Effects of the residual Fabry–Pérot cavity modes on the non-degenerated four-wave mixing in DFB semiconductor lasers

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In this paper, the influence of the residual Fabry–Pérot (F-P) cavity mode on the non-degenerated four-wave mixing (FWM) in DFB semiconductor lasers (DFB-SLs) has been investigated experimentally. The results show that the FWM can be enhanced obviously when the probe wavelength matches one of the F-P cavity modes, and the high conversion efficiency can be achieved even if the frequency detuning between the injection probe frequency and free-running frequency of the DFB-SL is up to THz.

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1. Introduction

All-optical wavelength conversion based on four-wave mixing (FWM) is one of key technologies in future multi-wavelength telecommunication systems [1]. Compared with other conversion technologies, FWM has some advantages such as modulation format transparency, identicalness between the converted signals and the original, broader wavelength conversion range, continuous tuning, simultaneous conversion for multiple wavelengths et al.. Therefore FWM has great potential application in future all-optical telecommunication network [2-5].

Most of the reported FWM experiments for wavelength conversion usually use semiconductor optical amplifiers (SOAs) as the mixing device, and high conversion efficiency (up to 20 dB) can be achieved and continuous tuning can be realized. However, FWM based on SOAs require a strong external optical pump and a probe signal, which results in the structure complex. Moreover, the output signal-to-background noise-ratio (SNR) is limited by the strong amplified spontaneous emission noise [6-11]. Comparatively, FWM in DFB semiconductor lasers (DFB-SLs) not only can provide very high SNR but also has the advantage of simple structure for only an external probe signal is needed [12-13]. Based on the above-mentioned factors, this paper will present detailed experimental investigation of FWM in a DFB laser, especially emphasizes on the influence of residual Fabry–Pérot (F-P) cavity mode in DFB laser.

2. Experimental setup

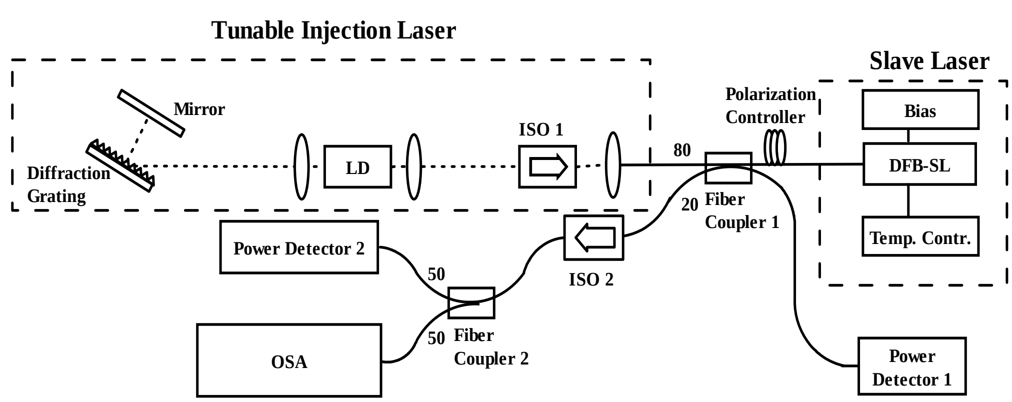

Fig. 1. Experimental setup for FWM in a DFB-SL. LD: laser diode; ISO: optical isolator; DFB-SL: DFB semiconductor laser; OSA: optical spectrum analyzer.

Fig. 1 shows the schematic of the experimental setup. The output of the tunable injection laser (SMSR>50dB) is coupled into a single-mode fiber and spilt by the optical fiber coupler 1 (20:80), 20% of the output is sent to the power detector 1, and the other 80% is injected into the DFB-SL. The DFB-SL is driven by ultra-low-noise current source (ILX-Lightwave, LDX-3412) at 35.02mA. Using a temperature controller (ILX-Lightwave, LDT-5412) with ±0.01K accuracy, the DFB-SL is stabilized at the temperature of 17℃. The output of the DFB-SL is sent to a detection system through the coupler 1 and the ISO 2. An optical spectrum analyzer (Ando AQ6317C) with a wavelength resolution of around 0.01nm is used to detect the optical spectra. Optical isolators are used to ensure unidirectional coupling.

In this experiment, we used an index-coupled DFB (threshold current is 8.2mA) semiconductor laser as the mixing device. Without the external optical injection, the optical spectrum of the DFB-SL at free running has been given in Fig. 2. When the current is 35.02 mA and the temperature is 17℃, the lasing wavelength is around 1550.3nm and some residual F–P modes beside the main peak can be found obviously.

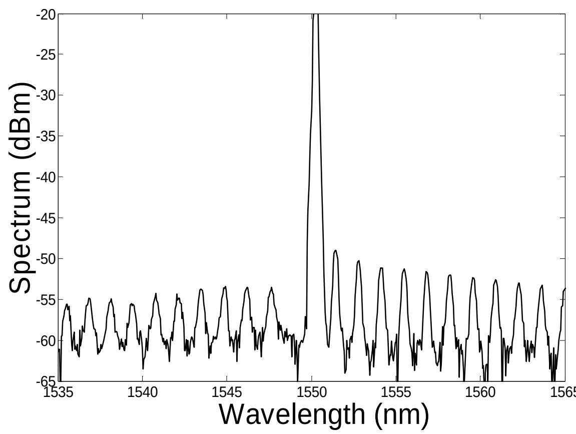

Fig. 2. The DFB-SL output spectrum at free running.

If the bias current and the temperature of DFB-SL being fixed, the characteristic of FWM in a DFB-SL is only determined by the detuning frequency Δf (= $f_m - f_0$, f_m is the frequency of the tunable injection laser and f_0 is the frequency of the DFB-SL at free running) and the injection power *P*. The Δf can be varied by changing f_m (which can be achieved through tuning the angle of reflection of the grating), and the different injection power *P* can be obtained through adjusting the bias current of the tunable laser or the coupling efficiency between the injection laser and the DFB-SL.

3. Results and discussion

3.1. Small frequency detuning

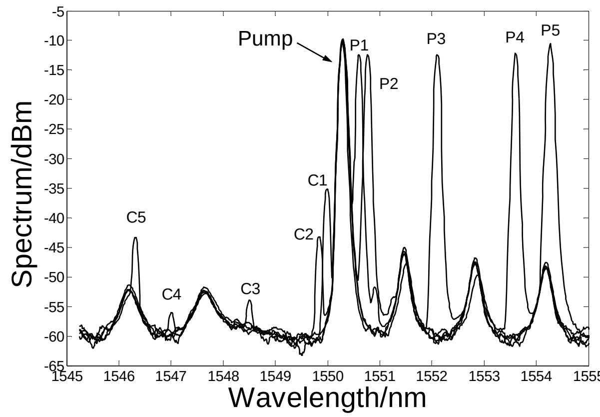

Fig. 3. Overlapped spectra of DFB-SL for probe signals with different wavelength and identical power.

Fig. 3 shows the overlapped spectra of DFB-SL for probe signals with different wavelength and identical power, where P1, P2, P3, P4 and P5 describe the probe power with different wavelengths, respectively, and C1, C2, C3, C4 and C5 are the conjugate-wave. From this diagram, it can be seen that a series of conjugate-wave have been generated by FWM, and the powers of conjugate-wave are obvious different for different probe light wavelength.

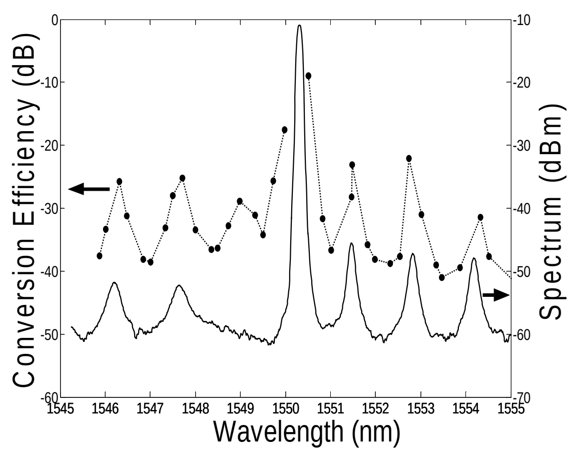

Fig. 4. Measured FWM conversion efficiency with conjugate-wave wavelength.

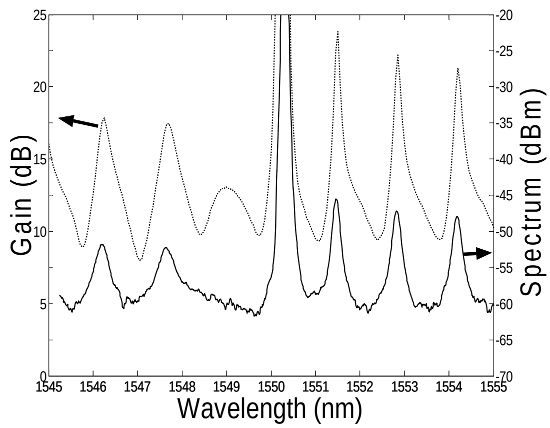

Fig. 5. Measured self-gain with different probe-wave different wavelength.

Fig. 4 shows the dependence of the conversion efficiency of FWM on the conjugate-wave wavelength. The FWM conversion efficiency is periodical fluctuation with the conjugate-wave wavelength, and the varying trend is agreed with the DFB-SL spectrum perfectly. Therefore the residual F-P cavity mode in DFB-SL will affect obviously the conversion efficiency of FWM. Additionally, there is an unexpected peak at 1549nm, which is owing to the combined action between resonant amplification effect of F-P cavity and the third-order nonlinear susceptibility [8]. The dependence of the gain obtained by the probe light on the wavelength has the similar characteristic, which is given in Fig. 5. The solid line indicates the DFB-SL spectrum at free running, and the dotted line is the gain obtained by probe light when the probe light power is very weak (about 0.013w). The peaks of gain can not be predicted only through using weak-probe wave theory, the effect of the cavity in DFB-SL must be considered. Combining Fig. 4 and Fig. 5, it can be concluded that the FWM in DFB-SL can be enhanced obviously when the probe light is located at one of the residual F-P cavity modes.

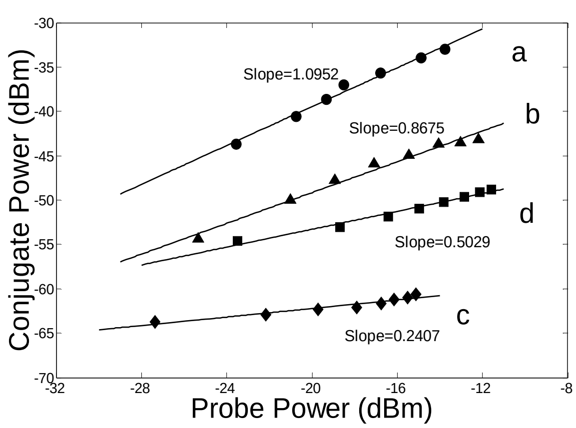

Fig. 6. Dependence of the measured multiple conjugate-wave output powers on the probe power.

The dependences of the output power of conjugate-wave on the probe light power have been given in Fig. 6 at different probe light wavelength. In Fig. 6, curves a, b, c, and d are correspond to probe light wavelengths are 1550.53 nm, 1550.68 nm, 1553.68 nm, and 1554.46 nm, respectively, where the straight lines linking each two points are obtained by the least squares theory, and the distribution of the line indicates the magnitude of the conversion efficiency. It is clear that the logarithm of conjugate-wave light power varies linearly with the logarithm of probe light power, and the conversion efficiency decreases generally with the increase of the frequency detuning. Especially, through comparing curves c and d, it can be seen that the conversion efficiency for 1554.46 nm (lager frequency detuning) is more than the conversion efficiency for 1553.686 nm (smaller frequency detuning), which is because 1554.46 nm is just located at one of the F-P cavity modes (see Fig. 3).

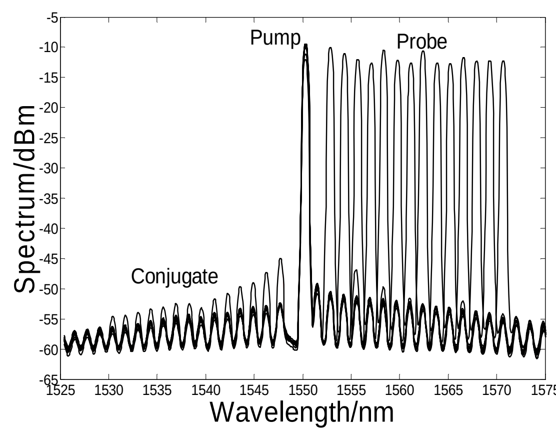

Fig. 7. Measured DFB laser spectra with probe detuning THz domain for FWM.

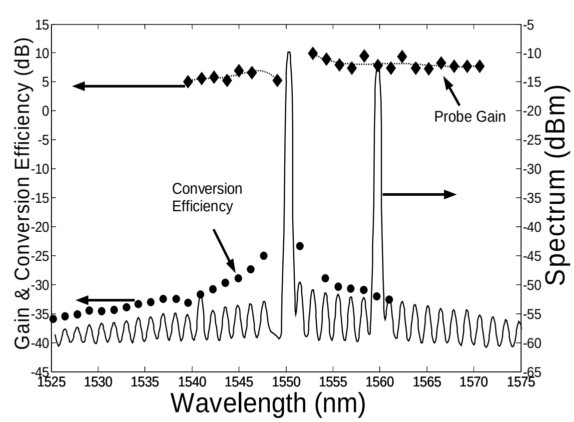

Fig. 8. Signal wavelength dependence of signal gain an internal conversion efficiency.

3.2. Large frequency detuning

Utilizing the amplification effect of the residual F-P cavity mode, the FWM with large range of frequency detuning (-1.25THz ~ +2.5THz) can be achieved, which is shown in Fig. 7, 8. It must be pointed that all the wavelength of the probe light are adjusted to match one of the F-P cavity modes so as to obtain the larger conversion efficiency. Fig. 7 is the overlapped spectra for different wavelength probe light, and Fig. 8 is the dependence of the gain obtained by probe light and the conversion efficiency on the wavelength of the probe light. From Fig. 8, it can be seen that large conversion efficiency can be obtained at large range of frequency detuning (>2THz), and the positive frequency detuning is more favorable to generate FWM, i. e., the conversion efficiency of FWM has the asymmetric characteristics [14]. In general, the FWM phenomenon in the DFB-SL can be observed in a broad wavelength range due to the enhancing action of the residual F-P cavity.

4. Conclusions

In summary, the influence of the residual F-P cavity mode on the non-degenerated four-wave mixing in a DFB semiconductor laser has been investigated experimentally. The results shows that the FWM will be enhanced obviously when the wavelength of the probe light is identical to one of the F-P cavity mode, and the FWM phenomenon in the DFB-SL can be observed in a larger wavelength range (-3.1THz~1THz) due to the enhancing action of the residual F-P cavity. We hope that the obtained results in this paper will be useful to improve the wavelength conversion technology based on FWM.

Acknowledgements

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