All-Optical Wavelength Conversion Using Absorption Modulation of an Injection-Locked Fabry–Pérot Laser Diode

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***Abstract*—A novel all-optical wavelength converter based on the transverse-magnetic (TM)-mode absorption modulation of a Fabry–Pérot laser diode (FP-LD) is proposed and demonstrated. An FP-LD shows absorption nulls for TM mode probe beam, which are red-shifted by an additional optical pump injection. Using this, the transmission of the continuous-wave probe beam can be optically controlled and wavelength conversion is, thus, achieved. The proposed scheme is simple and cost-effective, and can be used for very wide-range wavelength conversion. Bit-error-rate measurements at 2.5 Gb/s were performed, and the power penalties of 2 and 6 dB were observed, respectively, for noninverted and inverted wavelength conversion.**

***Index Terms*—All-optical wavelength conversion, Fabry–Pérot laser diode (FP-LD), injection locking, optical communications, wavelength-division multiplexing.**

I. INTRODUCTION

ALL-OPTICAL wavelength converters are key functional elements that can allow transparent interoperability, contention resolution, wavelength routing, and, in general, better utilization of the network resources under dynamic traffic patterns in wavelength-division-multiplexed optical networks [1]. Various methods for all-optical wavelength conversion have been investigated up to now, including nonlinear optical gating based on fiber loop, cross-gain modulation, cross-phase modulation, four-wave mixing techniques using semiconductor optical amplifiers [1], [2] and difference frequency generation in quasiphase-matched waveguides [3].

One of the major goals of the current research is to develop simpler cost-effective wavelength converters that can operate at submilliwatt input powers and, thus, avoid the need of an additional amplifier stage. A promising approach for such a wavelength converter is to use an injection-locked Fabry–Pérot laser diode (FP-LD). An all-optical wavelength converter based on dual-wavelength injection locking (DWIL) of an FP-LD was recently proposed [4] and experimentally demonstrated at 3 Gb/s using a commercially available FP-LD [5]. Furthermore, by polarization switching of the converted output, an optically controlled 1×2 switch was also proposed [6].

In this letter, we propose a novel all-optical wavelength converter using the absorption modulation of an FP-LD, which is based on transverse-magnetic (TM)-mode absorption nulls of an FP-LD and its red-shift, which is induced by an additional optical injection. The proposed scheme differs from the DWIL-based schemes in that the absorption modulation of the probe beam is used here, whereas the gain modulation due to injection-locking of the probe signal is utilized in the DWIL-based schemes. The proposed wavelength converter has the advantages of a simple and cost-effective configuration and the capability of both logically inverted and noninverted conversion. Moreover, since the TM-mode absorption property of an FP-LD is utilized, the proposed wavelength converter can be used for very wide-range wavelength conversion, whereas the range of wavelength conversion using DWIL is limited by the gain bandwidth of an FP-LD since the probe signal should lie at one of the lasing modes.

II. SYSTEM CONCEPT

The FP-LD used in the experiment has a multiple quantum-well structure, and it favors the transverse-electric (TE) mode and has a gain bandwidth of about 20 nm. When an FP-LD is injected with a TE-polarized light with its wavelength close to one of TE longitudinal modes of the FP-LD, the corresponding mode is locked while side modes are suppressed. This injection-locking phenomenon is well known and has various applications such as stabilization of light sources, as wavelength converters, and for polarization control. However, the FP-LD shows absorption nulls at its TM longitudinal modes when injected with a TM-polarized wavelength tunable signal instead of a typical injection-locking characteristic for TE-polarized optical input [7]. Fig. 1 shows the absorption spectra obtained by feeding an amplified spontaneous emission (ASE) source through a polarizer that is aligned with the TM axis of an FP-LD biased at near threshold (11 mA). The absorption nulls appear at each TM longitudinal mode and the span of the spectra is only limited by the ASE source bandwidth. It is also noted in Fig. 1 that an additional TE-polarized optical pump, which is injected to one of the TE longitudinal modes, locks the FP-LD, and causes the change of carrier density that results in the red-shift of absorption nulls due to the strong coupling between gain and refractive index in semiconductor materials [4], [5].

Fig. 2(a) shows the proposed wavelength conversion mechanism utilizing these two properties of an FP-LD, TM-mode absorption nulls, and the red-shift of the absorption nulls

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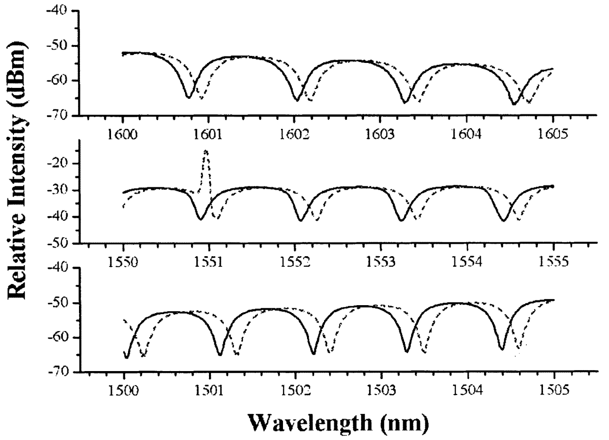
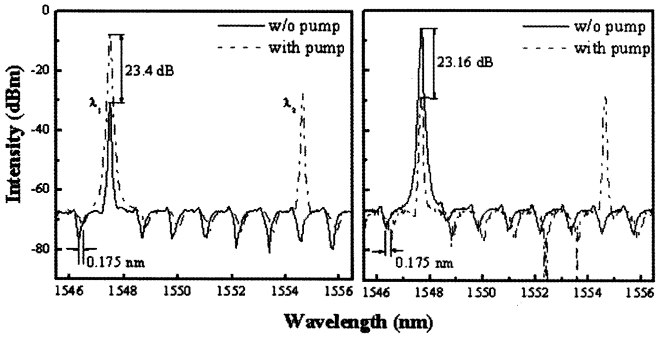


Fig. 1. TM-mode absorption spectra of FP-LD with (dotted line) and without (solid line) TE mode injection-locking by optical pump.



(a) (b)

Fig. 2. Proposed wavelength conversion mechanisms for (a) noninverted wavelength conversion and (b) inverted wavelength conversion.

by the TE-mode optical pump injection. The TM-polarized continuous-wave (CW) probe signal λ_1 is coupled into an FP-LD after being spectrally aligned with one of the TM longitudinal modes. Then, the probe signal is filtered out by the absorption property of the FP-LD. With the TE polarized optical pump signal λ_2 aligned with one of the TE longitudinal modes, the red-shift of absorption nulls causes the transmission of the probe signal. Thus, noninverted all-optical wavelength conversion is achieved from λ_2 to λ_1. In Fig. 2, it is noted that the red-shift of 0.175 nm is sufficient to obtain the change of probe power over 23 dB. Conversely, the probe signal can be located at a 0.175-nm-longer wavelength relative to its local absorption minimum. Then, an incoming pump light shifts the mode toward the minimum. As a result, inverted wavelength conversion can be realized, as shown in Fig. 2(b).

III. EXPERIMENT AND RESULTS

Fig. 3 shows the experimental setup for the proposed scheme. An FP-LD with a nominal lasing wavelength around 1550 nm and longitudinal mode spacing of 1.16 nm was used for the proposed wavelength converter. The FP-LD was biased at 16 mA, which is above threshold ($I_{\text{th}} = 11$ mA). The pump beam from a tunable laser (TLD1) was first modulated by a 2.5-Gb/s external modulator and then coupled into the FP-LD after being aligned with the TE polarization via PC1 and a polarization beam splitter (PBS). The injection-locking of the FP-LD at the wavelength of the pump beam was achieved by adjusting the TLD1's wavelength (1554.44 nm). The CW probe light from another tunable laser (TLD2) was then sent into the FP-LD via a circulator and the PBS. The polarization of the probe signal was aligned with the TM polarization by controlling PC2. The wavelength of the probe signal was adjusted to locate at the absorption null when the pump signal was at "0" level. Next, PC3 was adjusted so that the pump and probe beams, after passing through the PBS, were aligned with the TE and the TM axes of the FP-LD, respectively. Among the reflected outputs from the FP-LD, only the TM-polarized probe light was distinguished by the PBS and the optical circulator and was amplified by an erbium-doped fiber amplifier (EDFA). A bandpass filter was used to suppress the spontaneous emission noise of the EDFA. Tunable lasers were used in order to match the wavelengths of the pump and the probe signals to the TE and the TM longitudinal modes of the FP-LD. However, if an FP-LD with a temperature control circuit is specially designed so that it has the mode spacing of an ITU-T grid, then the temperature control of the FP-LD can be easily used to match the modes of the LD to the input pump and the probe wavelengths [5].

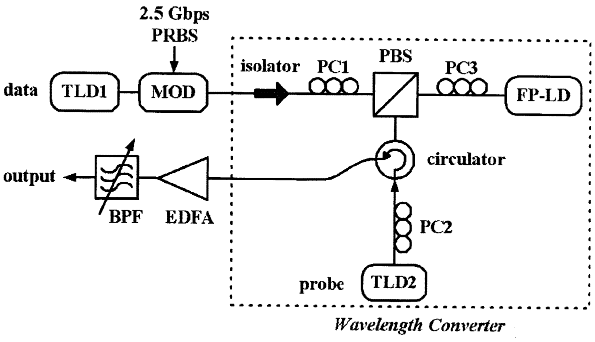


Fig. 3. Experimental setup for the proposed wavelength converter using the absorption modulation of an injection-locked FP-LD.

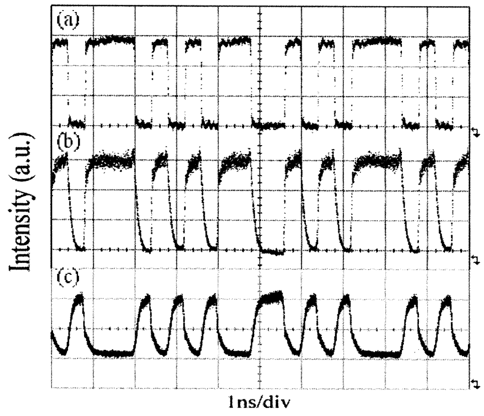


Fig. 4. Oscilloscope traces of the wavelength converted signals at 2.5 Gb/s (a) input data, (b) noninverted, and (c) inverted signal.

The oscilloscope traces of input data and the converted outputs for logically noninverted and inverted operations are shown in Fig. 4(a)–(c). The average power of the modulated pump signal before wavelength conversion was −2.4 dBm, and the input power of the probe signal was 6.7 dBm. For the operation of the noninverted wavelength conversion, the wavelength of the probe signal was set to 1550.03 nm by tunable laser, whereas for the inverting operation, it was set at slightly longer wavelength

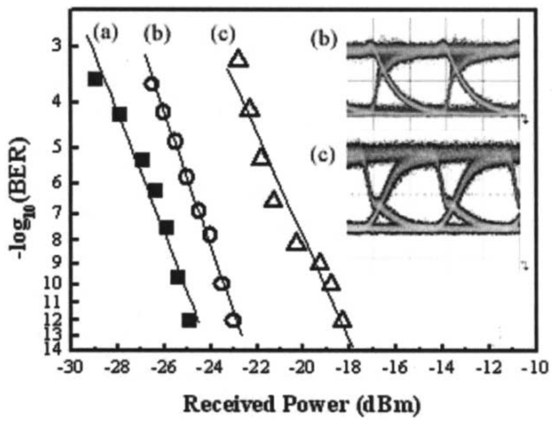


Fig. 5. Plot of 2.5-Gb/s BER measurements for wavelength converted signals and corresponding eye diagrams (a) the back-to-back, (b) noninverted (ER = 11.7 dB), and (c) inverted signal (ER = 5.2 dB).

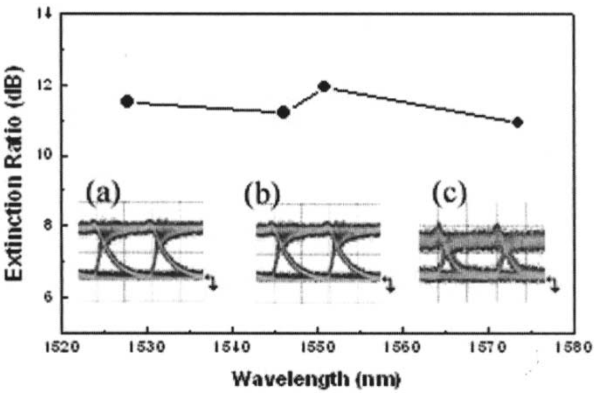


Fig. 6. Extinction ratios and corresponding eye diagrams for converted 2.5-Gb/s outputs with different prove wavelengths, (a) 1527.66 nm, (b) 1550.80 nm, and (c) 1573.42 for pump wavelength of 1566.12 nm.

by about 0.15 nm. The operations of both logically inverted and noninverted conversions were clearly observed.

Fig. 5 shows the measured bit-error-rate (BER) curves of the converted signal for noninverted [Fig. 5(b)] and inverted operation [Fig. 5(c)], together with back-to-back measurements at a data rate of 2.5 Gb/s [Fig. 5(a)]. The data format of $2^{31} - 1$ nonreturn-to-zero pseudorandom bit stream was used. It can be seen that the noninverted conversion leads to a penalty of 2 dB at a BER of 10^{-9}, whereas a penalty of 6 dB is obtained for the inverted conversion. Moreover, it is noted that no BER floor is observed up to BERs as low as 10^{-12}, which proves the excellent performance of the wavelength converter. The inset of Fig. 5 shows the corresponding eye diagrams of converted signals. The eye diagram for the inverted conversion shows a relatively smaller extinction ratio and higher amplitude jitter than that of noninverted conversion. This can be explained by the asymmetric shape of the absorption null of the FP-LD with bias current above threshold. When the bias current to the FP-LD is increased above threshold, the left side of the absorption null becomes steeper than the right side. It causes the relative difference of the extinction ratios for the logically noninverted and inverted wavelength conversion outputs. However, this problem can be solved if we use an additional CW holding beam to increase the operation speed of the proposed scheme because we can operate the FP-LD near threshold current where the shape of the absorption null is symmetric.

In the experiment, an EDFA is used to compensate the overall insertion loss of the wavelength converter for the CW probe light. Since the proposed scheme uses the absorption modulation property and the probe signal is reflected back from the FP-LD, relatively high insertion loss was observed. However, the reflectance of the facets of the FP-LD can be optimized so that the insertion loss of the proposed wavelength converter is minimal.

To verify the wide-range conversion capability, eye diagrams and extinction ratios were measured for noninverted wavelength conversion with different prove wavelengths, as shown in Fig. 6. Since the absorption nulls are observed to span over 100 nm, and the red-shift of the nulls caused by TE mode injection-locking is also present almost equally over the span, an over 100-nm range of wavelength conversion can be possible with the proposed technique.

IV. DISCUSSION AND CONCLUSION

A novel configuration for all-optical wavelength conversion based on the absorption modulation of an injection-locked FP-LD has been proposed and experimentally demonstrated. The scheme utilizes the TM-mode absorption nulls and the red-shift of the absorption spectra caused by an additional optical pump injection. Both the logically inverted and noninverted wavelength conversions were experimentally demonstrated. Error-free wavelength conversion at 2.5 Gb/s was obtained and no error floors were observed. The operation speed of the proposed scheme is limited by the carrier recovery time at the falling edge and trailing edge for the noninverted and the inverted operation, respectively, where the pump injection is released to cause the FP-LD to become unlocked. An additional CW holding beam can be used to lock the FP-LD when the pump injection is released and then the operation speed can be increased up to 10 Gb/s [7]. The proposed wavelength converter has the advantage of simple and cost-effective configuration and can be applied to local area networks or metropolitan area networks where the simple configuration and cost-effectiveness are major issues.

REFERENCES

[1] J. M. H. Elmirghani and H. T. Mouftah, "All-optical wavelength conversion: Technologies and applications in DWDM networks," *IEEE Commun. Mag.*, vol. 38, pp. 86–92, Mar. 2000.

[2] T. Durhuus, B. Mikkelsen, C. Joergensen, S. L. Danielsen, and K. E. Stubkjaer, "All-optical wavelength conversion by semiconductor optical amplifiers," *J. Lightwave Technol.*, vol. 14, pp. 942–954, June 1996.

[3] S. J. B. Yoo, C. Caneau, R. Bhat, M. A. Koza, A. Rajhel, and N. Antoniades, "Wavelength conversion by difference frequency generation in AlGaAs waveguides with periodic domain inversion achieved by wafer bonding," *Appl. Phys. Lett.*, vol. 68, pp. 2609–2611, 1996.

[4] J. Horer and E. Patzak, "Large-signal analysis of all-optical wavelength conversion using two-mode injection-locking in semiconductor lasers," *IEEE J. Quantum Electron.*, vol. 33, pp. 596–608, Apr. 1997.

[5] H. K. Tsang, L. Y. Chan, S. P. Yam, and C. Shu, "Experimental characterization of dual-wavelength injection-locking of a Fabry–Pérot laser diode," *Opt. Commun.*, vol. 156, pp. 321–326, Nov. 1998.

[6] C. W. Chow, C. S. Wong, and H. K. Tsang, "All-optical format and wavelength conversion using polarization switching in a FP laser diode," in *Proc. LEOS 2002*, 2002, pp. 629–630.

[7] L. Y. Chan, W. H. Chung, P. K. A. Wai, H. Y. Tam, and M. S. Demokan, "Simultaneous repolarization of two 10-Gb/s polarization scrambled wavelength channels using a mutual-injection-locked laser diode," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 1740–1742, Dec. 2002.