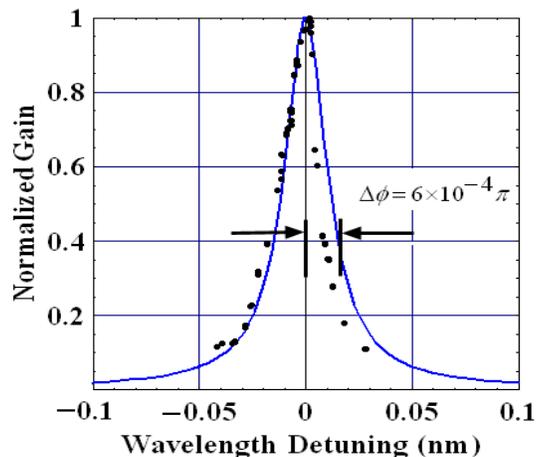


Fig. 4. Gain spectrum of a VC SOA biased at 95% of its lasing threshold: Solid line is theoretical curve and dots are the experimental measurements

Numerical simulations based on Adam's model and our device parameters are shown in Fig. 5 and Fig. 6. We calculate I_{out} and I_{in} as functions of I_{av} using Eq. (1)-(5) and the parameters in Table 1. R_1 and R_2 are calculated based on the device structure. For a VC SOA, $\Gamma=1$ is a good approximation [15]. The optical loss αL is estimated by comparing the unsaturated gain spectrum width to the gain spectrum predicted by the F-P gain Eq. [16]. The unsaturated gain is obtained by measuring the gain spectrum with very low input power (100nW). At these levels, the Eq. (1) is dominated by the constant term. The optical transfer curve is then obtained by parametrically plotting I_{out} vs. I_{in} , ignoring the independent variable

I_{av} . Compared with Fig. 2 and Fig. 3, it may be noted that there are some discrepancies in the exact form of the theoretical solution and experimental measurements. These differences are likely due to the omission of higher order term in the carrier rate equation in Refs. [1,7]: In order to get an analytical expression, the gain coefficient g has been treated as a linear function of injected carrier density N_e , which is an approximation [15]. Furthermore, Auger recombination ($\propto N_e^3$) and spontaneous emission ($\propto N_e^2$) are neglected for the sake of simplicity when evaluating the carrier density [15]. To exactly fit the measured data and reproduce the higher order features observed, a more complex and fully numerical solution would be necessary. However, even with this simplified form, the major features and trends are accurately reproduced, with good agreement to the experimental measurements.

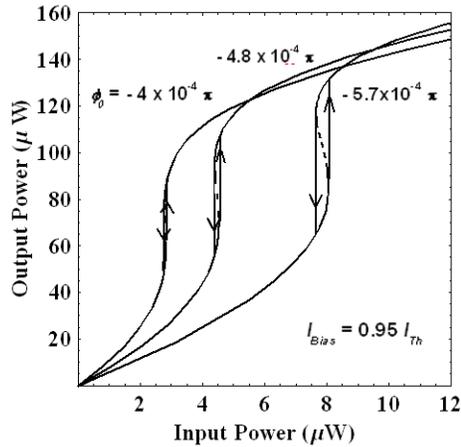


Fig. 5. Numerical simulation of the optical bistability in a VC SOA with $I_{Bias} = 0.95 I_{Th}$

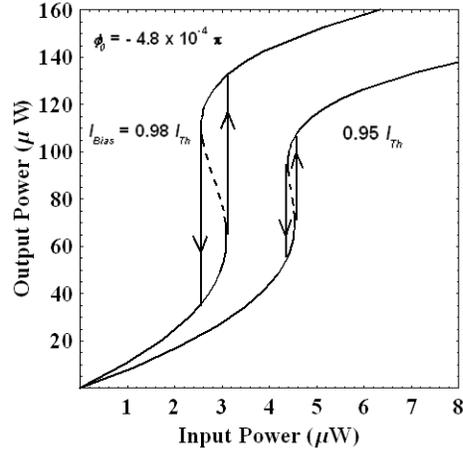


Fig. 6. Numerical simulation of the optical bistability in a VC SOA with a fixed initial phase detuning at different bias current

Table 1. Parameters used in calculation of theoretical curves

Parameter	Value
R_1	0.9925
R_2	0.9987
b	2.7
Γ	1.0
αL	0.0016
P_x	200,000
P_y	260,000

4. Conclusion

In this paper, we report, the first time to our knowledge, the experimental observation of optical bistability in a vertical-cavity semiconductor optical amplifier (VC SOA) operated in reflection mode. The counterclockwise hysteresis loops are observed over a range of bias currents and initial phase detuning. All-optical switching is obtained experimentally at an optical input power of 2 μ W. We also briefly investigate the dependence of the reflective optical bistability on bias current, initial phase detunings and input power for the first time in a VC SOA. The experimental results are consistent with our simulation based on a model developed by Adam *et al.* The low input switching energy and vertical emitting structure make VC SOAs the ideal devices for parallel logic operations.