Optical AND operation based on Vertical-Cavity Semiconductor Optical Amplifiers (VCSOAs)

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Abstract: We have demonstrated, the first time to our knowledge, a low input intensity (16nW/µm²) high contrast (10:1) optical AND gate based on a VCSOA. In the experiment the device also shows an optical gain of 10dB.

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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 for decades [1, 2]. Optical bistability refers to the situation in which two stable optical output states are associated with a single input state. Due to its low switching energy and the presence of optical gain, optical logic, optical memory functions and frequency-selective amplifications have been demonstrated based on the optical bistability in SOAs since the 1980’s[2 ,3, 4]. The first optical AND gate based on OB which switches with microwatts of optical power has been reported in 1986 [5]. Such a device is favorable for signal regeneration and data switching in all-optical networks. Furthermore, a two-dimensional array of optical AND gates could also act as an optical crossbar switch [6].

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. 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. In this paper, we demonstrate, the first time to our knowledge, an optical AND gate based on a VCSOA. Experiment shows that the switching intensity could be as low as 16nW/µm², which is about 2 orders of magnitude lower than the typical value in in-plane SOAs.

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 biased below its threshold, 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

Fig. 1: (a) Differential gain (b) Truth table for AND gate
optical signal power shift the cavity resonance through the signal wavelength, thereby reinforcing the power change and creating a positive feedback loop[7]. The detailed theory can be found in reference [8].

By setting the parameters to proper values, we can also obtain differential-gain characteristics in SOAs subject to an external injection [8]. In this degenerated case of OB, the hysteresis disappears and the nonlinear input-output characteristics depicted in Fig. 1(a) provide 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 another beam on or off). In terms of experiments, optical switching based on the optical nonlinearity in SOAs caused by OB has been reported in all communication wavelengths [2, 9,10]. 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 $1\mu W/\mu m^2$ [1]. 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.

By contrast to uncoated facet in-plane SOAs, vertical-cavity semiconductor optical amplifiers (VCSOAs) have much higher mirror reflectivities (>98%) since 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, to achieve the same average intensity in the amplifiers, input intensity required for VCSOAs is much lower than for their in-plane counterparts.

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) power 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 850nm VCSEL with 20µm aperture size and $1-\lambda$ 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 exists 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 1µA. The source laser is also temperature and current controlled with a high precision source, so the input wavelength is stabilized with a precision of $\pm1$pm.
The steady state input-output (differential gain) characteristic is plotted in Fig. 3(a). We can see that both arms experience the same optical nonlinearity when the input power reaches about 6 µW. Results of optical AND gate operation are illustrated in Fig. 3(b): input B is switched on/off by input A. Optical AND function is performed. Fig. 3(b) shows 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, 16nW/µm², which is about 2 orders of magnitude lower than in in-plane SOAs. In addition, the optical gain for the input optical signal is 10dB.

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 well (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 16nW/µm² has been demonstrated. We believe this value can be further reduced to below 10nW/µm² by adopting higher reflectivity DBR structures. Low intensity switching makes VCSOAs favorable for the applications, where low optical intensity is critical, i.e. bio-photonic detection of live cells.

Another potential advantage associated with VCSOA as optical AND gates is the high-frequency performance. It has been shown that the carrier lifetime limits the high-frequency response of OB [11]. For VCSOA, due to its quantum wall structure and small volume of gain medium, it should have better high-frequency performance. We will report this part of the results in the conference. Finally, the 2-D array fabrication capability makes VCSOA very attractive in 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. Experiment shows that the minimum input intensity is 16nW/µm², which is about 2 orders of magnitude lower than in-plane semiconductor optical amplifiers. Meanwhile, the measurement also shows that the AND gate has an on/off ratio of 10:1 and 10dB optical gain for input signals.