Vertical-cavity optical AND gate

Pengyue Wen*, Michael Sanchez, Matthias Gross, Sadik Esener

Electrical and Computer Engineering Department, University California, San Diego, 9500 Gilman Drive, La Jolla, CA 92037-0407, USA

Received 30 August 2002; received in revised form 6 February 2003; accepted 11 February 2003

Abstract

We have demonstrated, the first time to our knowledge, a low-input intensity high-contrast (10:1) optical AND gate based on the differential gain (optical bistability) observed in an 850 nm GaAs vertical-cavity semiconductor optical amplifier (VCSOA). The input switching power is about 6 \mu W, which equals to the intensity of 16 nW/\mu m^2. It is about 2 orders of magnitude lower than in in-plane semiconductor optical amplifiers. In the experiment the device also shows an optical gain of 10 dB.

© 2003 Elsevier Science B.V. All rights reserved.

PACS: 42.79.Ta; 42.65.Pc; 42.60.Da; 85.60.Jb

Keywords: Optical logical elements; Optical bistability; Amplifiers; Light-emitting devices

1. Introduction

The optical bistability (OB) occurring in semiconductor optical amplifiers (SOAs) has been studied extensively in view of the potential applications in all-optical signal processing [1,2]. Optical bistability refers to the situation in which two stable optical output states are associated with a single input state. The physical mechanism is based on a dispersive optical nonlinearity. The device consists of a resonator with a nonlinear medium that has a refractive index dependent on the incident light intensity. Hence, the optical path length of the cavity is a function of the incident light intensity. For a negative nonlinear medium, when an optical signal detuned to the long-wavelength side of a cavity resonance is fed into the amplifier, changes in the signal intensity shifts the cavity resonance towards the signal wavelength, thereby amplifying the intensity change. Researchers seeking to utilize the low switching energy and the presence of optical gain have demonstrated optical logic, optical memory functions and frequency-selective amplifiers based on the optical bistability in SOAs since the 1980s [2–4].

The first optical AND gate [5] based on OB which switches with microwatts of optical power has been reported in 1986. The experiment has shown a contrast of the high output state (with both input) to the low output state (with either input) of 5:1. The authors claimed [5] for an
optimized device with appropriate detuning the maximum contrast can be expected to be 10:1. Such a device is favorable for signal regeneration and data switching in all-optical networks. Furthermore, a two-dimensional array of optical AND gates [6] has been proposed to act as an optical crossbar switch.

Vertical-cavity semiconductor optical amplifiers (VCSOAs) are drawing increasing research attention in the past few years [7,8]. As compared with in-plane SOAs, VCSOAs exhibit several advantages including higher coupling efficiency and lower noise figure, due to their circular geometry and small dimensions. Devices operated at 850, 970 nm, 1.3 and 1.55 µm have been reported by several research groups [7–9]. For parallel optical processing, VCSOAs are more attractive since arrays are inherently easy to produce. Previously, we have reported the optical bistability observed in a VCSOA [10]. In addition to the advantages described above, the mature epitaxy growth technology makes it fairly easy to fabricate high-reflectivity distributed Bragg reflectors (DBRs). Therefore, high-Q cavity can enhance the nonlinear interaction between photons and gain medium inside VCSOA cavities, resulting in stronger device nonlinearity [10]. In this paper, we demonstrate, the first time to our knowledge, an optical AND gate based on optical bistability in a VCSOA. Experiments show that the switching intensity could be as low as 16 nW/µm², which is about 2 orders of magnitude lower than the typical value estimated in in-plane SOAs [1]. Furthermore, the device also amplifies the input signal by 10 dB.

2. Theory

The physical origin of OB in semiconductor optical amplifiers mainly arises from the change in the refractive index due to the change of free carriers [1]. The stimulated emission caused by the input optical signal reduces the free carrier concentration and hence the optical gain per length in the active region of the device. Since the material gain is related to the refractive index via the Kramers–Kronig relation, the refractive index in the active region is a function of the input optical signal. Hence, the effective cavity length is also dependent on the input optical signal. When an optical signal detuned from the resonant wavelength is fed into the optical amplifier, this input optical signal leads to a change of the refractive index of the active region. That, in turn, causes the resonant wavelength of the optical amplifier to shift. Thus, there is a change in the detuning, and, as this passes through the cavity resonance, it gives rise to optical bistability. In other words, OB occurs when changes in input optical signal power shift the cavity resonance through the signal wavelength, thereby reinforcing the power change and creating a positive feedback loop [11]. The process is damped by gain saturation. In the case of bistable operation, the continued shift past also damps the feedback. The detailed theory can be found in [12].

By setting the parameters to proper values, one can also obtain differential-gain characteristics in SOAs subject to an external injection [12]. In this degenerate case of OB, the hysteresis disappears and the nonlinear input–output characteristics became similar to the curve in Fig. 1(a). Such a transfer curve provides the possibility of logic operations. Two horizontal bands superimposed in Fig. 1(a) correspond to two logic states. Fig. 1(a) also shows the input optical intensities in order to perform AND operation. The truth table for AND operation is shown in Fig. 1(b). Essentially, the optical AND operation is optical switching (one beam switches the other beam on/off.)

In terms of experiments, optical switching based on the optical nonlinearity in SOAs caused by OB

![Fig. 1. (a) Differential gain and (b) truth table for AND gate.](image-url)
has been reported in GaAs devices at 0.8 μm [2], InGaAsP devices at 1.3 μm [13] and InGaAsP–InP devices at 1.5 μm [14]. Both theoretical analysis and experiments show that in order to achieve optical switching, the minimum input intensity for uncoated facet in-plane SOAs is of order 1 μW/μm² [1]. Thus for a laser whose active area is about 100 μm², one needs to inject light at a power level of around 100 μW to stand a chance of observing optical switching (or, optical bistability). This result is mainly due to the low facet reflectivity of the devices used in the experiments. Photon lifetime has been dramatically reduced by the low-Q cavities, and hence the average intensity in the optical amplifiers, which causes the stimulated emission, is lowered. This conclusion can also be obtained from the expression of the ratio of average intensity in the amplifiers to input intensity, which is given [11]

\[ I_{av} = \frac{(1 - R_1)(1 + R_2e^{2\Delta L})}{g\sqrt{1 - R_1R_2e^{2\Delta L}} + 4\sqrt{R_1R_2e^{2\Delta L}} \sin^2 \phi} \]

(1)

where \( R_1 \) and \( R_2 \) are the cavity mirror reflectivity. \( L \) is the cavity length. The net optical gain per unit length is denoted by \( g \). \( \phi \) is the single-pass phase delay.

By contrast to uncoated facet in-plane SOAs, VCSOAs have much higher mirror reflectivities (>98%). They have the same structure as vertical cavity surface emitting lasers (VCSELs), in which two high-reflectivity distributed Bragg reflectors (DBRs) are used as cavity mirrors. As a result of the high-Q cavity, input intensity required to achieve the same average intensity in the amplifiers for VCSOAs is much lower than for their in-plane counterparts [10].

3. Experiment

Our experimental setup is shown in Fig. 2. The whole setup is similar to an optical interferometer. A tunable DBR laser (TuiOptics DC100) is used as the input light (signal) source. Its wavelength is measured by the optical spectrum analyzer (OSA) after a 50/50 beam splitter. The spatial filter cleans up the spatial profile of the input beam to increase the coupling efficiency. Four beam splitters are put in the optical path to form two arms. A chopper is placed in one arm to modulate the light intensity. Meanwhile, a phase compensator is used in the other arm to keep the two optical arms in phase. A polarizer is used in the setup to align the input light polarization to the primary polarization direction of the VCSOA. The input and output (amplified) powers are measured by power meters A and B, respectively. Since the splitting ratio of the beam splitters are all 50/50, the optical signal measured by power meter B is 1/4 of the total output power from VCSOA.

In our experiment, an 850 nm VCSEL with 20 μm aperture size and 1 – λ cavity fabricated as a discrete light transmitter has been used as a VCSOA. This device has high-reflectivity DBR structures (top mirror: \( R_t > 98% \), and bottom mirror: \( R_b > 99.5% \)). The device is operated in the reflection mode (signal enters and exits the device from the same DBR mirror) and is biased at about 90% of its lasing threshold. In order to achieve stable dispersive switching operation, precise wavelength and temperature controls are needed. To this end, the device is mounted in a temperature-controlled holder with precision of 0.01 °C to minimize thermal fluctuation. The current source for the VCSOA has output accuracy of 1 μA. The source laser is also temperature and current controlled with a high precision source, so the input wavelength is stabilized with a precision of ±1 pm.

The steady-state input–output (differential gain) characteristic is plotted in Fig. 3. From it we can
see that both arms experience the same optical nonlinearity when the input power reaches about 6 µW. As discussed earlier, the device bias condition and the detuning of input signal from the cavity resonance determine this switching power. Results of optical AND gate operation are illustrated in Fig. 4: input B is switched on/off by input A. The on/off ratio is about 10:1. In the experiment, the optical power in each arm is chosen to be 5 µW, or, equivalently, 16 nW/µm², which is about 2 orders of magnitude lower than in-plane SOAs. In addition, the optical gain for the input optical signal is 10 dB. Although the input in our experiment are split beams from a single laser, in practice, they could be replaced by two separate laser sources as long as the light from them are coherent to each other.

4. Discussion

From the experiment, we have observed a much lower minimum switching intensity in a VCSOA compared to in-plane SOAs. This is due to the structure of VCSOA, which has the quantum wells (active region) centered around two high-reflectivity DBRs with the standing wave peaks at the
active region. The active region experiences the highest photon intensity, and hence the optical nonlinearity is dramatically enhanced. Experimentally, a minimum switching intensity of 16 nW/μm² has been demonstrated. We believe this value can be further reduced to below 10 nW/μm² by adopting higher reflectivity DBR structures. Low-intensity switching makes VCSOAs favorable for the applications where low optical intensity is critical, such as bio-photonic detection of live cells.

Another potential advantage associated with a VCSOA as an optical AND gate is the high-frequency performance. It has been shown that the carrier lifetime limits the high-frequency response of OB [15,16]. For VCSOA, due to its quantum well structure and small volume of gain medium, it should have better high-frequency performance. Finally, the 2D array fabrication capability makes VCSOAs very attractive for parallel optical information application.

5. Conclusion

In this paper, we have demonstrated a low-input intensity high-contrast optical AND gate based on a VCSOA. Experiments show that the minimum input intensity is 16 nW/μm², which is about 2 orders of magnitude lower than in in-plane semiconductor optical amplifiers. The AND gate has an on/off ratio of 10:1 and 10 dB optical gain for input signals.

References