CW laser light source with three-cascaded etalons for characterizing broad-band nonlinear complex-refractive-index modulations in ultrafast semiconductor optical amps

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Abstract

Nonlinear complex-refractive-index modulations, i.e. gain modulation and phase modulation, in semiconductor optical amplifiers (SOAs) are important factors in designing ultrafast and low power consumption all-optical devices. These modulation properties, which originate in carrier density changes of material, have a mutual dependence through Kramers-Kronig relation[1]. However, these modulation properties depend greatly on nano-structure of SOA. Therefore, a systematic understanding about these dependences is needed in order to reduce further the power consumption of SOAs. In this research, we have developed a new broad-band tunable continuous-wave (CW) laser light source for characterizing the nonlinear complex-refractive-index modulations in ultrafast SOAs.

1. Introduction

All-optical signal processors based on SOA's nonlinearities are promising devices for future high-capacity optical time division multiplexing-wavelength division multiplexing networks, due to their ultrahigh response, low power consumption, and integration potential[2]. In fact, all-optical demultiplexing, 3R regeneration, and wavelength conversion based on cross-phase modulation (XPM) in SOAs have been achieved for operation frequencies exceeding 100 GHz [3-5]. These all-optical demonstrations typically consumed of 0.4~1.0 W electrical power[6], while latest electrical demultiplexer consumed 5.5 W in 100-GHz operation[6].

In order to develop even lower power consumption all-optical devices, we focus on the confinement effect of electrons in low dimension nano-structures. This effect can raise the unsaturated optical gain, which will result in a lower power consumption of SOA. However, it also narrows the bandwidth of gain spectrum, which will limit the all-optical devices' speed in ultrafast operation region. This trade-off relation between power consumption and operation speed is now a main limitation for developing low power consumption ultrafast all-optical signal processors. To solve this trade off problem, a systematic study of gain modulation and phase modulation properties in different SOA's nano-structures are required. For this purpose, a broad-band CW tunable laser light source is necessary.

In the work, we have developed a new tunable CW laser scheme, utilized the Vernier effect of three-cascaded etalons, for characterizing broad-band nonlinear complex-refractive-index modulations in ultrafast SOAs.

2. Vernier magnification principle

Utilizing Vernier magnification effect is a popular method for realizing the tunable function of laser[7]. In our CW laser light source, we utilize this effect to magnify the shift amount of peaks in transmission spectrum when tuning the etalon's incident angle.

The decrease of free spectral range (FSR), when increasing the incident angle of etalon from 0 rad. to θ rad., will result in the blue shift of transmission spectrum. The ratio of this blue-shift amount $\delta\lambda$ to peak wavelength λ_{peak} is given by

$$\delta\lambda / \lambda_{peak} = -2\sin^2\left(\theta / (2n_r)\right) \cdots (1)$$

Where n_r is the refractive index of etalon.

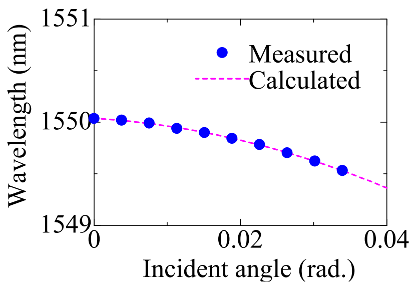

Fig. 1. Blue-shift amount and etalon's incident angle (FSR: 39.92 GHz)

Fig. 1 shows measurement and calculation results of blue-shift amount of one transmission peak, when increasing etalon's incident angle. The measurement result, which has a very good agreement with calculation result, suggests a new method of controlling laser wavelength by etalon. However, the effective tuning range of 40 GHz FSR etalon is only 0.31 nm at 1550 nm wavelength region. Hence, we need to magnify this amount to realize the broad-band tunable function of laser light source. In this case, Vernier magnification effect is a good candidate. The Vernier magnification factor of two-cascaded etalons scheme can be defined as:

$$A_{ver} = FSR_2 / \left| FSR_1 - FSR_2 \right| \cdots (2)$$

Where FSR_1, FSR_2 is free spectral range of etalon 1 and etalon 2, respectively.

Fig. 2 shows measurement and calculation results of blue-shift amount of one transmission peak in two cascaded etalons scheme, when increasing 1 etalon's incident angle. A very good agreement between the measurement result and the calculation in this case shows that two-cascaded etalons (FSR_1: 41.31, FSR_2: 39.92 GHz) scheme had successfully magnify the blue-shift amount of transmission peak by 30 times compare to the single etalon case.

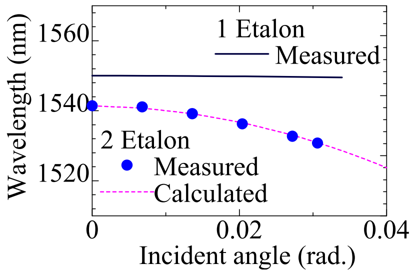

Fig. 2. Blue shift amount and incident angle in two-cascaded etalons (FSR: 41.31, 39.92 GHz) scheme

According to (2), we can get a larger magnification factor by minifying the difference of two FSR. However, this will cause the decreasing of extinction ratio in transmission spectrum as calculation results shown in Fig. 3. We also measured the extinction ratio in two different magnification cases (Magnification factor: 30, finesse: 93, 37; Magnification factor: 1000, finesse: 93, 93) and found that experimental result has a same trade-off relation (Fig. 3). This trade-off is the main limitation to tunable range of two-cascaded etalons scheme.

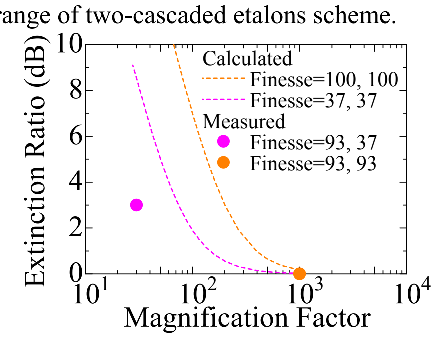

Fig. 3. Trade off relation between extinction ratio and magnification factor of two-cascaded etalons

3. Three-cascaded etalons scheme

In two-cascaded etalons scheme, we can only have high extinction ratio with small magnification factor or low extinction ratio with large magnification factor. To realize high extinction ratio and large magnification factor at the same time, we proposed three-cascaded etalons scheme, which can be considered as 2 two-cascaded etalons schemes separately. With three-cascaded etalons scheme we aimed to make a 100-nm tunable CW laser with the signal-to-noise ratio over 20 dB. Our experimental setup is shown in Fig. 4.

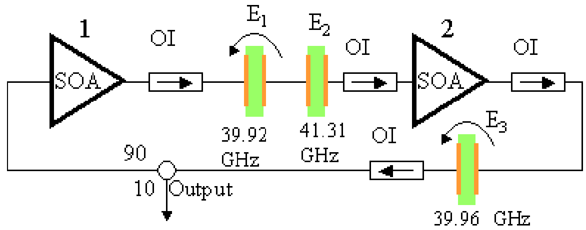

Fig. 4. Three-cascaded etalons CW laser light source
SOA: Semiconductor Optical Amplifier,
E: Etalon, OI: Optical Isolator

Bulk SOAs (Inphenix, Inc.) used in CW laser light source, have a wide gain band in order to support the broad-band tunable function. The SOAs' injection current was set from 100 mA to 250 mA depend on CW laser light's wavelength. To compensate optical losses at etalons, we used 2 SOAs as shown in Fig. 4. FSR of etalon 1, 2, 3 are 39.92, 41.31, 39.96 GHz, respectively. The finesse of etalon 1, 2, 3 are 93, 93, 37, respectively. Optical isolators are inserted in front and back of SOA to prevent light of backward direction consumes SOA's gain. In this setup, two-cascaded etalons 1 and 2 act as a broad-band tunable band-pass filter to light from SOA 1. While etalon 3 selects single peak from that transmission spectrum and feed it back to SOA 1. If total gain is larger than total loss then laser oscillation occurs.

4. Experimental results

In this setup, we can tune laser wavelength in steps of 10 nm by adjusting incident angle of etalon 1 only or that of etalon 3 only. Besides, the wavelength can be tuned in steps of 0.3 nm by adjusting incident angle of etalon 1 and 3 at the same time. 10-patterns wavelength spectra of CW laser light generated by three-cascaded etalons scheme are shown in Fig. 5. With this scheme, tunable width of 90 nm and signal-to-noise ratios larger than 25 dB CW laser source is achieved. The remaining limitations of tunable width in this scheme are the increase of optical loss when increasing etalon's incident angle, the limited SOA's gain band and the amplified spontaneous emission noise of SOA.

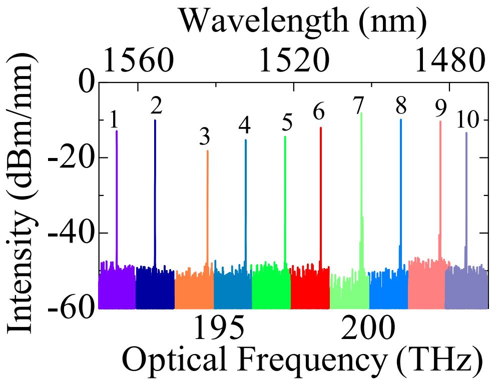

Fig. 5. 10-pattern wavelength of CW laser light source (Resolution= 1.3 GHz or 10 pm)

We used this three-cascaded etalons CW laser light source for measuring unsaturated gain spectra and nonlinear phase shift spectra of bulk SOA (Inphenix Inc.). The results are shown in Fig. 6. The gain error causes by the time fluctuation in intensity of CW laser light source's output is about 1dB. However, the agreement with results measured by utilizing commercially available distributed feedback laser diode (DFB-LD) in Fig. 6 shows the reliable of our new laser scheme. To measure nonlinear phase shift spectrum, we input pulse light (pulse energy: 100 fJ, center wavelength: 1555 nm, repetition frequency: 12.5 GHz, pulse width: 2 ps) and CW laser light (small signal) into SOA at the same time[2]. Pulse light modulates carrier density of SOA then that carrier density change causes phase shift of CW laser light. Because this unsaturated gain spectrum and nonlinear phase shift spectrum strongly depend on nano-structure of SOA. We hope that the measurement results in different SOA's nano-structure will give us a deeper understand about the effects of nano-structure to SOA's nonlinear complex-refractive-index modulations and SOA's power consumption.

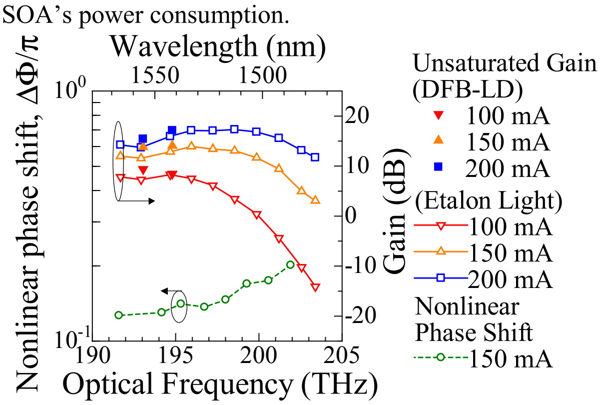

Fig. 6. Unsaturated gain and non-linear phase shift spectrum of bulk SOA at different injection current

5. Conclusions

In order to systematically study about the dependence of SOA's nonlinear complex-refractive-index modulations on nano-structure, we proposed a three-cascaded etalons scheme for broad-band tunable CW laser. With this scheme we experimentally achieved a tunable width of 90 nm, signal-to-noise ratio of over 25 dB CW laser source. We also utilized this laser light source in measuring the nonlinear complex-refractive-index modulations in bulk SOA. We hope that this ability for evaluating the complex-refractive-index modulations will help the other research groups design more effective SOAs, which can reduce power consumption of all-optical signal processors significantly in the near future.

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