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Nonlinear Behavior and Applications of Vertical Cavity
Semiconductor Optical Amplifiers

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy
in
Electrical Engineering (Photonics)

by

Haijiang Zhang

Committee in charge:

Professor Sadik Esener, Chair
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2007
The Dissertation of Haijiang Zhang is approved, and it is acceptable in quality and form for publication on microfilm:

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Chair

University of California, San Diego

2007
To my family
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PUBLICATIONS

Journal Articles


Haijiang Zhang, Pengyue Wen, Sadik Esener, “All-optical active pass transistor based on a bistable Vertical Cavity Semiconductor Optical Amplifiers,” to be submitted to Optics Letters, 2007

Haijiang Zhang, Christopher F. Marki, Pengyue Wen, Sadik Esener, “All-optical oscillator based on a single bistable Vertical Cavity Semiconductor Optical Amplifier (VCSOA),” to be submitted to Optics Letters, 2007


Conference Articles


Haijiang Zhang, Deqiang Song, Pengyue Wen, Sadik Esener, “Optical Image Inversion and Edge Detection Based on Vertical Cavity Semiconductor Optical Amplifiers (VCSOAs),” OSA Information Photonics, June 6, 2005
ABSTRACT OF THE DISSERTATION

Nonlinear Behavior and Applications of Vertical Cavity Semiconductor Optical Amplifiers

by

Haijiang Zhang

Doctor of Philosophy in Electrical Engineering (Photonics)
University of California, San Diego, 2007
Professor Sadik C. Esener, Chair

This dissertation mainly focuses on two closely-related research topics about Vertical Cavity Semiconductor Optical Amplifiers (VCSOAs). One is theoretical study, modeling, and characterization of the nonlinear gain characteristics of VCSOAs due to the dependence of nonlinear refractive index on carrier concentration in its Fabry-Perot (FP) cavity; the other is the experimental investigation of the feasibility of all-optical logic operations.

First, the theoretical study and demonstration of Wavelength Bistability (WB) and Multiple Bistability (MB) in a VCSOA are presented. It is proved both experimentally and theoretically that WB and Power Bistability (PB) are inter-
related through the same bistable switching points. MB is observed by sweeping the optical input power, with input wavelength fixed at the longer-wavelength side of two Polarization-Dependent Gain (PDG) windows of a VCSOA while the input polarization direction is set to a specific angle with respect to two intrinsic principal axes of material birefringence in the VCSOA.

Secondly, a cascadable All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF) and All-Optical Pass Transistor (AOPT) are proposed and demonstrated experimentally based on VCSOAs. The operation of cascadable AOI is based on three types of nonlinearities in a VCSOA: Cross-Gain Modulation (XGM), nonlinear gain characteristics (including optical bistability), and polarization gain anisotropy. The demonstrated AOI shows fast switching time <80ps, low switching threshold (~10μW), and a high noise margin for cascadability. AOFF is realized by a cross-coupled AOI pair, demonstrating all-optical memory functionality at a low switching power. The realization of AOPT is based on a bistable VCSOA, where the signal output of a transistor is switched ON/OFF by an optical control beam that alters the bistable switching threshold for the signal beam through Cross-Phase Modulation (XPM).

Finally, the nonlinear gain characteristics of VCSOAs subject to external feedback are studied. If optical feedback is constructive and co-polarized with the input beam, the resonant wavelength of the VCSOA experiences a red-shift and increased gain as the feedback is increased, resulting in enhanced nonlinear gain. When coherent optical feedback is cross-polarized with the input and its
wavelength is detuned to the longer-wavelength side of both VCSOA intrinsic PDG windows, a self-sustained optical oscillation is obtained.
1. INTRODUCTION

Semiconductor optical amplifiers (SOAs) have been studied extensively since 1963 as a modification of laser diode obtained by antireflection (AR) coating of mirror facets [1]. A major driving force for research on SOA is optical fiber communication systems, where three types of optical amplifiers: SOA, Raman amplifier and Erbium-doped fiber amplifier (EDFA), are commonly used to amplify attenuated optical signals. Raman amplifier and EDFA are also known as Optical Fiber Amplifiers (OFAs) since their optical amplifications are performed in a span of fiber that needs to be optically pumped by an external laser source. In comparison to SOAs, OFAs provide linear and high-speed optical amplification with higher optical gain (~40dB), lower noise figure (3-5dB) and larger gain bandwidth. SOAs typically exhibit optical gain of 10-20 dB with noise figure of 5-8 dB, and suffer from high insertion loss and polarization-dependent gain in fiber systems. Therefore, OFAs have dominated conventional applications such as in-line amplification in long-haul fiber communications [2-4]. In the past decades, however, SOAs have continued to be a hot research area because of their advantages over OFAs in two aspects.

First, the operations of OFAs require an additional external laser source providing high pumping power (~10mW-1W) injected into a span of fiber with length of 10m-10Km. Therefore, the overall OFA systems are very bulky, expensive (several thousand dollar a piece) and complicated, which make OFAs very difficult and uneconomical for dense integration either in arrays or with other optical elements for advanced optical systems. In contrast, SOAs are inherently
integrable and compact due to their on-wafer fabrication and electrical pumping scheme. The total volume occupied by a conventional SOA is about 1 cm$^3$, while its cost can be as low as about a hundred dollar per piece. Those features of SOAs are favorable for mass-production and integration.

Secondly, owing to the high nonlinearity of semiconductor materials in a resonant cavity structure, SOAs usually exhibit very strong nonlinear effects, including electro-optical effect, wave mixing, cross-gain/phase modulation and optical bistability [5-10]. Therefore, in addition to being used as common optical gain elements, SOAs are also capable of performing various functions that are difficult to be realized by OFAs. Those functions include wavelength conversion, all-optical switching, optical pulse generation and optical logic operations, which are inspired by optical signal processing and advanced optical communication systems [6, 10-12].

Due to advances in SOA fabrication techniques and design, SOAs have been realized in various semiconductor materials and structures to meet various requirements imposed by different optical systems [5]. Based on the cavity orientation relative to plane of growth wafer, SOAs can be categorized into two classes: in-plane SOAs (see Fig.1.1) and Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs) (see Fig.1.2). The propagation of optical mode is parallel to the plane of wafer surface in a waveguide structure for in-plane SOAs, while it is perpendicular to wafer substrate for VCSOAs.

In addition to the difference in cavity orientations, in-plane SOAs usually have much longer cavity length and less mirror reflectivity than VCSOAs. In order
to maintain broad gain bandwidth for high-speed amplification, the reflectivity of in-plane SOAs is usually less than 30% for Fabry-Perot SOAs, and almost reaches zero for Traveling-Wave SOAs [5]. Since the effective interaction length degrades as the mirror reflectivity decreases, the cavity lengths of in-plane SOAs have to be maintained very long (100μm~1mm) for achieving the desired optical amplification gain.

Fig. 1.1 In-plane Semiconductor Optical Amplifier

Fig. 1.2 Vertical-Cavity Semiconductor Optical Amplifier
In a VCSOA, the cavity is formed by two Distributed Bragg Reflector (DBR) mirrors, whose index contrast is realized by alternating two different material compositions by layers [13]. Accordingly, the whole VCSOA cavity can be treated as 1-D photonic crystal waveguide with a “defect” (cavity) introduced deliberately for photon confinement. Its gain medium is one or multiple quantum wells located in the middle of cavity and can be pumped either optically or electrically. The typical aperture size for VCSOAs ranges from 2-30μm, depending on the design considerations for different applications and material systems. The cavity length of VCSOA is usually on the order of emission wavelength for single longitudinal mode operation. To compensate the short cavity length and thin layer of gain medium for high optical gain, the VCSOAs usually have extremely high mirror reflectivity (~99.9%) resulting in very high-Q and narrow wavelength selectivity of the resonant cavity.

Due to its compact size, low cost and especially vertical emission structure, VCSOAs have been implemented as pre-amplifiers for massive optical interconnect or image detection in 2-D arrays. Accordingly, previous work has focused on improving VCSOA stability, integration capability and noise performance [14-16]. But in comparison to in-plane SOAs, the potential approaches of the nonlinearity of VCSOAs have not been investigated and studied, especially for the possibilities of using VCSOAs for massive all-optical logic operations.

This dissertation focuses on two aims that are closely-related. The first aim is to study the behavior of VCSOAs nonlinearity under various operation
conditions. A second one is the investigation of the potential all-optical logic operations based on the combinations of three primary features of VCSOAs: optical bistability, gain anisotropy and Cross-Gain Modulation (XGM).

In Chapter 2 and 3, two types of optical bistabilities (*wavelength and multiple bistabilities*) are studied both theoretically and experimentally. First, with input linear polarization aligned to one of two PDG windows, optical wavelength bistability is demonstrated and modeled in VCSOAs for the first time. Simulation and experiment are in good agreement demonstrating that the power and wavelength bistabilities are closely linked through the same bistable switching threshold. Secondly, a new mechanism for multiple bistability has been proposed and demonstrated in a VCSOA.

Chapter 4 focuses on the characterization of the bistable behavior of VCSOA subject to two cross-polarized incident beams, *optical bias* and *signal input*, under various operation conditions including optical bias power, and operation wavelengths of two beams. Additionally, a cascadable All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF) based a cross-coupled AOIs pair and All-Optical Pass Transistor (AOPT) are demonstrated successfully. The switching time of VCSOA_based AOI is measured to be <80ps.

In Chapter 5, the nonlinearities of VCSOAs subject to two different types of external feedbacks are studied both theoretically and experimentally. In the first case, the feedback is co-polarized with input beam, resulting in enhanced nonlinearity of VCSOAs. In the second case, the polarization of feedback is rotated by 90 degree before being coupled back into the VCSOA input. With such
a cross-polarized feedback, a strong all-optical oscillation is obtained under proper operation conditions. This oscillation exhibits a square-like waveform and is self-sustained by the bistable switching of the VCSOA. The repetition rate is adjustable by the feedback distance while the switching speed is limited by the dynamics of VCSOA bistability and XGM. Preliminary measurements show an extinction ratio of 5:1 at 66MHz repetition rate.

Chapter 6 summaries our findings. Future research directions and other potential applications are also discussed.
1.1 References


2. WAVELENGTH BISTABILITY OF VCSOAs

2.1 Background on optical bistabilities

A system is said to be bistable if it has two or more than two output states at the same input. In optical systems, the study of optical bistabilities can be traced back to 1974 when the first optical bistable behavior was observed in a passive, unexcited medium of sodium vapor by McCall. Since then, optical bistabilities have drawn increasing research attention due to their potential applications, especially for all-optical logic operations. A large number of optical bistable phenomena have been observed and studied in variety of materials and systems [1,2]. Depending on specific systems, the input parameters of optical bistabilities can be pump intensity (electrical or optical), input wavelength and incident angle while the outputs can be optical intensity, emission wavelength, polarization, etc [1,2].

In general, the occurrence of optical bistabilities requires two necessary conditions to be satisfied [2]. First, the optical system needs to have a nonlinear response to the optical radiation that changes the characteristics of the system. It is impossible for bistability to occur in a linear system, whose input and output are related unambiguously. Secondly, the bistable systems require “longitudinal” feedback mechanisms. With the absence of feedback, the system can only be mono-stable, even though it is a nonlinear system [2]. The feedback can be realized both externally and internally by various means. The external feedback
is mostly obtained by partially reflecting the emitting radiation back to the system through a reflective boundary. Such a boundary is one of the inherent features of all laser systems, whose resonant cavities are formed either by various conventional reflective mirrors, or by the effective mirrors based on grating structures including Distributed Bragg Reflector (DBR) and Distributed Feedback (DFB) mirrors. The internal feedback mechanisms can be intensity-dependent spatial dispersion, absorption or other various transport phenomena in nonlinear medium [2].

This chapter studies two types of dispersive optical bistabilities in a VCSOA: Power Bistability (PB), Wavelength Bistability (WB). The observation of PB in a VCSOA was first reported by Wen in 2002, where the optical intensity at output exhibited counter-clockwise hystereses as optical input intensity sweeping at a constant input wavelength [3]. In this chapter, the observation of WB in an 850nm VCSOA is reported for the first time. Study of WB, especially the connection between PB and WB, has its significance in understanding and engineering bistability-based all-optical logic systems.

### 2.2 Wavelength bistability of VCSOA

#### 2.2.1 Origin of optical bistabilities in VCSOA

The origin of optical bistability in semiconductor optical amplifiers, which is applied for both Power Bistability and Wavelength Bistability, mainly arises from optical phase modulation that is caused by intensity-dependent nonlinear index
of refraction in a Fabry-Perot (FP) cavity [1,4,5]. The operation mechanism can be understood based on two fundamental equations as follows.

\[ T = \frac{P_t}{P_i} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(\phi)} \]  \hspace{1cm} (2.2.1)

\[ \phi = \frac{2m_\lambda l}{\lambda} + \frac{2m_\lambda l}{\lambda} |E|^2 = \phi_0 + \gamma P_t \rightarrow T = \frac{P_t}{P_i} = \frac{\phi - \phi_0}{\gamma P_i} \]  \hspace{1cm} (2.2.2)

The first equation (2.2.1) is known as the transmission equation of FP-cavity, where the transmissivity T is defined as ratio of transmitted power \(P_t\) over incident power \(P_i\), and is a function of mirror reflectivity \(R\) and single-pass phase shift \(\Phi\). With nonlinear material inserted in such FP cavity shown in Fig. 2.2.1, the single-pass phase shift \(\Phi\) can be modeled as a function of the intra-cavity intensity via the nonlinear index \(n_2\) and is expressed in the form shown in Equ. (2.2.2). \(\lambda, l\) is wavelength of incident beam and length of resonant cavity, respectively. \(n_0\) is the refractive index with absence of optical input. \(E\) is the electric field inside cavity, and \(\gamma = 2\pi n_2 l/(\lambda T)\). Accordingly, with proper modification, the transmissivity T can be also expressed as a linear function of \(\Phi\) as shown in (2.2.2). Hence, both (2.2.1) and (2.2.2) can be plotted graphically in the same
coordinate of T Vs. Φ in Fig. 2.2.2(a), where the plot of Equ 2.2.1 is the well-known FP response curve while Equ 2.2.2 represents itself as a line with the slope of $1/\gamma P_i$. Mathematically, the intersections of two curves correspond to the solutions of Equ. (2.2.1) and (2.2.2).

![Diagram](image)

**Fig. 2.2.2:** Power bistability scenario. (a) Nonlinear refractive Fabry-Perot interferometer. (b) Graphical solution of (2.2.1) and (2.2.2)

In the scenario of power bistability (see Fig. 2.2.2), the input power is sweeping while the initial phase detuning $\Phi_0$ is fixed by a constant input wavelength. According to (2.2.2), mathematically, sweeping input power is equivalent to altering the slope of the line corresponding to the nonlinear effect in a dispersive material. Therefore, in Fig. 2.2.2 (a), sweeping the input power upward and downward is equivalent to moving the intersection point across the FP response curve back and forth continuously except for two discontinuities at point “C” and point “F”. Accordingly, a sudden physical switching from state “C” to state “D” occurs as input power sweeping from “A” to “E”. Similarly, a sudden
physical switching from state “F” to state “B” occurs as input power sweeping from “E” to “A”. As shown in Fig.2.2.2(b), those sudden switching occurring at different input levels forms the well-known counter-clockwise hysteresis of power bistability in the input-output characteristics of dispersive devices [1-8].

Fig. 2.2.3: Wavelength bistability. (a) Nonlinear refractive Fabry-Perot interferometer. (b) Graphical solution of (2.2.1) and (2.2.2)

In the case of wavelength bistability, where the input wavelength is sweeping at a constant optical input power, its operation principle can also be understood with aid of a graph similar to that of power bistability. As shown in Fig.2.2.3 (a), sweeping input wavelength results in both the change of slope and lateral shift of the nonlinear index line. This is due to the wavelength dependence of both $\gamma$ and $\Phi_0$ in Equ. (2.2.2), where the increase in input wavelength reduces initial phase detuning $\Phi_0$ and slightly increases the line slope. Similar to power bistability, as the nonlinear index line crosses the boundaries at point “C” and point “F” by sweeping input wavelength, a clock-wise hysteresis is obtained in the $\lambda$-Gain transfer characteristics. Since both power and wavelength bistabilities
share the same physical origin and process, it is reasonable to expect that wavelength bistability exists in the same dispersive device that exhibits power bistability.

There is one thing to be addressed for both power and wavelength bistabilities. The number of the intersection points between nonlinear index line and FP response curve vary from one to three depending on the different conditions. As the number of intersection points is more than one, multiple solutions coexist mathematically, with each solution corresponding to one physical steady state of the device. In the region of multiple solutions, however, it is nature that device can only stay at one of physical states at one time, and the switching among those coexisting states doesn’t occur spontaneously in a “noiseless” environment. Additionally, the change of physical characteristics of a bistable system has its preference on following the continuity in its solutions, showing its “memory” on previous physical states. Bistable switching occurs only when the continuity in the solutions is broken by the change of its input. For instance, in the bistable region discussed above, there are total three distinct states that coexist under the same operation condition. But only two of them can be probed with two available physical paths entering such bistable region. One is by sweeping input parameter from low to high values, while the second one is by sweeping input in opposite direction. Although the third state, which corresponds to the solutions within the region from point “C” to point “F” on the FP response curve, exists both mathematically and physically, such a state is hidden from being probed experimentally by continuously sweeping the input parameter. This
is because the physical path leading to that region is blocked by two discontinuity points “C” and “F” as shown in Fig. 2.2.2(a) and Fig. 2.2.3(a).

2.2.2 Experimental setup and observation

The device being tested in this experiment is an electrical-pumped, proton-implanted 850nm VCSOA manufactured by Emcore. Such a device operates at the reflection mode (signal enters and exits from the same side of the device) and has a circular aperture with a diameter of 20μm. During the measurement, the current bias for such a VCSOA is kept constant at 95% of its threshold.

![Experimental Setup Diagram](image)

**Fig. 2.2.4: Experimental Setup**

The experimental setup is illustrated in Fig. 2.2.4. The input beam is coupled into VCSOA through a laser objective lens designed for 850nm, and the input and output powers are monitored by two power meters around a 50/50 Beam-Splitter (BS) positioned in optical input path. In general, there are usually
three conditions that are critical for the successful observation and the accurate measurement on the optical bistabilities of VCSOAs.

First, the explicit observation of optical bistability requires high quality of input beam. Spatially, the distribution of input intensity needs to be clean and symmetric for uniform injection within the aperture of the VCSOA. Spectrally, the input beam needs to have a narrow spectral linewidth in order to obtain high optical gain and minimize noise fluctuation. In this experiment, the optical input beam is provided by a high-quality tunable diode laser (New focus TLB-6316) and is cleaned and collimated carefully by a spatial filter.

Fig. 2.2.5: Intrinsic Polarization-Dependent Gain windows of VCSOA that are probed by 100nW input power at two orthogonal polarization state, separately.

Secondly, owing to material birefringence, VCSOAs exhibit two split intrinsic Polarization-Dependent Gain (PDG) windows [9-12]. The spectral separation of two PDG windows ranges from several pm to ~50pm based on the experimental observation. Therefore, to obtain a strong bistable switching, the
polarization state of input beam, which is set by a polarizer this experiment, needs to be aligned accurately to one of two intrinsic PDG windows of the VCSOA. The intrinsic PDG windows can be probed by sweeping input wavelength with input beam being kept at a very low intensity (~100nW). The Fig. 2.2.5 shows the two PDG windows of a VCSOA that are characterized separately, and are over-plotted in a single graph. It can be said that the input polarization is aligned to one of two intrinsic polarization states of VCSOA if only one peak is observed with input wavelength sweeping across whole gain region covering both two gain windows. The observation of multiple peaks in a single gain curve usually indicates the misalignment of polarization states between input and the VCSOA being tested.

Lastly, of all three conditions, the spatial alignment of input beam to the VCSOA plays the most important role. The input beam needs to be focused symmetrically down to the VCSOA aperture through the center of an objective lens, and be coupled into the VCSOA precisely along the resonant direction of the cavity. That is because that the occurrence of optical bistability requires the strong coupling of input beam to device in order to excite whole resonant cavity forming a stable and strong intra-cavity optical intensity. The poor spatial alignment, including beam tilting or non-uniform optical injection, significantly weakens the optical resonance and causes the instability of optical intensity inside cavity. Accordingly, to ensure the precise alignment in this experiment, both objective lens and the VCSOA are mounted on and adjusted by two 5-dimension high-precision stages, respectively.
With those three conditions satisfied and optimized, the strong wavelength bistabilities of VCSOA are observed and shown in Fig. 2.2.6.

Fig. 2.2.6: Observation of wavelength bistabilities in a VCSOA. (a) Output power Vs. Input wavelength at different input powers. (b) Normalized gain Vs. Input wavelength at different powers.

Fig. 2.2.6(a) illustrates the change of output power as input wavelength sweeping at various input powers, while Fig. 2.2.6(b) shows the response of the normalized
gain windows to the different input powers. The measurements clearly show the clockwise hysteresis when input wavelength sweeping with input power being kept constant at a certain value. Here, we define those power-dependent gain windows as **effective gain windows** in order to distinguish them from the power-independent intrinsic gain windows of VCSOAs.

Two noticeable features of the effective gain windows of the VCSOA are shown in Fig.2.2.6. One is that, with the increase of the input power level, the effective gain window of the VCSOA experiences a redshift towards the longer wavelength. This is mainly due to the increase in the cavity refractive index caused by the depletion of the carrier density resulting in an increase in the effective optical length of resonant cavity. The second feature is that increasing in input power level broadens the wavelength bistable region and increases bistable switching amplitude. The bistable region here refers to the area where two switching states are available at the same input wavelength.

Those two features of the effective gain windows can be explained graphically in Fig. 2.2.3. The width of the bistable region $\Delta \lambda$ shown in Fig. 2.2.3(b) corresponds to the phase difference $\Delta \Phi$ between two nonlinear index lines that are tangential with the FP response curve at the points “C” and “F” in Fig. 2.2.3(a), respectively. And such a phase difference $\Delta \Phi$, which is actually the distance between those two nonlinear index lines along the phase axis, increases geometrically as a result of the decrease in the slopes of the nonlinear index lines as input power increases. The increase in $\Delta \Phi$ manifests itself in wavelength bistability as the broadening in the bistable region ($\Delta \lambda$ is proportional
to $\Delta \Phi$). Conversely, the similar phenomena observed in power bistability, where its bistable region is broadening as the input detuning increasing, can also be explained geometrically in Fig. 2.2.2.

2.2.3 Wavelength bistability Vs. power bistability

Since both power and wavelength bistabilities in optical semiconductor optical amplifiers arise from the same origin, finding and understanding the connection between those two types of bistabilities would give us an insight in the bistable behavior of VCSOAs. This study has its importance for engineering the VCSOA-based bistable systems for all optical logic processing that is to be discussed.

Mathematically, the bistable threshold point ($\lambda^*, P_{in}^*$) in both wavelength and power bistabilities is essentially one of multiple solutions of Equ. (2.2.1) and Equ. (2.2.2). Accordingly, it is expected that the same bistable threshold point ($\lambda^*, P_{in}^*$) can be probed by either sweeping $P_{in}$ with input wavelength fixed at $\lambda^*$ (power bistability), or sweeping $\lambda$ with input power fixed at $P_{in}^*$ (wavelength bistability). In other words, WB and PB are essentially linked to the same bistable point ($\lambda^*, P_{in}^*$).

In order to prove our speculation, a special characterization experiment is conducted as follows. First, two normalized gain windows for $P_{in}=100nW$ and $P_{in}=30uW$ are measured by sweeping the input wavelength and plotted in Fig. 2.2.7(a). Note that the plot for $P_{in}=30W$ shows two bistable threshold wavelengths $\lambda_1$ (841.726nm) and $\lambda_2$ (841.735nm) indicating two bistable points
(\(\lambda_1\), \(P_{in}=30\mu W\)) and (\(\lambda_2\), \(P_{in}=30\mu W\)). Then, two power bistable transfer characteristics are measured separately with their operation wavelengths being set at \(\lambda_1\) and \(\lambda_2\), respectively. The measurements indicated in Fig. 2.2.7(b) clearly show a power bistable threshold of \(~30\mu W\) that is shared by both two power bistable curves.

Fig. 2.2.7: Wavelength Vs. Power bistabilities. (a) Normalized gain windows for input powers of 100nW and 30\(\mu W\), respectively. (b) Power bistability measured with input wavelengths of \(\lambda_1\) (841.726nm) and \(\lambda_2\) (841.735), respectively.
In other words, the two bistable switching thresholds recorded on a single wavelength bistable curve as shown in Fig.2.2.7(a) are also observed at their corresponding two power bistable curves as shown in Fig.2.2.7(b), respectively. Such an observation agrees nicely with the theoretical prediction discussed above. Conversely, it is also expected that the two bistable switching thresholds occurring on a power bistable transfer curve can also be observed at two corresponding wavelength bistable transfer curves, where each one of the bistable points in observable on one of the corresponding wavelength bistable curve.

2.2.4 Simulation verification

The most commonly used simulation model for optical bistabilities in an SOA was proposed by Adams in the 1980’s [4-8]. Adams’ model is essentially derived from the modification of (2.2.1), (2.2.2). For SOAs operating at reflection mode, optical bistabilities can be calculated based on four primary equations as follows [4,14].

\[
\phi = \phi_0 + \frac{g_0 L b}{2} \left( \frac{I_{av}}{I_s + I_{av}} \right) \quad (2.2.3)
\]

\[
g = \Gamma g_0 + \frac{\Gamma (\phi_0 - \phi)}{L} \frac{2}{b} = \frac{\Gamma g_0 I_s}{I_s + I_{av}} - \alpha \quad (2.2.4)
\]

\[
I_{av} = \frac{(1 - R_1)(1 + R_2 e^{gL})(e^{gL} - 1)}{\left[1 - \sqrt{R_1 R_2 e^{gL}}\right]^2 + 4 \sqrt{R_1 R_2 e^{gL}} \sin^2(\phi)} g L \frac{P_{in}}{P_x} \quad (2.2.5)
\]

\[
P_{out} = \frac{\left(\sqrt{R_1} - \sqrt{R_2 e^{gL}}\right)^2 + 4 \sqrt{R_1 R_2 e^{gL}} \sin^2(\phi)}{(1 - R_1)(1 + R_2 e^{gL})(e^{gL} - 1)} I_{av} \frac{P_y}{P_x} \quad (2.2.6)
\]
Equation (2.2.3) and (2.2.4) describe the impact of the change of the nonlinear refractive index on the phase and optical gain due to the external photon injection, respectively. $\Phi_0$ is initial phase detuning, and $L$ is the cavity length. $\Gamma, \alpha$ is the confinement factor and the effective loss coefficient, respectively. $g_0$ is unsaturated net gain per unit length that is approximated as a linear function of carrier density below threshold (see 2.2.7) [13].

$$g_0 = a(N - N_0) \quad (2.2.7)$$

where $a$ and $N$ is optical gain coefficient and carrier density, respectively. $N_0$ is transparent carrier density, at which the absorption and gain are equal to each other [7].

$b$ is the linewidth enhancement factor, which is defined as ratio of real to imaginary index changes, or equivalently the ratio of small change in refractive index $dn$ over small change in optical gain $dg$ (see 2.2.6) [13].

$$b = -\frac{\partial \chi_r}{\partial N} \cdot \frac{4\pi}{\lambda} \cdot \frac{dn}{dg} \quad (2.2.8)$$

$I_{av}$ is the intracavity average intensity while $I_s$ is the saturation intensity. As shown in (2.2.7), $I_s$ is a function of photon energy $E_p$, differential gain coefficient $\alpha$ and electron lifetime $\tau$.

$$I_s = -\frac{E_p}{\Gamma a \tau} \quad (2.2.9)$$

Equation (2.2.5) and (2.2.6) establish the mathematical connection between optical input and output through $I_{av}$. $R1$ and $R2$ are the front and rear mirror reflectivity. $P_x$ and $P_y$ are the scaling factors that count for two things. One
is conversion between power and intensity, and another one is coupling loss between inside and outside of resonant cavity.

Based on those four primary equations, with a careful adjustment of parameter values that are referred from previous work [3,14], the simulated results are in a good agreement with the experimental observation (see Fig.2.2.8).

![Simulation and experiment comparison](image)

Fig. 2.2.8: Simulation and experiment comparison. (a) (b) are simulated wavelength and power bistable curves, respectively. (c) (d) are the experimental observation of wavelength and power bistable curves.
It is noted that the main goal of this simulation work is to qualitatively study the optical wavelength bistabilities and their connection with power bistabilities. Although the simulated curves seem to fit the measurements quantitatively, it doesn’t mean that all the parameter values used in the calculation are validated. This is because that the same set of bistable curves may be fit by many different combinations of the parameter values. For instance, the change of bistable curves due to slightly decrease in the front mirror reflectivity $R_1$ can be compensated by increasing $g_0$ or reducing loss coefficient $\alpha$.

2.3 Conclusion

In this chapter, wavelength bistability in VCSOAs is studied and discussed in details. Clock-wise hystereses in the $\lambda$-output transfer curve are observed experimentally for the first time in an 850nm VCSOA. Additionally, it is proved both experimentally and theoretically that WB and PB are essentially inter-related through the same bistable switching points. The study of WB in VCSOAs has its significance in engineering and optimizing bistability-based all-optical systems (To be discussed in other chapters).
2.4 References


3. MULTIPLE POWER BISTABILITIES IN VCSOAs

3.1 Operation principle

Multiple Bistabilities (MB) is usually defined as two or more bistable regions co-existing in an input-output transfer curve. This is different from multistability, which is defined as three or more stable output states corresponding to one input level [1-3]. Both optical multiple bistabilities and multistability have many potential applications, such as optical Analog-to-Digital (A/D) conversion, multi-level logic operations, optical limiter, waveform reshaping, etc [1-3]. Previously, optical MB has been demonstrated by using two different approaches. One approach is based on the interaction between multiple nonlinear resonant cavities, where MB is observed with an optical-fiber double-ring resonator using Kerr effect [2]. The second approach is based a Fabry-Perot type Laser Diode (LD) amplifier, whose cavity length (1.35mm) is more than a thousand times larger than its input wavelength (1.3μm) [3]. Such a large cavity length of the LD amplifier allows successive input-induced effective longitudinal mode switching, resulting in MB in LD amplifiers [1,3]. In a VCSOA, however, it is impossible to observe MB by implementing either of those two approaches. This is due to the single cavity structure and single-longitudinal mode operation of the VCSOA. The single longitudinal mode operation of VCSOAs is assured by their short cavity length (~1μm) in the order of the wavelength, preventing longitudinal
mode switching from occurring. Accordingly, the realization of optical multiple power bistability in a VCSOA demands a fundamentally different approach.

In this chapter, a novel approach for realizing multiple power bistabilities in a VCSOA is proposed and demonstrated. The proposed approach is essentially based on the superposition of two mismatched bistable states of two separated PDG windows in a VCSOA.

![Fig. 3.1.1](image)

Fig. 3.1.1: (a) The measurement of PDG windows of VCSOA. (b) Power bistability for P gain window. (c) Power bistability for S gain window.
As mentioned in Chapter 2, VCSOAs usually exhibit two separated PDG windows owing to material birefringence [4]. Fig. 3.1.1 (a) shows the measured intrinsic PDG windows of a VCSOA while Fig.3.1.1 (b) and (c) show the Power Bistability (PB) of each gain windows that are characterized separately by an input whose polarization is aligned to P and S, respectively. Here, “P” and “S” are used to refer those two orthogonal linear polarization states of material birefringence, and “d” is used to stand for wavelength separation between two peaks of intrinsic PDG windows.

It is noticed in Fig. 3.1.1 that the two PDG windows of the VCSOA being tested exhibits almost identical nonlinear behavior, where the same changes in their input detunings result in the similar changes in their bistable transfer curves in terms of bistable amplitude and switching threshold. In details, as shown in Fig.3.1.1(b) and (c), increasing in input detuning increases the bistable amplitude and shifts switching threshold to a high level. Accordingly, in a VCSOA with a nonzero separation of two gain windows (d=20pm in this case), when the input wavelength is set at a longer wavelength relative to both two intrinsic PDG windows, the input beam polarized at P direction always experiences the larger detuning than the one polarized at S direction. In this case, the detuning for P_polarized beam is D+20pm, while the detuning for S_polarized beam is D in Fig. 3.1.1(a). This indicates that, with the same operation wavelength shown in Fig. 3.1.1(a), the bistable curve in P polarization should exhibits the higher switching threshold and the larger bistable amplitude than those in S polarization. Accordingly, it is expected that MB may be emerging from the superposition of
two mismatched bistable states of two PDG windows when the linear polarization of optical input is set properly at a certain non-zero angle relative to P and S polarization states. Such a prediction is nicely proved by both experimental observation and theoretical analysis. The details of them are presented in sections as follows.

### 3.2 Experiment

The goal of this experiment is to examine the polarization response of VCOSOAs to various input polarization angle $\theta$ as input power sweeps. Here, polarization angle $\theta$ is defined as the angle between P and linear polarization state of optical input.
Fig. 3.2.1 shows the experimental setup, which is very similar to that used for observing wavelength bistability in chapter 2. The only difference between them is that, in this experiment, a Polarization Beam-Splitter (PBS) and a half-wave plate are inserted at the output of the VCSOA. PBS is used to decompose the output into P and S polarization directions, and half-wave plate is adjusted carefully to match the intrinsic polarization states P and S of the VCSOA to those of PBS. In this experiment, the output powers in S and P polarizations are monitored simultaneously by two power meters as the input power is sweeping.

Fig. 3.2.2: Measurement of polarization response of bistable VCSOA for different input polarization angles. (a) Output of VCSOA in P polarization; (b) Output of VCSOA in S polarization.

The experimental measurements of polarization response of the VCSOA to various input polarization angles $\theta$ ($0^\circ$, $20^\circ$, $45^\circ$, $70^\circ$, $90^\circ$) are shown in Fig. 3.2.2, where the transfer curves in the P and S directions are shown in (a) and (b), respectively. The device being tested is the same one that is characterized in
Fig. 3.1.1 with a gain window separation d=20pm. And the input wavelength is kept at D=7pm during measurement. There are two observations to be addressed based on the experimental results shown above.

First, at some input polarization angles, the bistable switching are observed in both P and S directions, where the bistable outputs in P polarization exhibit the larger bistable amplitudes and the higher switching thresholds than those in S polarization. As discussed previously, such an asymmetry between the P and S bistable states is caused by the different detunings in P and S directions [5-9]. In this experiment, with D=7pm and d=20pm, the detuning in P polarization is 27pm while it is 7 pm in S polarization. Hence, by adding up two output powers of the same input polarization angles in P and S directions, a multiple bistable curve is observed at a specific input polarization angle $\theta=20^0$ as shown in Fig. 3.2.3.

Fig. 3.2.3: Total output powers of VCSOA
As shown in Fig. 3.2.4, the observed multiple bistable curve clearly shows three distinct logic levels at 0 µW, 160 µW and 320µW, respectively. Two bistable switching thresholds are recorded around 10 µW and 23µW, respectively. Since the first transition region experience a rapid false bistable switching caused intensity noise over the first narrow bistable region, the averaged value recorded by optical power meter is used to plot this static transfer curve shown in Fig. 3.2.4. The averaging leads to a transition that is less sharp than typical bistable curve. However, the sharp turning point at the upper corner of the first transition is a clear indication that this is bistable switching.

![Graph showing polarization response of bistable VCSOA for θ = 20° and D=7pm](image)

Fig. 3.2.4: Polarization response of bistable VCSOA for θ = 20° and D=7pm

The second thing to be noticed is that, as shown in Fig.3.2.4, as soon as P bistable switch-on occurs, the output power in S polarization gets suppressed simultaneously to a very low intensity level, indicating a strong self-polarization
switching occurring at output of the VCSOA. This additional feature of MB in VCSOAs is potential for more interesting applications that are to be discussed in details.

### 3.3 Modeling and simulation

It is apparent that the MB observed in this experiment is caused by two physical processes. One is the optical power bistability of the VCSOA, which can be described by Adam’s model [7-10]. Another one is the Cross-Gain Modulation (XGM) between two decomposed optical inputs resulting in the self-polarization switching between P and S. In this case, XGM occurs through gain saturation effect in homogeneous gain material, where two PDG windows share and contend for the same carriers for optical amplification in their own polarization states [11,12].

To explain and verify the observation and discussion above, a simulation is carried out based on a modified Adams’ model. In the modified model, the electrical field $E_{in}$ of optical input is first decomposed into P and S directions as $E_{in,1}$ and $E_{in,2}$. Correspondingly, optical powers along S- and P-direction have a form shown below.

$$P_{in,1} = P_{in} \times \cos^2(\theta)$$

$$P_{in,2} = P_{in} \times \sin^2(\theta)$$

![Diagram](image_url)

*Fig. 3.3.1: Modeling of multiple bistability of VCSOAs*
With a non-zero $\theta$, $P_{in_1}$ and $P_{in_2}$ can be treated as two independent input beams. Therefore, as indicated in Fig. 3.3.2, two sets of Adams’ Equ. (2.2.3), (2.2.5) and (2.2.6) are employed to describe the bistable behavior in S and P directions, separately, and two sets of parameters $P_{out}$, $I_{av}$, $L$ and $\phi$ are assigned for each direction. The material birefringence in a VCSOA can be modeled by setting different values for $L_1$ and $L_2$, where the difference between them is proportional to the wavelength separation of two intrinsic PDG windows. The gain saturation effect between two beams is described by the cross-coupling terms that are modified from Equ. (2.2.4). Since the two decomposed input beams are cross-polarized, the total intra-cavity intensity $I_{av}$ can be simply represented as the sum of $I_{av_1}$ and $I_{av_2}$ corresponding to $P_{in_1}$ and $P_{in_2}$, respectively. Generally, this special treatment, however, is invalid for two independent optical beams that are not orthogonally polarized or misaligned to the intrinsic polarization states of VCSOAs. In those cases, some additional treatments are needed to take into account the polarization rotation effect or beating between two beams [13].

Set #1

\[
\begin{align*}
\phi_1 &= \phi_{o1} + \frac{g_s L_1 b_1}{2} \frac{I_{av}}{I_s + I_{av}} \\
I_{av_1} &= F_{I_{av}} (P_{in_1}, \lambda_1, g) \\
P_{out_1} &= F_{I_{out}} (P_{in_1}, \lambda_1, g)
\end{align*}
\]

Cross-Coupling

\[
I_{av} = I_{av_1} + I_{av_2}
\]

\[
g = \frac{\Gamma g_0 I_s}{I_s + I_{av}} - \alpha
\]

Set #2

\[
\begin{align*}
\phi_2 &= \phi_{o2} + \frac{g_s L_2 b_1}{2} \frac{I_{av}}{I_s + I_{av}} \\
I_{av_2} &= F_{I_{av}} (P_{in_2}, \lambda_2, g) \\
P_{out_2} &= F_{I_{out}} (P_{in_2}, \lambda_2, g)
\end{align*}
\]

Fig. 3.3.2: Modeling of multiple bistability of VCSOAs

This modified Adams’ model shown in Fig. 3.3.2 actually can also be used to describe the general bistable behavior of VCSOAs with two cross-polarized...
incident beams operating at the arbitrary and different wavelengths, which will be
discussed in details in chapter 4. In this case, $\lambda_1$ and $\lambda_2$ are kept at the same
value of the single input beam. With input polarization angle and other
parameters being adjusted properly, both MB and polarization switching are
calculated by using MathCad.

Fig. 3.3.3: Multiple bistability with $\theta=10^\circ$. (a) Curve 1: D=10pm; Curve 2:
D=16pm; (b) (c) Polarization switching in curve 1 and 2, respectively
Fig. 3.3.3 shows two multiple bistable curves that are calculated by setting $\theta = 10^\circ$ and bias current at 95% of its threshold. In Fig.3.3.3 (a), the multiple bistable curve 1 is calculated for $D=10\text{pm}$, while the curve 2 is simulated with $D=16\text{pm}$ (the values for other parameters are adjusted around the values reported in [6]). Fig.3.3.3 (b) and (c) show the transfer curves in both P and S directions that are decomposed for the multiple bistable curves 1 and 2, respectively.

The simulation results shown in Fig. 3.3.3 proves that the multiple bistable curves are essentially formed by the superposition of two mismatched bistable states in P and S directions. Additionally, it is also proved that the phenomenon of polarization switching is a result of XGM between two decomposed input beams and well predicted by this modified Adams’ model. The theoretical analysis is in a good agreement with the experimental observation qualitatively demonstrating the validity of the proposed explanation.

### 3.4 Optimization and applications

The characteristics of MB in VCSOAs are sensitive to many different factors. Basically, there are three major tunable parameters for adjusting and engineering multiple bistable curves. Those parameters are polarization angle, current bias level and input wavelength.

The most sensitive parameter is input polarization angle that determines the ratio of $P_{in,1}$ and $P_{in,2}$. A small value of $\theta$ results in the small bistable amplitude in S direction with strong bistable switching in P direction. A large
value of $\theta$ strengthens bistable switching in S direction while smoothing out both the bistable and polarization switching within the second transition region of MB. Additionally, the change of input polarization angle also varies the switching thresholds of MB as a result of Cross-Phase Modulation (XPM) between two decomposed optical inputs. This will be discussed in more details in section of All-Optical Pass Transistor (AOPT) in chapter 4.

![Fig. 3.4.1: Gain Vs. Current bias of a VCSOA](image)

Current bias is an apparent freedom for reshaping the bistable curves for two causes. One is due to the strong dependence of refractive index on free carrier density; the other one is that, in an electrical-pumped VCSOA, the material gain is determined by the carrier injection level [11]. Accordingly, the change of current bias is equivalent to changing the effective wavelength detuning by shifting the intrinsic PDG windows to a different position instead of by changing input wavelength. Meanwhile, since optical bistability is very sensitive to material gain, the change of current bias also varies the bistable characteristics of each gain windows, especially for their bistable amplitudes [1,6].
Since the occurrence of strong bistable switching requires large gain, in general, it is preferred to keep the current bias close to the device threshold because the gain drops very quickly with current bias decreasing (See Fig 3.4.1).

The input wavelength is the key parameter to manipulate two mismatched bistable characteristics in P and S directions. As shown in Fig. 3.3.3, the increase in the input wavelength increases the detuning of both S and P beams decomposed from a single input, shifting both two bistable thresholds of MB to the higher values.

In addition to those three adjustable parameters discussed above, obviously, it is also desired that two intrinsic PDG windows can be also adjusted for different spectral separation, polarization orientation, the width and amplitude of gain windows, etc. Various research works have been conducted to study this subject [14-24]. Basically, several mechanisms contribute to the polarization anisotropy in semiconductor lasers and amplifiers. One mechanism is geometric imperfections that break the circular symmetry of the resonant cavity [17-19]. Another one is material birefringence, which can be caused either by residual stress or strain via elasto-optic effect, or by electro-optic effect in VCSOAs [20-21]. The elasto-optical birefringence can be randomly oriented while the electro-optical birefringence tends to be aligned with the principal optical axes of the material [4, 22, 23]. So far, it has been identified that the electro-optical effect is the dominant cause for the observed gain splitting in VCSOAs [4]. Accordingly, it has been suggested that the separation of PDG windows in a VCSOA may be possibly manipulated by controlling its cavity length and mirror reflectivity, where
the gain splitting can be enhanced by decreasing the cavity length and increasing
the mirror reflectivity [24]. As a whole, the full control of anisotropy of VCSOAs
requires more research efforts in future and is out of scope of this dissertation.

Multi-level bistable switching and polarization switching demonstrated in a
VCSOA suggest various interesting applications. In addition to those mentioned
at beginning of this chapter, it can also be implemented for the polarization
modulation, waveform conversion/regeneration, etc.

Polarization modulation can be realized by modulating optical input power
around the threshold of polarization switching. In a pure all-optical system, this
proposed scheme for polarization modulation enables the all-optical modulation
conversion from optical On-Off Keying (OOK) format to polarization coding, or
vice versa.

![Fig. 3.4.2: Waveform conversion and reshaping](image)

The operating scheme for waveform conversion/regeneration is illustrated
in Fig. 3.4.2, which shows the input-output transfer curve in S polarization
exhibiting a square-like shape with the sharp bistable transition edges on its both
sides. Such a square-like transfer curve suggests that the arbitrary waveform of input, including the distorted and noisy signals, can be converted or reshaped as long as the swing of optical input amplitude covers the width of the square-like transfer curve as shown in Fig. 3.4.2.

### 3.5 Conclusion

In this chapter, an original approach for realizing multiple bistabilities in a VCSOA is proposed and demonstrated experimentally in an 850nm VCSOA. In experiment, both multi-level bistable switching and strong self-polarization switching as input power sweeping are observed explicitly. The modeling of this MB in VCSOAs is carried out based on the modification of Adams’ model. The simulation is in a good agreement with the experimental observation. The successful demonstration of multiple bistability in a VCSOA, as well as the resulting polarization switching, opens a door for various potential applications in future, including optical A/D conversion, polarization modulation, waveform conversion, etc.
3.6 References


4. ALL-OPTICAL LOGIC OPERATIONS BASED ON BISTABLE VCSOAs

4.1 Introduction

With today’s growing and insatiable demand for the higher data processing and transmitting speed in computing and communication industry, designing electronic systems are becoming more and more challenging when data rate approaching >10Gbit/s. To increase the data rate further, optical systems becomes a very attractive alternative due to its enormous bandwidth [1]. In order to take the full advantages of extremely high optical bandwidth, the optical systems aredesired to be fully optical transparent. Any EO and OE conversions need be avoided to bypass the speed bottleneck limited by the low bandwidth of electrical components. In this Chapter, all-optical logic operations based on bistable Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs) in Cross-Gain Modulation (XGM) are to be studied.

In the past several decades, all-optical logic operation systems have been studied extensively. Various all-optical logic gates and devices, including XOR, NOT, NOR, AND, Flip-flop, have been proposed or demonstrated experimentally by employing different mechanisms and devices [3-10, 22-35]. However, those previous work usually suffers from various drawbacks, such as complex configuration, instability, high power consumption and high cost, lack of capability of 2-D integration on silicon wafer, etc [17]. Therefore, they have not been
adopted in practical systems. Compared with others’ work, due to the inherent features of VCSOAs and its well-developed on-wafer fabrication techniques, the VCSOA-based all-optical logic operations exhibit both the performance and the feasibility for being implemented in practical systems. In this chapter, three types of the high-performed all-optical logic gates based on the nonlinear VCSOAs are demonstrated for the first time. Those logic gates are All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF) and All-Optical Pass Transistor (AOP), which are to be discussed in details in sequence.

### 4.2 VCSOA-based All-Optical Inverter (AOI)

#### 4.2.1 Background & Operation principle

Inverter (NOT gate) is one of the fundamental and universal logic gates used to construct any logic algorithms and functionalities. Hence, All-Optical Inverter (AOI) has attracted extensive research attentions since 1980’s in view of potential applications in all-optical signal processing [4-10]. All-optical inversion has been demonstrated in various devices including a light-emitting laser diode combined with a photodetector [4], both Fabry-Perot(FP) and traveling-wave Semiconductor Optical Amplifiers (SOAs) by employing cross-gain modulation [2,5], erbium-doped fiber amplifiers or SOAs with feedback [6,7], Vertical Cavity Surface Emitting Lasers (VCSELs) using transverse-mode switching, etc [8-10]. In terms of performance, those existing approaches typically suffer from instability, high switching power (>1mW), and particularly, the poor output-input
Transfer Characteristics (TC), preventing the cascaded inter operation and logic level restoration critical for building more complex logic circuits.

Accordingly, in addition to realizing the fundamental functionality of signal inversion, the high-performance inverters also need to have desired TC exhibiting very steep transition slope (<-1) between two flat logic levels. This is critical to obtain a robust logic system with high reliability, large cascadability and high noise immunity. The TC of an inverter is commonly justified by a figure of merit known as Noise Margin (NM), which is defined as below.

Fig. 4.2.1: Definition of Noise Margin (NM)

The OH (Output High) and OL (Output Low) indicated in Fig. 4.2.1 represent the high and low logic levels, respectively, where applying OH to the input gate yield OL at the output and vice versa. The difference between OH and OL is the logic swing. The regions of acceptable high and low logic levels are delimited by the IH (Input High) and IL (Input Low), which are defined by the points where the TC slope equals to -1. The region between IH and IL is called
the undefined region or Transition Width (TW), which need to be avoided by signals in steady state.

\[
NM_L = IL - OL \\
NM_H = OH - IH
\]  

(4.2.1)

Accordingly, the noise margins NML (Noise Margin Low) and NMH (Noise Margin High), which are defined in (4.2.1), represent the levels of noise that can be tolerated to sustain proper logic operations, especially for the cascaded logic systems, such as flip-flops and FIFO. Obviously, the noise margins are desired to be positive and as large as possible [11]. Such requirements are applicable for both electrical and optical inverters.

In this section, a novel high-performance AOI is proposed by employing three types of nonlinearities in a VCSOA: Cross-Gain Modulation (XGM), nonlinear gain characteristics (including optical bistability) and polarization gain anisotropy. The preliminary measurement of TC shows high noise margins, low switching power (~10μW) and high extinction ratio (~9.3dB). The switching time is observed to be <80ps.

Similar to the approaches demonstrated in SOAs [5], the fundamental signal inversion in a VCSOA is obtained through XGM between two cross-polarized incident beams, \textit{optical signal} and \textit{optical bias}. The same as what has been discussed in Chapter 3, XGM here occurs via the gain saturation effect in a homogeneous material [12]. With a constant carrier injection, the presence of the signal beam suppresses the gain for the bias beam by consuming free carriers in
the amplifier gain region. This effectively causes the inverted relation between the output of the bias beam and the input of the signal beam. However, the optical inversion based on XGM alone exhibits very poor TCs showing smooth transition region and negative noise margins. To overcome this problem, researchers have proposed to introduce positive feedback to a SOA to reshape its TC in an effort to realize optical flip-flop [7]. However, the response time is inherently increased by the feedback configuration, and its resulting TC is still poor with negative noise margins.

In order to obtain the desired TCs, the nonlinear gain characteristic (optical bistability) is introduced deliberately in the signal beam. As discussed previously in Chapter 2 and 3, a sharp input-output transition curve can be obtained in a VCSOA operated in its highly nonlinear (bistable) region with a single input beam whose wavelength is detuned from the amplifier intrinsic resonance. Similarly, with two beams (the bias and signal) being coupled into a VCSOA simultaneously, the signal beam can also experience an abrupt change when its wavelength is detuned relatively larger than that of bias beam. By the well-known gain-carrier relation [12], such an abrupt change in the optical gain can imprint the inverted signal to the output of the bias beam through the change of the carrier density in the shared gain region resulting in an extremely sharp transition in the inverter TC.

Additionally, as shown in the previous chapter, owing to material birefringence, VCSOAs exhibit two separated Polarization-Dependent Gain (PDG) windows corresponding to two orthogonal linearly polarization states,
respectively [13]. Therefore, the input signal and optical bias can be set to be orthogonally polarized accordingly. The polarization dependence of the VCSOA gains naturally isolates the optical bias beam from the input signal beam during the whole inversion processing, while the frequency separation of two PDG windows also naturally allows the single-wavelength operation of the AOI for a simple configuration, where both signal and bias beams operate at the same wavelength. Such a single wavelength operating scheme will be shown and discussed in details in the rest of section.

![Fig. 4.2.2: The symbol of VCSOA-based All-Optical Inverter](image)

Here, a symbol analogous to that of electronic inverter is used to describe the functionality of this AOI and is shown in Fig. 4.2.2. Such device possesses 4 terminals (2 Input and 2 Output), and the input and output of such an inverter is defined by the signal input beam and output of optical bias beam, respectively. It is noted here that the polarization states of two cross-polarized beams need to be aligned precisely to those of intrinsic PDG windows, respectively, for two
reasons. One is to enhance the nonlinear gain characteristic of the VCSOA, while another one is to minimize the crosstalk between two incident beams caused by polarization rotation effect [14],

4.2.2 Experimental demonstration

![Experimental Setup of VCSOA-based All-Optical](image)

Fig. 4.2.3: Experimental Setup of VCSOA-based All-Optical

The experimental setup is illustrated in Fig. 4.2.3. The device being tested here is an electrically pumped, proton-implanted 850nm VCSOA biased at 95% of its threshold. In this experiment, a chopper is inserted in the optical path to modulate the intensity of input signal beam. Before those two input beams are combined and coupled into the VCSOA, their wavelengths, powers and
polarizations are carefully adjusted individually by controlling the associated laser sources, optical attenuators and polarizers, respectively. After the amplification, the outputs are separated by a Polarization BS splitter, whose polarization direction is matched precisely with respect to the input polarization directions by using a half-wave plate. The outputs of both optical bias beam and signal beam are measured by two optical power meters and displayed on an electrical oscilloscope. As discussed previously, the observation in the nonlinear behavior of the VCSOA is very sensitive to the spatial alignment. The key task to succeed this experiment is to overlap two optical beams precisely in free space and couple them accurately into the VCSOA.

![Figure 4.2.4: Outputs of all-optical inverter. (a) Transfer curve of signal beam. (b) Transfer curve of optical inverter.](image)

The Fig.4.2.4 shows the first observation of the nonlinear TC of the VCSOA-based AOI with optical bias power of 3.5μW, and wavelength detunings
of signal beam and optical bias beam of 30pm and 10pm, respectively. The noise margins of measured inverter TC show $N_{M_L} = \sim 9\mu W$ and $N_{M_H} = \sim 16\mu W$.

Fig.4.2.5: All-optical inversion with an on/off ratio of $\sim 9.3$dB

The demonstration of signal inversion of such an AOI in real-time is shown in Fig. 4.2.5. The measurements show an On/Off ratio of $9.3$dB and switching threshold around $10\mu W$. The observation in the time domain is consistent with those measured in the TCs of this AOI.

Two things are to be addressed in such an AOI. First, the measurements shown in Fig. 4.2.4 and Fig 4.2.5 are measured with optical bias and signal beams operating at the exact same wavelength. This is because that the sum of the separation between two separated gain windows (27pm) and the detuning of the optical bias beam (10pm) is equal to the detuning of the signal beam (37pm). Undoubtedly, optical inverters operating at the single wavelength will significantly
simplify the system configuration and hence reduce the system cost since less laser sources are needed. In addition, single-wavelength operation avoids the potential wavelength confliction in a cascaded optical logic system, including the inverter-based ring oscillators that are to be discussed in Chapter 5.

Secondly, such an AOI is an active element providing positive gains for both optical CW bias beam and signal beam. In other word, both two input beams, signal and bias, are being amplified when passing through such an AOI. This feature provides us extra optical power to compensate the optical signal attenuation that is caused by the coupling loss, material absorption and fan-out. Therefore, this multi-functional AOI can simplify all-optical logic systems significantly by reducing the number of elements needed for signal power recovery.

4.2.3 Transfer Characteristics (TC)

Since the performance of the inverters is mainly determined by their transfer characteristics (TC), understanding the factors affecting the TC is important for device optimization. For this VCSOA-based AOI, the TC is mainly determined by three parameters: optical bias power, optical bias detuning and signal beam detuning. In this subsection, the effects of those three parameters on the TCs of the AOI is investigated experimentally and discussed in details. The goal of this work is to gain an insight in the nonlinear gain characteristics of VCSOAs in XGM and search for guidance for the system optimization.
Fig. 4.2.6: The normalized PDG windows probed by 100nW input power.

“D1” and “D2” represent detuning of optical bias beam and signal input beam, respectively. “d” is the separation of two intrinsic PDG windows

The intrinsic PDG windows of a VCOSA being tested are characterized by a 100nW input power and shown in Fig. 4.2.6, in which “D1” and “D2” stand for detunings of the optical bias and the signal input, respectively, and “d” is the spectral separation of two intrinsic PDG windows. Such a device is the same one as used for Fig. 4.3.1, which shows symmetric nonlinear properties of both two gain windows.

(1) Effect of signal bias detuning D1

Fig. 4.2.7 shows the TCs of the AOI that are characterized for various signal detuning D1. The measurements are done under two different optical bias conditions. One group of TCs measured with D1=15pm and the bias power of
9μW are shown in Fig. 4.2.7 (a), while the Fig. 4.2.7 (b) shows the measurements for D1=7pm and bias power of 4μW. From the figures, it is noticed that three operation regions can be identified based on their resulting TCs. Those three regions are D2<D1, D2≈D1 and D2>D1, respectively.

![Fig. 4.2.7: Effect of signal bias detuning on TCs. (a) TCs measured with D1: 15pm, bias power: 9μW; (b) TCs measured with D1: 7pm, bias power: 4μW](image)

Under the condition of D2<D1, the measured TCs resemble a straight line with low slopes exhibiting very low extinction ratio and poor XGM efficiency. This can be understood as a result of detuning-gain relation [15-17], where the larger detuning results in the larger consumption of free carriers for stronger amplification (refer to Fig.2.2.6 (a)). Accordingly, the beam with large detuning is expected to be less sensitive to XGM effect caused by the presence of the other beam operating at small detuning.
When D2 increases and approaches to D1, the inverter TC starts bending inward with increased extinction ratio. The Fig.4.2.8 shows some additional TCs that are measured by keeping D2 equal to D1 at various values. It is noted that all those TCs still exhibit the negative noise margins though their XGM efficiencies are improved dramatically.

![Graph showing Transfer Curves characterized by keeping D1=D2.](image)

Fig. 4.2.8: Transfer Curves characterized by keeping D1=D2.

As shown in Fig. 4.2.7, when the signal detuning D2 is further increased into the region of D2>D1, the desired nonlinear TC start emerging, and the noise margins converts from the negative to positive values. In this region, the increase in D2 tends to flatten the high-logic levels and improve the extinction ratio of TCs at the expense of the increased bistable switching thresholds.

In summary, the VCSOA_based AOI needs to operate in the region of D2>D1 in order to obtain the desired TC exhibiting high noise margins. Other two regions can not meet the requirements of the standardized AOI. Due to the
multiple effects of D2 on the inverter TC, the optimal signal detuning needs to be determined based on the requirement of specific logic systems, in terms of extinction ratio, defined logic levels, switching threshold and operation wavelength.

(2) Effect of optical bias power

Fig. 4.2.9: Effect of optical bias power on TCs.

With detuning D1 and D2 being kept constant, altering optical bias power affects the TCs in two different noticeable ways. As indicated in Fig. 4.2.9, the increase of optical bias power lifts both “1” and “0” logic levels and reduces the switching threshold. It is because that the elevated logic levels are a result of the enhanced stimulated emission in optical bias beam caused by the increase in its optical input power. On the other hand, the Effective Gain Windows (EGWs) or the amplifier resonant frequency for signal beam experiences a red-shift in
wavelength as optical bias power increases. That’s because that the refractive index decreases with the increase of carrier density [12]. With a constant operation wavelength, the red-shift of its gain window reduces the effective detuning of signal beam lowering its bistable switching threshold, which explains the reduction in the switching threshold of TCs when optical bias power increase.

(3) Effect of optical bias detuning D2

In the previous discussion on wavelength bistability, it has been shown that the Effective Gain Windows (EGWs) can be distorted into bistable region exhibiting asymmetric wavelength response around its gain peak. Accordingly, in this experimental study, the values of optical bias detuning D1 are chosen in three different regions denoted as “A”, “B” and “C” as shown in Fig. 4.2.10.

With signal detuning D2=27pm and optical bias power of 9 μW, three TCs are characterized for D1=7pm, 15pm and 20pm, which correspond to the point
“A”, “B” and “C” in Fig. 4.2.10, respectively. The measured TCs are plotted in Fig. 3.2.11 and denoted by the corresponding letters. The difference between TC “A” and TC “B” can be well understood in the similar way explaining the change of TCs with optical bias power.

![Graph showing effect of optical bias detuning on TCs](image)

Fig. 4.2.11: Effect of optical bias detuning on TCs. Measurement is taken with D1=27pm, optical bias power: 9μW.

For all three curves, the curve “C” distinguishes itself from other two by its sudden upward bistable switching when input power exceeds 10μW. To explain this, one can still refer to the mechanism that causes the reduction of switching threshold of TC due to the red-shift of EGW of signal beam as optical bias power increases. In this case, similarly, with signal input increasing, the EGW of optical bias beam shown in Fig. 4.2.10 also experiences a red-shift. The observed upward bistable switching occurs as soon as its wavelength bistable edge
crosses point “C” resulting in a sudden increase in optical gain for optical bias beam. After then, the further increase in signal input power eventually suppresses the gain for optical bias beam via XGM resulting in a spike-like shape in the curve “C”. The mechanism behind curve “C” will be discussed in details in section 3.4.

Based on the experimental observations and discussion above, it is found that the VCSOA-based AOI needs to operate under the three general conditions as follows. (1) Increase detuning of signal input beam D1 into its nonlinear gain region to introduce the optical bistable switching obtaining positive noise margins in its TC. (2) Keep optical bias beam at relative low and proper power level. (3) Slightly increase optical bias detuning D2 to optimize the gain for optical bias beam, but avoid entering its bistable region. The purpose of both condition (2) and (3) is to optimize extinction ratio, flatness of logic level and noise margins of TC without affecting the nonlinear gain characteristics of signal beam too much.

Fig. 4.2.12: Simulation model for All-Optical Inverter
All TCs of the AOI discussed so far can be simulated by using the similar model for studying multiple bistability of the VCSOA (see Fig. 3.3.2, and Fig. 4.2.12). The experimental observations are well consistent with the simulations results (see Fig. 4.2.13) qualitatively that are not to be discussed in details here. For detailed description of Adams’ model, please refer to chapter 2 and [17,18].

![Simulation Results for All-Optical Inverter. (a) transfer curve for signal beam; (b) transfer curve for AOI](image)

4.2.4 Speed measurement

The goal of this subsection is to estimate the speed of AOI experimentally. Owing to the nature of optical bistability, the AOI demonstrated here is actually a nonlinear and discontinuous system, where the switching occurs as soon as input power is sweeping across the bistable threshold \(P_t\) (see Fig. 4.2.12). In other word, the bistable switching speed is mainly determined by the characteristics of the VCSOA itself and independent of the input waveform and speed. Therefore, the conventional testing methods for linear and continuous systems can not be employed here [19].
Since the interest of this measurement is the bistable region B shown in Fig. 4.2.14, whose time response is independent of input waveform and speed, it is required that the input intensity is noiseless and weakly modulated around Pt with jitter-free. Noisy and jittering input will cause the false switching preventing accurate measurement, while a strong modulation will imprint input waveform to its output of the VCSOA through region A and C causing an additional difficulty in extracting the bistable switching region B from the output waveform. Practically, such a desired input is not easy to be obtained by using a chopper or the 850nm external modulators available commercially. In this experiment, as alternative, the input is obtained by directly modulating the diode laser into its nonlinear and distorted region deliberately, where the rising edge of the output from the diode laser is extremely sharp and clean with little jitter. Such a nonlinear and distorted input waveform is obtained by driving the current bias across the threshold of diode laser with a sinusoidal RF signal at a modulation frequency of ~400MHz (the designed highest modulation frequency is 200MHz). By using such an output
of the diode laser as the input to the AOI, the output of AOI is recorded by a Digital Communication Analyzer (DCA), showing ~80pm falling time (see Fig. 4.2.15). The rising edge of AOI output is too noisy to be measured accurately due to its corresponding noisy falling edge of the output of the diode laser.

![Diagram](image)

**Fig. 4.2.15:** Measurement of time response of AOI. The estimated switching time is <80pm
The measurement shown in Fig. 4.2.13 is taken under the conditions of \( I_{bias}=95\%I_{th}, D_1=5\text{pm}, D_2=30\text{pm}, 3.2\mu W \) optical bias power and \( 27\mu W \) average power at the input of AOI. The measured average output power of the signal beam is about \( 180\mu W \), indicating a strong amplification of the input beam. Notice here that, due to the limits of modulation and detection equipments used in the experiment, the real switching time of the VCSOA-based AOI is expected to be shorter than 80pm. The time-dependent optical bistability and the response time of VCSOAs are affected by both carrier dynamics and cavity photon lifetime \([12,20,21]\). It has been studied that the VCSOAs have show a potential of 40Gbit/s operation capability with the optimized mirror reflectivity \([21]\).

One thing to mention is that due to the high nonlinear TCs of both VCSOAs and VCSOA-based AOI, it is evident that both the VCSOA and AOI can actually function as a waveform converter or regulator. It can be clearly seen in Fig. 4.2.16, where the sinusoidal optical input converts to square-like waveform by passing through a VCSOA operating within its nonlinear gain region. Such a sinusoidal optical input is obtained from the diode laser that is modulated by a sinusoidal RF signal within its non-distortion region.

![Output of a VCSOA](image)

**Fig. 4.2.16: Waveform conversion**
4.3 All-optical Flip-Flop (AOFF)

4.3.1 Background & Operation Principle

“Flip-Flop” is a common name given to two-state devices which offer basic memory function for sequential logic operations and are extensively used for digital data storage and data transfer in electronic systems. In optical domain, because of its significant roles in optical telecommunication and computing systems, realization of All-Optical Flip-Flop (AOFF) has been a hot research topic for decades. Various mechanisms and devices have been studied and implemented for realizing AOFF since 1980’s [22-30].

As shown in Fig. 4.3.1, the AOFF demonstrated here is formed by two cross-coupled VCSOA-based All-Optical Inverters (AOIs). Notice that the nodes combining Set/Reset beam with feedback function as AND gates. Hence, the whole scheme of AOFF here is equivalent to the classic S/R flip-flop formed by two cross-coupled NAND gates, whose truth table is shown in Table 3.3.1, where
Q^n stands for present state and Q^{n+1} represents the state afterward. Besides S/R flip-flop, other types are J-K flip-flop, D flip-flop, T flip-flop, etc. The detailed difference among them can be found in numerous digital circuit references and are not to be discussed here [11].

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Table 4.3.1: Truth table of S/R flip-flop

To demonstrate such an AOFF shown in Fig. 4.3.1, the first problem to solve is the wavelength confliction between two AOIs, which mainly results from the confliction between two types of operation conditions imposed by such an AOFF scheme. (1) **Physical matching conditions**: Different from the electrical inverter, the input and output of AOIs may be distinguished from each other by the difference of their physical properties in terms of polarization states and operation wavelengths. Due to the feedback configuration of the proposed AOFF, the output beam of an AOI is required to operate at the same polarization state and wavelength as those of input beam of another AOI. (2) **Detuning conditions**: as what have been discussed in the previous section, for a single AOI, the signal input detuning D2 needs to be larger than optical bias detuning D1, and the wavelengths of both signal and bias beams have to operate at the longer-
wavelength side of their intrinsic PDG windows, respectively. Accordingly, for the
two cross-coupled AOIs, with the same detuning-bistability characteristics of all
four PDG windows, two signal beams, as well as two bias beams, need to
experience the same detuning in order to obtain the same Transfer
Characteristics (TCs) of two AOIs. Therefore, to ensure the AOFF functioning
properly, it is important that both physical matching and detuning conditions are
satisfied simultaneously.

The confliction problem discussed above can be described with the help of
Fig.3.3.2, in which the “S” and “B” represent the gain windows of signal beam
and bias beam, respectively.

As indicated above, as long as \( \lambda_1 \) and \( \lambda_2 \) are different, both physical and
detuning conditions discussed above can’t be satisfied simultaneously by any
means as long as two AOIs are identical with each other. It is straightforward that
such a problem can be solved easily by employing the wavelength converters.
This solution, however, complicates the system and makes the system integration extremely challenging. Therefore, it is not adopted here though it is doable for experimental demonstration in lab. As alternative, two other solutions are discussed as follows.

(1) Choose two identical AOIs and set bias wavelength $\lambda_1$ and signal wavelength $\lambda_2$ at the same value $\lambda_0$ at the longer-wavelength of both two PDG windows as shown in Fig.4.3.3.

Undoubtedly, such a single-wavelength operation is very favorable for many practical and commercial considerations, such as the simplification of the system, cost reduction, high-dense integration, etc. In addition, such a scheme has its special significance in many other applications, including all-optical ring oscillator that is to be discussed in Chapter 5. In this experimental demonstration, however, such a scheme highly limits the freedom in engineering and debugging this VCSOA-based AOFF prototype because it imposes a strict requirement on the properties of two VCSOAs, which need have the identical nonlinearities and
characteristics with each other. Hence, a more flexible and configurable scheme is adopted in the experiment and is described below.

(2) Choose two AOIs that have different separations of their PDG windows, $d_1$ and $d_2$, and the wavelengths of signal and bias beams and their related gain windows are arranged in a way depicted in Fig. 4.3.4.

To obtain the same signal detuning $D_2$ and bias detuning $D_1$ for both two AOIs, the beam detuning $D_1$, $D_2$, and separations of gain windows $d_1$, $d_2$, need satisfy the relation shown in Equ. (4.3.1). It is noted that this relation may be compromised by two AOIs that exhibit slight difference in their detuning-bistability characteristics.

$$D_2 - D_1 = \frac{d_2 - d_1}{2}$$  \hspace{1cm} (4.3.1)
4.3.2 Experimental demonstration

The experimental setup for demonstrating AOFF is indicated in Fig. 4.3.5. Inverter 1 and 2 are optically biased by two diode laser 1 and 2, respectively. The
polarization states and wavelengths of two diode lasers are set properly according to the operation scheme shown in Fig. 4.3.4.

The cross-coupling between two inverters are realized by two mirrors and two PBSs located at the center of the setup shown in Fig. 4.3.5. Since the AOI here is a four-terminal device that have two output beams corresponding to signal beam and bias beam, respectively, so two optical isolators are inserted in each arms of the coupling loops allowing only the output of the bias beam passing through and being coupled into the other inverter. The half-wave plates in front of each inverter are used to match the polarization states between input beams and VCSOAs.

In order to operate two AOIs in the scheme described in Fig. 4.3.4, their intrinsic resonances need to be tuned close to each other. This can be done by either changing their temperature or current bias.

![Fig. 4.3.6: The change of resonant wavelength of VCSOAs with bias current and temperature.](image)
The Fig. 4.3.6 shows the actual measured emission wavelength of a VCSOA for various temperature and current bias. The dependence of emission wavelength on the current bias is about 60-70pm/mA, while its dependence on the temperature is around 57pm/°C.

With precise alignment and careful adjustment of parameters, the fundamental functionality of AOFF is demonstrated and shown in Fig. 4.3.7.

![Diagram of AOFF operation](image)

In this experiment, the outputs Q and Q' of the AOFF are recorded by an electrical oscilloscope via two optical power detectors as the set and reset pulses are turned on and off alternately. The observed overshoots in Q and Q' are actually caused by the presence of Set or Reset input powers. In other words,
the appeared overshoot is due to the difference between the steady-state power levels with and without Set/Rest inputs.

4.3.3 Discussion

It is important to mention that, as shown in Equ. (4.3.2), the minimum time $T_{\text{AOFF}}$ required by the AOFF to reach its steady state is determined by both response time of two AOIs, $T_{\text{AOI}}$, and the time delay $T_{\text{loop\_delay}}$ introduced by a round-trip propagation distance between two AOIs. $T_{\text{AOI}}$ determines the switching time of AOFF while $T_{\text{loop\_delay}}$ limits the data rate of incoming signal.

$$T_{\text{AOFF}} = 2T_{\text{AOI}} + T_{\text{loop\_delay}} \quad (4.3.2)$$

Therefore, such a dependence of AOFF response time on $T_{\text{AOI}}$ and $T_{\text{loop\_delay}}$ impose two additional requirements for obtaining the desired performance. First, the duration time of Set/Reset pulses need to be at least larger than $T_{\text{AOFF}}$ in order to avoid the unexpected optical oscillation or instability in the closed loop formed by two AOIs. Secondly, the round-trip distance between two AOIs is desired to be as close as possible in order to increase the operation speed. This demands a solution to convert and integrate the scheme shown in Fig. 4.3.5 into a small volume on a single chip. The integration of such AOFF is crucial for maintaining itself as a competitive logic element in comparison with its electronic counterpart.
4.4 All-Optical Pass Transistor (AOPT)

4.4.1 Background & Operation principle

As one of important logic elements to build all-optical logic systems, All-Optical Pass Transistor (AOPT) has been studied extensively for decades, and many approaches have been proposed and demonstrated based on nonlinear Photonic Crystals (PCs), silicon waveguides, Liquid Crystals (LCs), in-plane SOAs, nonlinear optical fiber systems, etc [29-33]. Those approaches, however, suffer from either complex configuration, low integration capability, such as fiber-based and SOAs-based solution, or high switching power due to low switching efficiency and high loss, such as those passive switching using LCs and PCs [31-35].

Here, an innovative All-Optical Pass Transistor (AOPT) based on a single nonlinear VCSOA is proposed and demonstrated for the first time. In such an AOPT, the ON-OFF of signal output is switched by another control input that distinguishes itself by different wavelength and polarization state from the signal beam. Benefiting from its high nonlinearity in small high-Q vertical cavity (~3-20μm aperture diameter), VCSOA-based AOPT can achieve both high switching efficiency and capability for high-dense integration, which make VCSOAs more practical for integrated all-optical switching system on silicon wafer than other existent devices.

Similar with OI and OFF demonstrated in the previous sections, the approach used for demonstrating AOPT here also employs three features of VCSOAs: Polarization gain anisotropy, optical bistability and Cross-Phase
Modulation (XGM). The detailed operation principle can be understood as follows.

As discussed previously, owning to the material birefringence, VCSOAs exhibit two separated intrinsic PDG windows. With the incidence of an optical input (signal beam) that is polarized along one of intrinsic polarization states with a certain detuning, optical bistable switching occurs as soon as the input intensity sweeps across its bistable switching threshold, And it has been learned that the bistable switching threshold is determined by the carrier density inside the cavity.

Now, with the incidence of an additional optical input (control beam) whose polarization is set properly to the second gain window, the carrier density as well as the refractive index is changed by the presence of these extra photons inside cavity resulting in a resonant frequency shift. In other words, the peak of the intrinsic gain window of signal beam experiences a red-shift with the increase of the input intensity of the control beam through XPM. As a result, the effective wavelength detuning for the signal beam is reduced, shifting the bistable switching threshold to the lower intensity level. Accordingly, optical switching for signal beam can be realized by switching the bistable switching threshold in and out of the swing range of signal input via the control beam

4.4.2 Experimental demonstration

In this experiment, two incident beams, signal input and control beam, are coupled into a single VCSOA. The polarization states of each beam are set properly regarding to two PDG windows, respectively.
First of all, the gain windows of signal beam are characterized by a $1\mu W$ signal input when control beam operates at $0\mu W$, $15\mu W$ and $30\mu W$ with $0$pm detuning. As indicated in Fig. 4.4.1, the measurements clearly show a red-shift of gain peaks as the control inputs increases. This is in a good agreement with the theoretical prediction discussed above.

Fig. 4.4.1: Red-shift of gain window for signal beam

Fig. 4.4.2: The intrinsic PDG windows of the VCSOA
Secondly, the optical bistable curves of signal beam are characterized for the same control input powers used for Fig. 4.4.1 and are shown in Fig. 4.4.3. In such a measurement, the detuning of signal and control beams are fixed at 30pm and 0pm, respectively (see Fig. 4.4.2)

![Optical power bistable curves of signal beam](image)

**Fig. 4.4.3: Optical power bistable curves of signal beam**

As shown above, the bistable switching threshold of signal beam is shifted to the low intensity level with the increase of the input power of control beam. Consequently, this allows the signal output switching from low-level state “A” to high-level state “B” by just turning on the control input reaching around 30μW, demonstrating the functionality of all-optical pass transistor.

The experimental setup for demonstrating AOPT is shown in Fig. 4.4.4, which is similar with the one for demonstrating all-optical inverter. Here, two optical choppers are used for modulating signal and control inputs individually at different modulation speed to simulate data flow and control signal.
The switching behavior of the AOPT recorded by an electrical oscilloscope is shown in Fig. 4.4.5. An extinction ratio of 6:1 is observed at the signal output as the control input is alternating between 0$\mu$W and 30$\mu$W.
According to Fig. 4.4.3, a higher extinction ratio for the same signal input intensity is possible by increasing the detuning of the signal beam. In doing so, the penalty will be the increase in the minimum control input required for such switching to occur. It is also noted in Fig. 4.4.5 that, when control input is ON, the signal input imprints itself on the output of control beam through Cross-Gain Modulation (XGM) [12].

4.4.3 Discussion

![Diagram]

Fig. 4.4.6 Two different operation schemes for AOPT.

(a) Positive AOPT; (b) Negative AOPT.

The scheme used for this experimental demonstration of AOFF can be described by employing the inverter symbol shown in Fig. 4.4.6(a). Compared
with the AOI, the output of AOPT is defined by the output of signal beam, instead of output of control beam (optical bias beam).

Additionally, the AOPT can be also realized by using the scheme shown in Fig. 4.4.6(b) under the same operation conditions for AOI. Its difference from AOI is that the signal input and optical bias beam for AOI are defined as control beam and signal input for AOPT, respectively.

There are several differences between those two operating schemes of AOPT shown above. First, the AOPT in Fig. 4.4.6(a) is turned ON as the control beam is ON (Positive AOPT), while the AOPT in Fig. 4.4.6(b) is ON as the control beam is OFF (Negative AOPT). Secondly, the output of positive AOPT is always operating at same wavelength as its signal input beam, while the operation wavelengths of input and output of negative AOPT may be different. Lastly, the operation mechanism for positive AOPT is based on XPM while the negative AOPT is based on XGM.

Two more things should be noticed on this VCSOA-based AOPT. First, such an AOPT is performing both optical switching and optical amplification. In this demonstration, the output of signal shows a 12dB gain, instead of loss. This is quite different from those passive optical switching approaches, which suffer from both high switching power and huge loss requiring power recovery implemented by the extra devices [31]. Secondly, as discussed previously, since the bistable switching is caused by the discontinuity of cavity characteristics, the bistable transition at signal beam occurs “instantaneously” as soon as the intensity of control input crosses certain threshold value. This indicates that the
time it takes for such a bistable transition is mostly determined by the dynamics of the VCSOA itself, and weakly dependent on the transition time of the external control input. Hence, the switching speed of such an AOPT can be expected to always operate close at its maximum speed capability that is potentially optimized for 40Gbit/s operation or higher [21].

4.5 Conclusion

In this chapter, three all-optical logic gates, All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF) and All-Optical Pass Transistor (AOPT) are demonstrated by employing nonlinear gain characteristics, Cross-Gain Modulation (XGM) and anisotropy of VCSOAs. For the AOI, the effects of optical bias and signal and optical bias power on its transfer characteristics are studied experimentally, and its switching time is measured to be <80ps. Based on the study of the AOI, two different operation scenarios are proposed for the AOFF formed by two cross-coupled AOIs. The AOFF demonstrated is realized by coupling two VCSOAs that have different gain windows separations. For the AOPT, it is realized by modulating the bistable switching threshold of signal beam by a control beam through XPM. All three logic gates demonstrated exhibit high extinction ratios, low switching powers and are potential for both high-speed operation and high-dense integration. These works significantly advance the VCSOAs as an ideal candidate for a building block in all-optical computing architecture.
4.6 Reference


33. Harm J. S. Dorren, Arvind K. Mishra, Xuelin Yang, Zhonggui Li, Heongkyu JU, Huug de Waardt, Djan Khoe and Daan Lenstra “All-optical switching and Wavelength Conversion Based on Ultrafast Nonlinearities

5. NONLINEARITIES OF VCSOAs WITH EXTERNAL FEEDBACK

5.1 Introduction

The behaviors of Semiconductor Lasers (SL) subject to external optical feedback have been an important research area almost since the invention of the semiconductor lasers [1-12]. The previous experimental work and studies have indicated that external optical feedback can actually be beneficial for performance of SL being used in optical communications, in terms of mode selection, narrowing emission linewidth, reducing waveform distortion, stabilizing frequency, etc [1, 7-10]. Additionally, introducing optical feedback to SL is promising for wide range of other functional applications in sensing and optical communications, including self-mixing interferometry with sub-nanometer sensitivity in path-length measurement, private communications based chaotic dynamics in SL subject to optical feedback, etc [1,5,11].

In this chapter, the nonlinear behavior of bistable Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs) subject to the external optical feedback are studied both theoretically and experimentally. In section 5.2, the optical feedback being studied is positive and co-polarized with regarding to that of input beam resulting in an enhancement in nonlinearity and optical gain. In section 5.3, an original self-sustained all-optical oscillation is demonstrated when optical feedback is cross-polarized with the input and its wavelength is detuned.
at the longer-wavelength side of two intrinsic Polarization-Dependent Gain (PDG) windows of a VCSOA [13].

**5.2 VCSOA with co-polarized feedback (Nonlinear enhancement)**

**5.2.1 Theoretical prediction**

The motivation of this work is to study the response of the nonlinear gain characteristics (optical bistability) of the VCSOA subject to an external positive optical feedback, whose linear polarization state is the same as that of the incident beam. The theoretical model that is proposed here is based on a modified Adam’s model. The original Adam’s model and physical explanation of parameters are described by Equ. (2.2.3) to Equ. (2.2.6) in Chapter 2 and the references [14, 15]. The modified Adams’ model describing the effect of positive feedback on nonlinearity is shown in Equ. (5.2.1) to Equ. (5.2.4) as follows.

\[
\phi = \phi_0 + \frac{g_s L b}{2} \left( \frac{I_{av}}{I_s + I_{av}} \right) \tag{5.2.1}
\]

\[
g = \Gamma g_0 + \frac{\Gamma (\phi_0 - \phi)}{L} \frac{2}{b} - \alpha = \frac{\Gamma g_0 I_s}{I_s + I_{av}} - \alpha \tag{5.2.2}
\]

\[
I_{av} = \frac{(1 - R_1)(1 + R_2 e^{g_l t})(e^{g_l t} - 1)}{\left(1 - \sqrt{R_1 R_2} e^{g_l t} \right)^2 + 4 \sqrt{R_1 R_2} e^{g_l t} \sin^2 (\phi)} \times \frac{(P_{in} + k \times P_{out})}{P_x} \tag{5.2.3}
\]

\[
P_{out} = \frac{\left(\sqrt{R_1} - \sqrt{R_2} e^{g_l t}\right)^2 + 4 \sqrt{R_1 R_2} e^{g_l t} \sin^2 (\phi)}{(1 - R_1)(1 + R_2 e^{g_l t})(e^{g_l t} - 1)} \times I_{av} \times P_y \tag{5.2.4}
\]
The only difference between those two models is that, in this modified Adams’ model, an additional term $k \times P_{\text{out}}$ is added to the input term $P_{\text{in}}$ shown in Equ. (5.2.3), where $k$ is the feedback ratio.

It is noted that the original Adam’s model is aimed to describe the optical bistability of semiconductor amplifiers that are biased below their lasing thresholds [14]. Therefore, the Spontaneous Emission (SE) is assumed to be negligible and is not included in its modeling. Accordingly, in this feedback configuration, the modified Adams’ model is valid under the condition that the SE is very weak so that the characteristics of the VCSOA are not affected too much by the feedback of SE itself. Practically, this assumption is reasonable when the current bias level of VCSOAs is kept away from being very close to its threshold.

**Fig. 5.2.1: Simulation of feedback effect on gain window.**

(a) without feedback; (b) with 4% feedback.

Based on the modified Adams’ model, the effects of the optical feedback on the nonlinear gain windows of a VCSOA is first calculated and shown in Fig. 5.2.1. In
this simulation, the current bias level is set at 87% of its threshold while R1 and R2 are set to 0.99 and 0.9995, respectively. The values of other parameters used in this simulation are adjusted based on others’ work [15, 16].

Based on the simulation results shown above, it is evident that a weak feedback helps to increase the amplitude of nonlinear gain windows while pulling the gain peak toward the longer wavelength (Red-shift). Those effects of positive external feedback on gain windows (the increase in optical gain and red-shift of amplifier resonance) indicate an enhancement in the nonlinearity (optical bistability) of the VCSOA. This prediction is proved by the simulation carried out for Input-output transfer curves of the VCSOA subject to external feedback. The simulation results shown in Fig. 5.2.2 clearly indicate that the increase in feedback ratio increases both amplitude and width of the nonlinear/bistable region, and reduces the bistable switching thresholds.

![Simulations of feedback effect on power bistability](image-url)
Physically, the external feedback can actually be modeled as an additional partially reflective mirror that is located outside of cavity [1]. Therefore, at steady state, such a partially reflective mirror can be treated as an increased in top mirror reflectivity. It is expected that the effect of the increase in top mirror reflectivity on nonlinearity of the VCSOA should be similar with those of the external optical feedback. This is proved theoretically by the simulation that is done by using the original Adams' model.

Fig. 5.2.3: Simulation on Effects of top mirror reflectivity. (a) gain windows without R1=0.99; (b) gain windows with R1=0.99037; (c) transfer curve with various R1.
Fig. 5.2.3 shows the effect of the top mirror reflectivity on the nonlinear gain windows and transfer characteristics of the VCSOA. For the purpose of comparison, the values of the parameters and operation conditions set for those calculations are the same with those used in Fig. 5.2.1 and Fig. 5.2.2, except for the top mirror reflectivity $R_1$ and the feedback ratio. By comparing Fig. 5.2.3(a) with Fig. 5.2.1(b), and Fig. 5.2.3(c) with Fig. 5.2.2, it is clear that the increase in top mirror reflectivity effectively has similar impacts on the nonlinear gain windows and power bistability of the VCSOA as the feedback does. Practically, however, the reflectivity of VCSOA DBR mirror is not an adjustable parameter after it is fabricated, while the feedback ratio can be controlled continuously simply by using an optical attenuator. Hence, introducing the optical feedback seems a very friendly means for engineering and optimizing the nonlinearity of the bistable VCSOAs.

5.2.2 Experimental verification

Fig. 5.2.4: Experimental setup for co-polarized feedback configuration
To prove the theoretical analysis shown above, an experiment is conducted on an 850nm Proton-confined VCSOA manufactured by Honeywell. Fig. 5.2.4 illustrates the experiment setup that is similar to the one used for studying the wavelength bistability (see Fig. 2.2.4). In both setups, the optical power is controlled by an attenuator while input polarization state is aligned to one of the intrinsic PDG windows by using a polarizer [13]. The only difference between two setups is that, in this experiment, an additional beam-splitter BS#1 is inserted in optical path to redirect a portion of VCSOA emission, which in turn couples back into the VCSOA by a dielectric mirror. Since VCSOAs provide the coherent amplification for its input [17], the feedback beam may interfere with the incoming beam from the diode laser. In order to avoid the destructive interference, the mirror shown in Fig. 5.2.4 is positioned precisely by a high-precision 5-axis stage for aligning the feedback beam with the incoming beam both in phase and in space. The device being tested is biased at 95% of its threshold, at which the SE is weak enough to be neglected. The feedback ratio is 4%, which is calculated based on BS#2 (40/60) and BS#1 (50/50).

In this experiment, first, the gains of different input powers are characterized without and with external feedback (4%), separately. And their experimental results are overplotted in Fig. 5.2.5. Secondly, the output-input transfer curves are also characterized without and with feedback (4%) with the detuning of the input beam fixed at 15pm (see Fig. 5.2.6). It is evident that the experimental observation is in good agreement with the theoretical prediction based on the modified Adams’ model qualitatively.
Fig. 5.2.5: Measurement of the gains for different input powers with and without feedback

Fig. 5.2.6: Measurement of optical power bistability with and without feedback
5.3 VCSOA with cross-polarized feedback (Optical oscillation)

5.3.1 Operation principle

All-Optical Oscillator (AOO) holds a special interest as optical subsystems for both all-optical and microwave transmission and processing systems. Several applications of optical oscillators are optical clock recovery, optical 3-R regeneration, optical analog-to-digital conversion, precise timing for phased radar array synchronization etc [18-20]. In general, the mechanisms for optical oscillation fall into two categories. One is based on optical self-pulsation of lasers, whose cavity characteristic is self-modulated automatically via several techniques, such as mode-locking, gain/Q switching, etc [19, 21,22]. The second category is based on optoelectronic oscillation (OEO) systems, which usually employ a hybrid feedback configuration involving conversion between optical and electrical signals [5,23-25].

In this section, an original mechanism for all-optical oscillation is proposed and demonstrated for the first time by employing the nonlinear inverted input-output transfer characteristic of Vertical-Cavity Semiconductor Optical Amplifier (VCSOA) via cross-gain modulation (XGM) in a feedback configuration. In comparison to other approaches [19-25], the VCSOA_based AOO proposed here exhibits several more attractive features, such as low cost and compact size, simple configuration, square-like oscillation waveform, continuously tunable oscillation frequency and potential for programmable pattern generation. Those features are to be discussed in details.
The mechanism and configuration being employed for this optical oscillation here is actually analogous to that in electronic world, where the self-sustained electronic oscillation is generated by an odd number of cascaded CMOS inverters in a close loop [26]. By analogy, the single VCSOA used in the demonstration functions as an All-Optical Inverter (AOI), which has been demonstrated in Chapter 4.

![Fig. 5.3.1: Operation scheme](image)

Fig. 5.3.1 shows the operation scheme of the proposed AOO. The VCSOA operates under the similar operation conditions for AOI, whose output (the output of optical bias) is coupled back to input after its polarization is rotated $90^0$. In order to obtain a stable and self-sustained oscillation, two general conditions are imposed on the transfer characteristics of those inverters used for oscillators in both the electrical and optical worlds. The first condition, obviously, requires logic
inversion between input and output of the device. In this experiment, as shown previously, the optical inversion is obtained through Cross-Gain Modulation (XGM) between two cross-polarized beams.

The second necessary condition is that the input-output Transfer Characteristics (TC) of inverters must exhibit a steep, nonlinear transition region between output high and output low to ensure stable operation with sufficient immunity to noise. In another word, the TC of VCSOA needs to exhibit high noise margins [26]. For VCSOA-based AOI, the desired nonlinear TC has been demonstrated previously in Chapter 4 by introducing the strong optical bistability in its input signal beam while keeping optical bias beam away from its bistable region.

5.3.2 Design considerations

In addition to those two general conditions discussed, there are several design considerations that need to be addressed to ensure the proper operation of this VCSOA-based AOI.

First, as mentioned previously, the bistable system is a nonlinear and discontinuous system that can not be treated in a conventional way. The desired nonlinear and steep transition region of the AOI is actually the bistable switching region, within which there is no steady-state solutions both mathematically and physically. In other word, no physical steady states exist during bistable switching. Accordingly, the time delay $T_f$ introduced by the finite feedback distance is required to be larger than the bistable switching time $T_s$ in order to sustain and
stabilize the oscillation. This is different from the electronic ring oscillator based on the cascaded inverters, in which oscillation can still occur when $T_f < T_s$ though its oscillation amplitude decreases with the decrease feedback loop distance.

Secondly, to simplify AOO configuration and avoid using wavelength converter, it is preferred that both signal and optical bias beams operate at the same wavelength. The desired TC discussed previously needs to be obtained under the condition of the single-wavelength operation. Therefore, as discussed in section 4.3, to satisfy both physical matching condition and the detuning conditions, the only degree of freedom available is the proper spectral separation between two intrinsic gain windows of input signal and optical bias beam, which is conveniently provided via the material birefringence of VCSOA itself [13].

Fig. 5.3.2: Spectral operation scheme for AOO. The intrinsic PDG windows are characterized by 100nW input power on the actual device being tested.
By choosing a VCSOA with proper gain window separation (20pm), the spectral operation scheme is engineered and shown in Fig. 5.3.2, where all required conditions are satisfied by coinciding wavelengths of two beams at the longer wavelength side of both two PDG windows. D1 and D2 in Fig. 5.3.2 represent wavelength detuning of optical bias beam and signal beam relative to the peaks of their own intrinsic gain windows, respectively, where D2=D1+20pm.

Lastly, the output power of AOI has to be larger than the sum of bistable switching threshold and loss in the feedback loop in order to trigger the logic inversion for the next cycle. The tolerance of loop loss or the desired switching threshold can be engineered with the help of the TCs of AOI. Therefore, given the spectral operation scheme shown in Fig. 5.3.2, the TCs of AOI are first characterized of various wavelength detuning and optical bias powers (see Fig. 5.3.3). The two input beams used for the measurement are kept at the exact same wavelength and are cross-polarized at “P” and “S” polarization states, respectively. The device being tested here is an ion-implanted VCSOA biased at its 98% of its threshold.
As shown in Fig. 5.3.2(a), with fixed optical bias power, the slight increase in detuning tends to increase output amplitude, extinction ratio and the power required for bistable switching. Fig. 5.3.2(b) indicates that, with fixed detuning (D1=7pm, D2=37pm), the increase of optical bias power reduces the switching threshold and deteriorates the output extinction ratio. It is noticed that the properties of real-time oscillated signal, such as extinction ratio, swing amplitude, oscillation waveform, are actually predicted by the TCs of the AOI. Hence, those characterized TCs shown in Fig. 5.3.2 are very useful as guidance for debugging and optimizing such AOO system.

5.3.3 Experimental demonstration

The experimental setup for demonstrating AOO, which is built based on the operating scheme illustrated in Fig. 5.3.1, is shown in Fig. 5.3.4.
Fig. 5.3.4: Experimental setup for All-Optical Oscillator

As shown above, the actual feedback loop is formed by a PBS and three mirrors surrounding it. Each one of three mirrors is precisely positioned by an adjustable mirror holder and a three dimension stage attached to it. In the feedback loop, a half-wave plate is placed as a 90 degree polarization rotator to convert polarization state of AOI output from S to P, while an optical isolator is used to prevent output of signal beam from being coupled back into the optical bias beam of the AOI.

In order to lock the free-running oscillation signal on Digital Signal Analyzer (DCA Agilent 86101A), the output of signal beam is employed as a trigger signal during the measurement. It is noted in this setup that the output of
AOI experiences only 6dB loss due to 50-50 BS#2 before being couple back into the VCSOA. This 6dB loss is within the tolerance of this AOO based on the characterized TCs shown in Fig. 5.3.3.

With the incidence of optical bias beam into the VCSOA, the oscillation starts automatically as soon as the loop is closed up. The steady state of oscillation depends only on the optical bias beam (detuning and power) and the intrinsic properties of the VCSOA itself, and is independent of the speed and means of closing the loop based on the previous discussion in Chapter 4.

![Figure 5.3.5: Recorded optical oscillation signal on DCA](image)

Fig. 5.3.5 shows the oscillation signals that are recorded by the DCA under the conditions of D1=7pm and 7μW optical bias power. The experimental results clearly present a square-like waveform with an extinction ratio of 5:1. The recorded repetition rate is 66MHz, which is consistent with the physical feedback distance ~2.3 meters. Notice that the feedback time delay as well as its
corresponding feedback distance is only for half period of oscillation signals. In addition to changing the feedback distance, the repetition rate can also be fine tuned by slightly adjusting the input wavelength and optical bias power based on experimental observation. This might be due to the dependence of nonlinear refractive index on input wavelength and power resulting in the variation of the effective optical path of the VCSOA [27].

With the averaging function turned off on DCA, the real-time output of optical bias beam and signal beam are recorded and shown in Fig. 5.3.6 (a) and (b), respectively. It is found that the actual real-time signals are very noisy preventing the accurate measurement of switching time due to the noise-induced jitter and intensity fluctuation on two logic levels.

![Fig. 5.3.6: (a) Output of optical bias beam; (b) Output of signal beam.](image)

5.3.4 Analysis & Discussion

It is identified qualitatively that the noise in oscillation signals are mainly attributed to three noise sources: thermal noise on photodetector, Amplified
Spontaneous Emission (ASE) noise from diode laser and Spontaneous Emission (SE) noise of the VCSOA itself [28-30].

The thermal noise of photodetector is one of limiting factors for its sensitivity [28]. Besides the noises on two logic levels, the thermal noise also contributes to jitter, which can be understood as a result of the projection of thermal noise on the finite switching slope. Under the condition that the switching time is independent of oscillation amplitude, the jitter caused by thermal noise is expected to be suppressed by increasing the swing of input amplitude. This can be done by inserting an additional optical amplifier before photodetector at expense of introducing additional SE noise to the signals.

Both the ASE noise of diode laser and SE noise of the VCSOA contribute to the false bistable switching, which also appears as jitter in measurement. As discussed in Chapter 2, the bistable switching occurs “simultaneously” as soon as the total intra-cavity intensity exceeds its bistable threshold. Obviously, since the intra-cavity intensity is subject to both input noise and SE noise of the VCSOA itself, the false switching is actually unavoidable in practice though it can be minimized to some extents. Also, as indicated in Fig. 5.3.6, the intensity fluctuation on the high logic level seems more severe than that on the low logic level. This is mainly due to the ASE noise of laser diode being amplified by the VCSOA. Additionally, it is also important to notice that the good isolation between optical bias beam and feedback beam, and the stable input wavelength are also critical to minimize the noise and jitter of oscillated signals.
It is noted in Fig. 5.3.6 that the output of signal beam is showing a strong overshoot in the upward bistable switching. Such overshoot has been well predicted by time-dependent Adam's model [31], and are identified as an unavoidable feature of bistable action in the Fabry-Perot (FP) cavities [31]

Besides optical oscillation, an additionally relevant feature is that this oscillator can be optically reset with ease by tuning on an external signal input beam to the VCSOA, which stops the oscillation by depleting the carrier density available to the oscillating beam. This reset capability offers potential of optically programmable pattern generation and optical memory where the incoming optical pulses are stored via a self-sustained oscillation.

Additionally, when the polarization rotation is not perfectly 90 degree, multi-level oscillation can be observed and shown in Fig. 5.3.7. This phenomenon can be well understood by using the explanation for multiple bistabilities in VCSOAs discussed in Chapter 3.

Fig. 5.3.7: Multi-Level Oscillation
5.4 Conclusion

In summary, the nonlinear behavior of bistable Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs) subject to an external optical feedback are studied both theoretically and experimentally.

When the optical feedback is positive and co-polarized with the input beam, with the increase of feedback ratio, the resonance of the VCSOA experiences a red-shift with the increased gain, resulting in the enhanced nonlinear gain characteristics of the VCSOA. Such a study has its importance to manipulate the nonlinearity of the VCSOA in the applications including VCSOA-based all-optical logic processing.

When the optical feedback is cross-polarized with the input and its wavelength is detuned to the longer-wavelength side of both intrinsic PDG windows of a VCSOA, a self-sustained optical oscillation is observed for the first time. This oscillation generates a square-like waveform with an extinction ratio of 5:1 at 66MHz repetition rate and is self-sustained by the bistable switching of the VCSOA. The repetition rate is adjusted by the feedback distance while the switching speed is limited by the dynamics of VCSOA bistability and XGM. This work may open a new research direction for all-optical oscillation in the future.
5.5 References


6. CONCLUSION

This dissertation is a study of the nonlinear behavior of VCSOAs and their applications. Emphasis has been focused on two areas. One is the theoretical study, modeling and characterization of nonlinear VCSOAs under various operation conditions. Several nonlinear phenomena of VCSOAs were observed for the first time, and analyzed successfully by the proposed theoretical models. The other area is the experimental investigation of the feasibility of using VCSOAs as a building block for all-optical logic operations. A cascadable All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF), All-Optical Pass Transistor (AOPT) and All-Optical Oscillator were proposed, demonstrated and analyzed, respectively.

6.1 Summary

In Chapter 1, the background on conventional optical amplifiers and their performance were introduced and compared briefly. Furthermore, the general difference between in-plane SOA and Vertical-Cavity SOA were discussed, indicating the advantages of VCSOA over in-plane SOA for the potential functional applications including high-dense optical logic operation, 2-D image detection.

In Chapter 2 and 3, Wavelength Bistability (WB) and Multiple Bistability (MB) in a VCSOA were studied both theoretically and experimentally. Clockwise hystereses in WB were obtained with input wavelength sweeping at a constant
input power. MB were observed by sweeping the optical input, whose operation wavelength is fixed at the longer-wavelength side of two separated Polarization-Dependent Gain (PDG) windows of a VCSOA while its linear polarization is set to a certain angle with respect to two intrinsic principal axes of material birefringence. Two distinguished bistable levels of MB are recorded at 160μW and 320μW, respectively. The experimental observation of both WB and MB are in good agreement with theoretical predictions based on Adams’ model [1,2].

In Chapter 4, three types of logic gates, All-Optical Inverter (AOI), All-Optical Flip-Flop (AOFF) and All-Optical Pass Transistor (AOPT), were proposed and demonstrated experimentally. The realization of AOI was based on three types of nonlinearities in a VCSOA: Cross-Gain Modulation (XGM), nonlinear/bistable gain characteristics, and polarization gain anisotropy. The dependence of its Transfer Characteristics (TC) on various parameters were characterized and analyzed experimentally in such a way that a general guidance for optimization was established for AOI. The switching time of AOIs was measured to be <80ps.

In the section of AOFF, two different operation schemes were proposed, and the flip-flop operation was demonstrated by cross-coupling a pair of AOIs that have different separations of their intrinsic PDG windows. The experimental results and analysis showed that the speed of AOFF is limited by the time delay due to the feedback distance between two cross-coupled AOIs. This indicates that densely integrated AOFF is required for its high speed operation.
For AOPT, the ON-OFF of signal output is switched by a control input, which modulates the bistable switching threshold of the signal beam through Cross-Phase Modulation (XPM). The measurement showed an extinction of 6:1 at signal output as the control input was alternating between 0µW and 30µW.

Chapter 5 studied the nonlinear gain characteristics of the VCSOA subject to the external feedback. When the optical feedback is positive and co-polarized with the input beam, with the increase of the feedback ratio, the resonance of the VCSOA experienced a red-shift resulting in the enhanced nonlinear gain characteristics of the VCSOA. When optical feedback is cross-polarized with the input and its wavelength is detuned at the longer-wavelength side of both intrinsic PDG windows of a VCSOA, a self-sustained optical oscillation is observed for the first time. This oscillation generates a square-like waveform with an extinction ratio of 5:1 at 66MHz repetition rate and is self-sustained by the bistable switching of the VCSOA. The repetition rate is adjustable with the feedback distance while the switching speed is mainly limited by the dynamics of VCSOA bistability and XGM [3,4].

In addition, this dissertation summarized four different methods for controlling the nonlinear transfer characteristics of VCSOAs. Those four methods are tuning input detuning [1,2,5], adjusting input polarization (Multiple bistability), introducing a control beam (AOPT) and providing a positive optical feedback. The last three methods were demonstrated for the first time in VCSOAs.
6.2 Future directions

There are many VCSOA-related research topics that can be basically classified into three categories: the study of VCSOAs fundamentals, the investigation of potential applications, and the development of design, manufacturing and integration techniques.

For VCSOAs fundamentals, there are three important research areas in view of VCSOA-based logic operations. Those three areas are dynamics, noise and coherence of VCSOAs. In this dissertation, one unanswered question is the speed capability of AOI, which is determined by the dynamics of both bistability and XGM. The study of noise and coherence of VCSOAs become important for optimizing the signal quality and the stability of cascaded systems.

So far, various applications based on VCSOAs have been proposed and investigated. In addition to VCSOA-based optical logic operations discussed in this dissertation, VCSOAs have also shown to have good potential for all-optical image processing due to their 2-D integration capability while preserving coherence in optical amplification. Accordingly, we have demonstrated all-optical image inversion and edge detection based on a VCSOA [6]. In free-space optical interconnects, VCSOAs have been proposed to be used as phase conjugators and pre-amplifiers for improving signal detection. Lately, it was found that VCSOAs also exhibit angle correction capability showing a tolerance angle of 4 degree [7].

The ultimate goal for VCSOAs is their commercialization. This requires a high level of maturity in the device design, manufacturing and integration
techniques, which are still in their infancy. For instance, one barrier for any applications based on VCSOA arrays is non-uniform characteristics of VCSOAs, even though those devices are grown on the same wafer through the same process. The different characteristics of VCSOAs, especially the different operating wavelengths, prevent VCSOAs from being used massively in both parallel and cascaded systems. In addition, integrating and coupling VCSOAs with waveguide and other photonic devices are critical for advancing VCSOAs into practical systems with competitive performance. Much work remains to be carried out in this area.
6.3 References


