IEICE Electronics Express, Vol.5, No.23, 1024–1029

Single to multi-wavelength conversion using gain modulation in an FP-LD

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Abstract: We demonstrate an all-optical single to multi-wavelength converter using gain modulation in a Fabry-Perot laser diode (FP-LD at 10 Gb/s. It can simultaneously provide 1 to 4 output channels and support both up and down conversion. We observed over 14 dB extinction ration (ER) and power penalty of around 1.5 dBm at a BER of 10^{-9}. The results ensure to increase the number of output channels. The proposed scheme can be applied to multicasting function as well as 1xN wavelength conversion in wavelength division multiplexed optical networks.

Keywords: multi-wavelength conversion, Fabry-Perot laser diode, gain modulation, injection locking
Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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DOI: 10.1587/elex.5.1024
Received October 24, 2008
Accepted November 07, 2008
Published December 10, 2008

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1 Introduction

All-optical wavelength converters will play an important role to increase the flexibility and capacity of WDM optical network [1]. To reduce the blocking probability of wavelengths and increase the capacity of WDM optical network, the concept of wavelength reuse is required. For a multi-wavelength converter (MWC), several schemes have been proposed so far; they were based on cross-absorption modulation in an electro-absorption modulator [2], or cross-gain modulation of amplified spontaneous emission spectrum of a semiconductor optical amplifier [3]. However, these schemes were suffered from high crosstalk power penalty (CPP), which is proportional to the number of channels [4]. In [4], it is proposed a MWC based on absorption modulation of an injection locked FP-LD. This scheme shows low power penalty and high ER. However, in this scheme, the speed is limited up to 2.5 Gb/s or an additional CW holding beam is required for increasing the bit rate over 2.5 Gb/s in absorption modulation technique [5] and this scheme requires an expensive and highly polarization sensitive polarization beam splitter (PBS) for transverse magnetic (TM) modes separation. Moreover, an extra polarization controller is required in FP-LD side in TM mode absorption scheme. Additional CW holding beam, PC and PBS makes the system complex and costly. Utilizing PBS inside the module seems the system impractical because the PBS is highly polarization sensitive.

In this paper, we demonstrate an all-optical MWC at 10 Gb/s using gain modulation of an injection-locked FP-LD. Principle of gain modulation is quite different from absorption modulation principle [4]. In gain modulation technique, it doesn't require any PBS and it supports high speed operation without additional holding beam. The architecture of gain modulation is simple and cost-effective and it supports high-speed operation with up and down wavelength conversion.

2 Operation Principle

If the transverse electric (TE) polarized light of any single mode laser beam with the power over a certain threshold is injected slightly longer wavelength side of any longitudinal mode of the FP-LD, the corresponding mode of the FP-LD is locked by the TE polarized light of the injected beam and the injected beam experiences a power gain, while all other side modes of the FP-LD are suppressed. If the TE polarized light of another laser beam is injected to the FP-LD with a detuning range longer and the power is higher than the previous beam, the second beam experiences power gain and the second beam locks the FP-LD while the first beam experiences reduction of its gain by releasing the locking state. The pictorial presentation of gain variation of the first injected TE polarized light (probe) by the second TE polarized light (pump) is shown step by step in Fig. 1. In the real experiment, the second injected beam [Fig. 1 (d)] is considered as the input beam (pump) which carries digital information and the first injected beam [Fig. 1 (b)] is considered as the output beam (probe) by which input information is received

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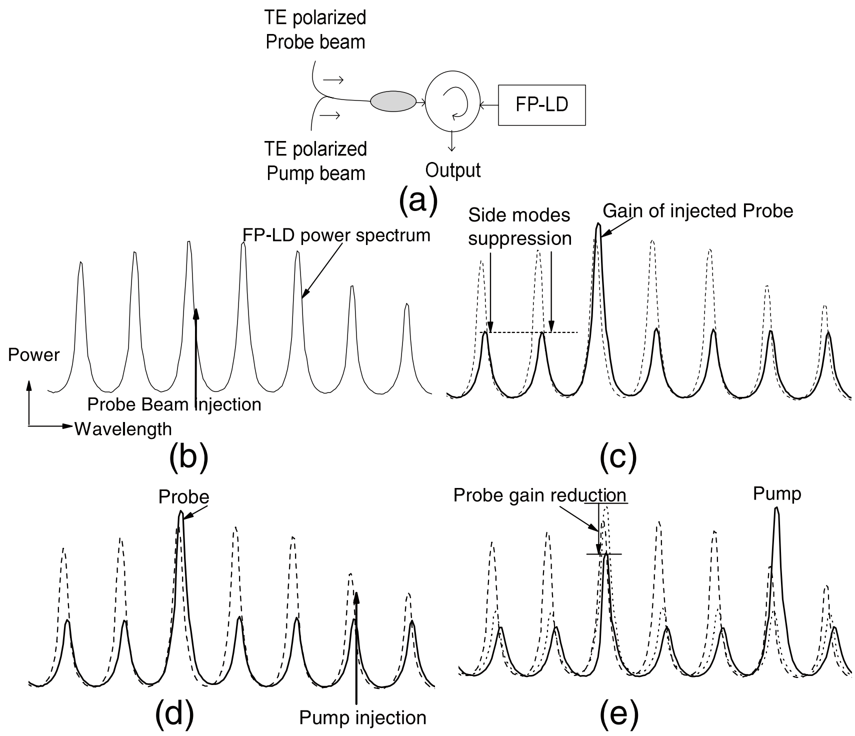

Fig. 1. Principle of wavelength conversion using gain modulation of TE polarized lights in an FP-LD. (a) Basic circuit of wavelength conversion. (b) Power spectrum of the FP-LD, (c) the gain of injected beam (probe) with suppression of side modes. (d) Pump beam injection to another longitudinal mode of the FP-LD. (e) the reduction of the gain of probe beam and the gain of the pump beam power with locking.

in the output terminal with a converted wavelength.

According to the principle, in absence of input (pump), the output power (probe) is logically HIGH [Fig. 1, (c)] and in presence of input, the output power is logically LOW [Fig. 1, (e)]. The power level variation of the probe beam in HIGH-LOW manner is the gain modulation of the probe beam by the pump beam. For gain modulation, the injection power of the modulated (probe) signal should be lower and the detuning should be shorter than that of pump signal. Based on this gain modulation, any digital data carried by the pump beam (input) can be receive from probe beam (outputs) in a complementary fashion, where the probe and pump wavelengths are different. Thus, the input information can be received in output terminal with different wavelength. This is the principle concept for all-optical wavelength conversion by the gain modulation of the TE polarized light. The operation of 1 to 4 channel wavelength converter will be discussed in experimental setup and results section.

3 Experimental setup and results

Fig. 2 shows the experimental setup for the all-optical 1x4 MWC. In this

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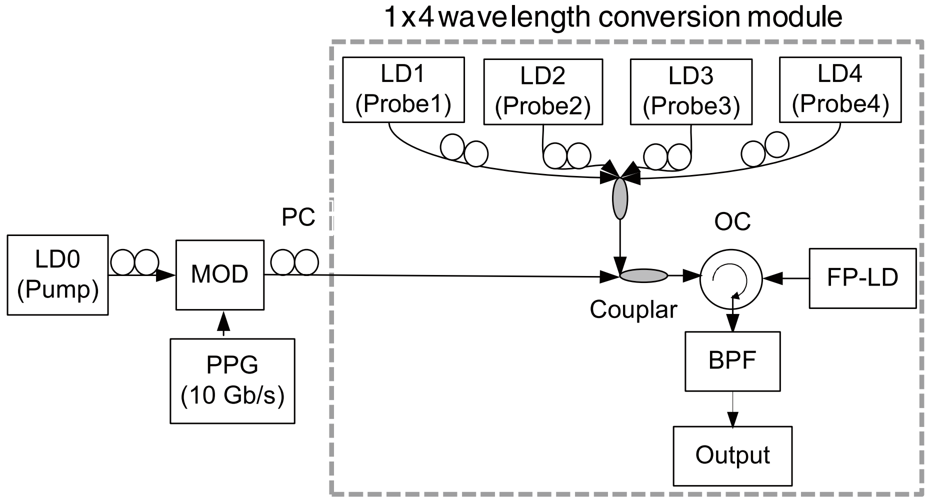

Fig. 2. Experimental setup for the 1x4 MWC. LD: Tunable Laser Diode, MOD: Optical intensity Modulator, BPF: Optical Band-Pass Filter, PC: Polarization Controller, OC: Optical circulator, FP-LD: Fabry-Perot laser diode.

figure, the FP-LD has a nominal lasing wavelength of 1550.16 nm and longitudinal mode spacing of 1.12 nm. The FP-LD has threshold current (I_{th}) of 04 mA; and it was biased at 8 mA. The pump beam from LD0 was first modulated by a Mach-Zehnder intensity modulator at 10 Gb/s using non-return-to-zero signal of 2^{31}-1 pseudo random bit sequence. Then, it was aligned by PC to get TE polarization and was coupled into the FP-LD via the circulator. The pump beam wavelength was set at 1550.30 nm (detuning = 0.14 nm) near to the central longitudinal mode of the FP-LD, so the FP-LD is easily locked to the pump beam when the pump beam is at 1level. The TE modes continuous probe beams from tunable lasers (LD1 to LD4) were coupled into the FP-LD via the circulator. To have up and down wavelength conversion, the four probe wavelengths were adjusted such that two of them were adjusted to the lower side (for down conversion) of the pump wavelength and two of them were higher side (up conversion) of the pump wavelength. The detuning of each of the four probes was 0.06 nm and the wavelengths were as 1539.02 nm, 1541.24 nm, 1552.44 nm, and 1560.50 nm and the pump. The probes were set far from each other to investigate that this scheme guaranty wide band multi-wavelength conversion.

Fig. 3 (a1) shows the spectra of output signals after the circulator when the pump signal is activated (solid line) or not (dot line). Four probes [(a), (b), (c) and (d)] power spectrum show very similar on-off power difference and all the probes power on-off ratio were very high ($>$ 16 dB). The corresponding eye diagram of four converted wavelength are shown in Fig. (a1). We measured the extinction ratio from the eye diagram and it was around 14 dB in each of the conversion.

Bit-error-ratio (BER) is the fundamental measure of performance for a digital communications system. It shows how accurately the receiver can

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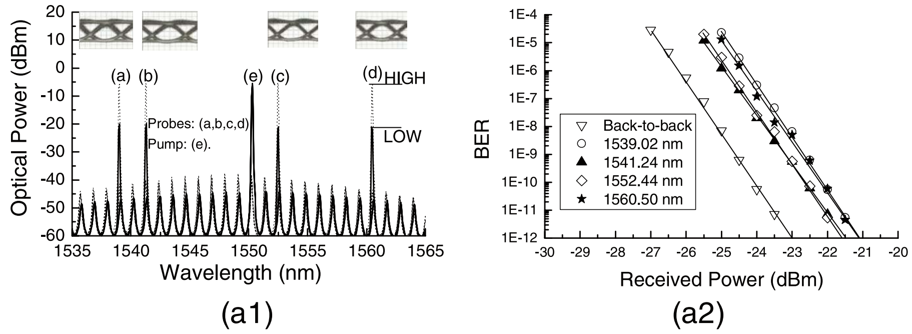

Fig. 3. Results: (a1) Optical power spectrum of four probes with (solid)/without (dot) pump, eye diagram of converted signal. (a2) BER tests.

determine the logic state of each transmitted bit. We performed the BER measurements in our experiment. Fig. 3 (a2) shows the measured BER curves of multi-converted wavelength signals at 10 Gb/s together with back to back measurements. The data format of 2^{31}-1 NRZ pseudorandom bit stream was used. It can be seen that the wavelength conversion leads to a power penalty of less than 2 dBm at a BER of 10^{-9}. Low power penalty proves that this wavelength conversion scheme performs well. Moreover, as can be noted that, no BER floor was observed up to BER values of 10^{-12}, which proves the excellent performance of the wavelength converter. According, to our observation, it can be noted that by controlling the polarization controllers precisely it is possible to reduce the penalty more. From the BER measurement, it can be noted that the probe wavelength closer to the nominal wavelength shows lower power penalty (< 1.5 dBm) than the probes set to longer distance from the nominal wavelength of the FP-LD. It can also be noted that we can get both up and down wavelength conversion by setting the pump in the nominal lasing mode of the FP-LD and the probes to both lower and higher wavelength sides. The investigated results of 1 to 4 wavelengths conversion guaranty to increase the number of channels. The expansion of the number of outputs could be the future works. The demonstrated all-optical MWC supports multiple outputs simultaneously which carry the same information but different wavelengths. Thus, this scheme can be used to implement multicasting functions in WDM systems.

4 Conclusion

We demonstrate an all-optical multi-wavelength converter using gain modulation of an injection-locked Fabry-Perot laser diode (FP-LD). A 10 Gb/s MWC of 1 to 4 output channels has been experimentally performed which supports both up and down wavelength conversion. We observed over 14 dB ER and power penalty of around 1.5 dBm at a BER of 10^{-9}. The results ensure to increase the number of output channels as well as higher speed operation. The proposed scheme can be applied to multicasting function as well as 1xN wavelength conversion in core node of wavelength division multiplexed optical networks as it is simple and cost-effective and supports high

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speed operation. We performed 10 Gb/s operation because in our laboratory we can perform maximum 10 Gb/s measurements. This scheme can be operated for higher speed wavelength conversion.

Acknowledgments

This work was supported by the Korean Science and engineering Foundation (KOSEF) grant funded by the Korean Government (MEST). (no. R11-2000-074-03002-0).

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