Optical bistability in a Vertical-Cavity Semiconductor Optical Amplifier (VCSOA): pulsed input

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Abstract: We report experimental observations of optical bistability in a vertical-cavity semiconductor optical amplifier subject to an external pulsed input. Results show that the nonlinear transition exists with 1ns-duration pulsed input.

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1. Introduction

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

So far, most of the experiments reported in the literature have been conducted with in-plane SOAs, in which the light input/output direction is parallel to the substrate. With in-plane devices, the possibility of the large-scale integration is limited. In the past few years, VCSOAs have drawn increasing research attention [7,8]. As compared to in-plane SOAs, they exhibit several advantages including higher coupling efficiency to optical fibers and lower noise figure due to their circular geometry and small dimensions, respectively.

Previously, we have reported the observation of optical bistability in a VCSOA [9]. The results have shown that the optical hysteresis loop can be obtained with CW input power as low as 2 µW when the device is biased close to its lasing threshold. In addition, based on this device nonlinearity, the first vertical-cavity optical AND gate has also been demonstrated [10]. In this paper, we report experimental results of the optical bistability in a reflection-mode operated VCSOA (input signal enters and exits from the same side of the device) subject to an external pulsed input. With the same experimental conditions, it shows that the optical input power required for pulsed input to obtain this nonlinearity is similar to the requirement for CW input. Furthermore, measurements also show that the rise and fall time of this nonlinear transition are on the order of 100ps. This indicates that VCSOAs are promising candidates to achieve fast optical logic operation.

2. Theory

The physical mechanism of the optical bistability in a SOA mainly arises from the dependence of the refractive index on the carrier concentration for wavelengths close to the forbidden band-gap [1,11]. Since the optical input can deplete the carrier concentration through stimulated emission, the length of the optical path of the cavity is a function of input intensity. When an optical input detuned to the long-wavelength side of the cavity resonance is fed into the amplifier, the resulting carrier depletion due to the increased internal intensity shifts the cavity resonance towards the input wavelength. This in return enhances the internal intensity, leading to a positive feedback loop. The detailed description can be found in [1,9,12].

3. Experimental results

The experimental setup is depicted in Fig. 1. A vertical-cavity surface-emitting laser (VCSEL) with center wavelength of 850nm was used as the input light source. In addition to the DC bias, an electric pulse generator (RF source) was utilized in the setup to modulate the VCSEL. The initial wavelength detuning of the input was adjusted by adjusting the VCSEL DC bias current and the temperature of the mount, thus varying the source wavelength. The spatial filter cleaned up the spatial profile of the input beam to increase the coupling efficiency. Input and output light powers were measured by a digital communication analyzer (DCA). For a VCSOA biased at a given current, a primary polarization direction exists along which the amplifier gain is maximum. Therefore, a polarizer
was used to align the input light to that polarization. Furthermore, an optical isolator inserted in the optical path prevented reflected light from the amplifier reaching the source laser and giving rise to spurious results.

The amplifier is also an 850nm vertical-cavity semiconductor optical amplifier, which is composed of two high-reflectivity distributed Bragg reflector (DBR) mirrors to form a high finesse Fabry-Perot cavity. The lasing threshold current of the VCSOA was about 5.6 mA at 297 K. Since the device substrate is not transparent at 850nm, the VCSOA was operated in reflection mode. The device is mounted in a temperature controlled holder with a precision of 0.01°C, in order to minimize thermal fluctuation.

Fig. 2 shows the nonlinear response of the VCSOA with CW input [9]. Two curves in Fig. 2 have the same initial detuning but different bias currents: one is biased at 95% of its lasing threshold and the other at 98%. Experimentally, the input power in order to achieve optical switching is reduced from 4µW to 2µW as bias current is raised from 95% to 98%. This is because that, as the bias current is increased, the nonlinearity caused by the interaction between input light and gain medium becomes stronger due to higher intracavity photon intensity. And thus with the same detuning, the optical bistability occurs at lower input power when the bias current is higher.

With the same bias condition \( I_{\text{bias}} = 98\% I_{\text{th}} \), Fig. 3 shows the results obtained in the experiments where the CW input is replaced by pulsed input. Optical pulses with two different powers are used here as the input. The pulse duration shown in Fig. 3(a) is about 3ns. The output from the VCSOA shown in Fig. 3(b) indicates that the output corresponding to the 1µW input is not distinguishable to the noise floor, which is about 5µW. However, when the input pulse power is increased to about 3µW, the output pulses with the similar duration are clearly present. The spikes in Fig. 3(b) are caused by the process in which the cavity resonant wavelength sweeps over the input wavelength [1,11]. Similar nonlinear results are also observed with 1ns pulses shown in Fig. 3(c) and 3(d). The profiles of the input pulses shown in Fig. 3(c) are not exactly square due to the imperfection of the electrical modulation pulses. Nevertheless, one can conclude that the switching power for pulsed input is between 1 to 3µW.
which is consistent with the CW measurement results shown in Fig. 2. Fig. 3(d) shows that the rise time is about 100ps when the pulse duration of the input is about 1ns.

Optical switching power observed here is an order of magnitude lower than previously reported in in-plane devices [5,6]. This improvement is likely due, in part, to better coupling efficiency, but another major contributor should be the very high mirror reflectivities. The low mirror loss means that the optical intensity inside the cavity at a given input level will be larger in a VCSOA than for most FPSOAs. Consequently, the strength of the nonlinear interaction is enhanced, contributing to the low switching threshold. In addition, compared to in-plane SOAs, the ultrashort cavity of VCSOAs leads to a shorter photon lifetime, resulting in a faster response time.

4. Conclusion

In this paper, we report the experimental results of optical bistability in a vertical-cavity semiconductor optical amplifier subject to an external pulsed input. The power required to achieve bistability for pulsed input is similar to the requirement for the CW input. Furthermore, results also show that the nonlinear transition has rise/fall time on the order of 100ps. The low input switching energy, fast response time and vertical emitting structure make VCSOAs the ideal devices for parallel logic operations.

References