# Simultaneous Repolarization of Two 10-Gb/s Polarization-Scrambled Wavelength Channels Using a Mutual-Injection-Locked Laser Diode

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***Abstract*—An all-optical polarizer, which can repolarize a high-speed data signal without converting the state-of-polarization variations into amplitude jitters, is realized using a mutual injection-locked laser diode. The all-optical polarizer is used to simultaneously realign the state-of-polarizations of two 10-Gb/s polarization-scrambled nonreturn to zero signals without state-of-polarization characterization and feedback control.**

***Index Terms*—Fabry–Pérot laser, injection locking, polarization control.**

## I. Introduction

REAL-TIME automatic polarization stabilization is crucial to the deployment of all-optical switches, add–drop multiplexers, polarization-multiplexed systems, and coherent detection systems in optical networks. Most of the polarization control schemes proposed to date are comprised of a polarization rotation unit and a complex feedback control unit. Polarization control is carried out either mechanically (e.g., fiber squeezers/paddles, MEMS [1]) or electrooptically (e.g., liquid crystal or electrooptics crystal [2], and PM-segment fibers [3]). In this letter, we demonstrate that a mutual injection-locked laser diode (MILD) functions as an all-optical polarization controller and can be used to repolarize 10-Gb/s polarization-scrambled nonreturn-to-zero (NRZ) signals. The MILD controls the state-of-polarization (SOP) of the input signal not by rotating its SOP but by functioning as an intensity-compensating polarizer. Thus, neither complicated SOP characterization nor a speed-limiting feedback control process is required. We further show that a single MILD can simultaneously realign the polarizations of two polarization scrambled 10-Gb/s signals.

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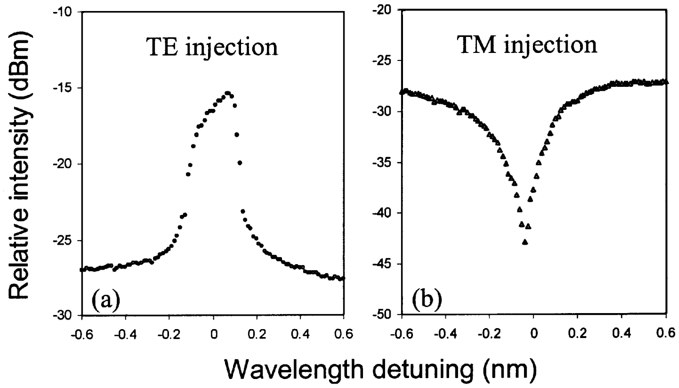
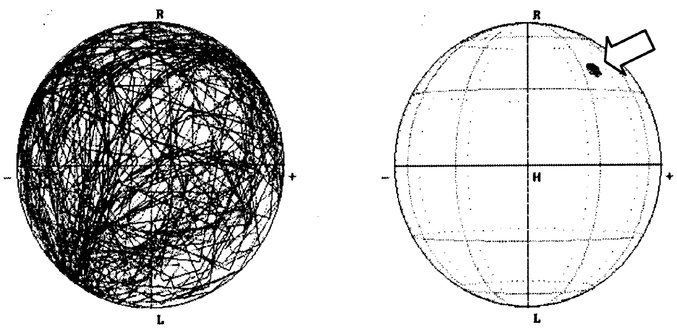



Fig. 1. The output spectra of Fabry–Pérot laser diode (FP-LD) when injected by CW signals at different wavelength which are detuned from the FP modes. (a) TE polarized. (b) TM-polarized CW signal.

## II. Polarization Stabilization by Injection Locking

The FP-LD used in the experiment supports both TE mode and TM mode emission during lasing but the double-channel planar-buried heterostructure of the FP-LD favors the TE mode. The power of the TM mode is less than 0.1% [4]. Fig. 1(a) and (b) shows the output spectra of the FP-LD when injected by a TE and a TM polarized wavelength-tunable signal, respectively. The injected signal power is $-17$ dBm and the wavelength step is 0.01 nm. Fig. 1(a) shows a typical injection-locking characteristic while Fig. 1(b) shows a typical reflection spectrum of a FP cavity. The peak of the output spectrum in Fig. 1(a) occurs when the injected TE signal is spectrally aligned with a TE longitudinal mode of the FP-LD, and the absorption minimum in Fig. 1(b) occurs when the injected TM mode is aligned with a TM longitudinal mode of the FP-LD. Therefore, for any injected signal that is spectrally aligned with a wavelength at which the TE and the TM modes of the FP-LD coincide, the TE component of the injected signal will be amplified with its intensity clamped and stabilized by injection locking [5] if the power of the TE component is above the injection-locking threshold. The TM component, however, is always suppressed. As a result, an injection-locked FP-LD can act as an intensity-compensating polarizer with TE polarized output. Fig. 2(a) depicts the Poincaré sphere representation of the SOP of a CW signal with a power of $-17.9$ dBm. When the polarization of the CW




(a) (b)

Fig. 2. Poincaré spheres for the polarization-scrambled signal (a) before and (b) after injection locking.

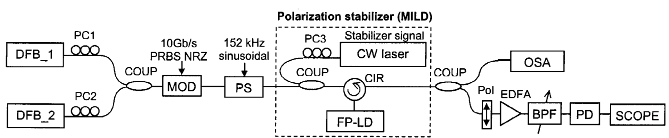



Fig. 3. Experimental setup for dual-wavelength polarization compensation using MILD. Notation: Distributed feedback laser (DFB); polarization controller (PC); intensity modulator (MOD); polarization scrambler (PS); intensity coupler (COUP); circulator (CIR); Fabry–Pérot laser diode (FP-LD); optical spectrum analyzer (OSA); polarizer (Pol); erbium-doped fiber amplifiers (EDFAs); bandpass filter (BPF); and photodiode (PD).

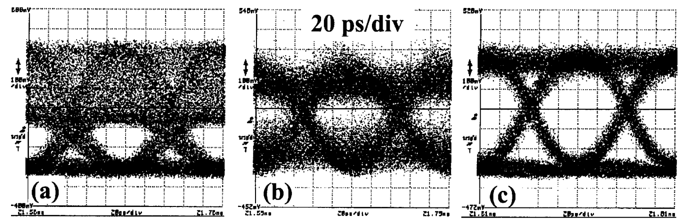



Fig. 4. Eye diagrams of a polarization scrambled 10-Gb/s signal measured after a polarizer (a) without injection locking, (b) with single wavelength injection locking, and (c) mutual injection locking with a CW stabilizer signal. The polarization scrambling rate is 152 kHz.

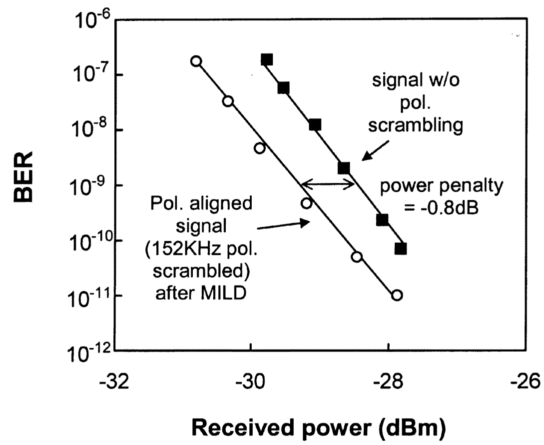



Fig. 5. BER performance for the 10-Gb/s input signal (■) without polarization scrambling and (○) polarization compensated signal after MILD. Both are measured after a polarizer.

signal is varied randomly by hand using a polarization scrambler, the SOP wanders randomly over the Poincaré sphere. After injection locking of the FP-LD, the SOP of the FP-LD output is confined to a small spot on the Poincaré sphere even when the polarization state of the CW signal is varied randomly as shown in Fig. 2(b). The applied current of the FP-LD is $1.6I_{\rm th}$ where $I_{\rm th}$ is the threshold current. The degree of polarization (DOP) for the output signal after polarization stabilization by the scheme is over 95% at a FP-LD current of $2.2I_{\rm th}$ [6]. We emphasize that only those FP modes having exact overlapping of the TE injection-locking peak and the TM absorption minimum will give optimal performance in the proposed scheme. In order to realign the polarization of a high bit-rate signal, it is necessary to simultaneously inject a CW stabilizer signal (wavelength matched with another FP-LD mode) with the input high bit-rate signal such that mutual injection locking of the FP-LD occurs. The functions of the CW stabilizer signal are to suppress the FP-LD modes during the "0" bits of the polarization varying input signals and to increase the response speed of the proposed scheme by shortening the fall-time of the compensated signal under stimulated emission.

## III. Simultaneous Repolarization of Two 10-Gb/s Signals

Fig. 3 depicts the experimental setup for the polarization compensation of both one 10-Gb/s NRZ signal and two 10-Gb/s NRZ signals using the proposed scheme. First, we study the repolarization of only one 10-Gb/s signal, which is generated by externally modulating the 1546.54-nm signal from a tunable laser. The SOP of the modulated signal is varied by a polarization scrambler (PS) which operate at a sinusoidal frequency of 152 kHz. Fig. 4(a) shows the eye diagrams of a polarization-scrambled signal measured by a photodiode (PD) after passing through a polarizer (Pol). The polarization-scrambled signal is injected into the MILD, which comprises of a DFB (the CW stabilizer signal) with an emitting wavelength of 1548.7 nm, a FP-LD with an applied current of $1.5I_{\rm th}$ and one circulator for separating the output polarization compensated signal from the input signals of the FP-LD. The FP-LD and the DFB are thermally tuned such that the polarization-scrambled signal and the CW stabilizer signal are within the injection-locking range of two different FP modes. The injected powers to the FP-LD are 0.73 dBm and $-4.69$ dBm for the 10-Gb/s 1546.54-nm polarization scrambled signal and the CW stabilizer signal, respectively. Fig. 4(b) shows the polarization scrambled 10-Gb/s signal after it is injection locked to one of the FP modes without the stabilizer signal. Although repolarization occurs as shown by the partial opening of the eyes, the intensity levels of the "1" and "0" are still rather noisy. In order to achieve better repolarization of the high-speed signal, the CW stabilizer signal which is wavelength matched to another FP mode is injected simultaneously with the input high bit rate signal such that mutual injection locking occurs. Fig. 4(c) gives the eye diagram of the polarization scrambled 10-Gb/s signals after it is polarization stabilized using the MILD. Much better eye-opening is observed. Fig. 5 shows the BER performance (measured after a polarizer) of the repolarized signal. There is a $-0.8$-dB power penalty improvement compared to the original signal without polarization scrambling due to noise suppression under injection locking [7].

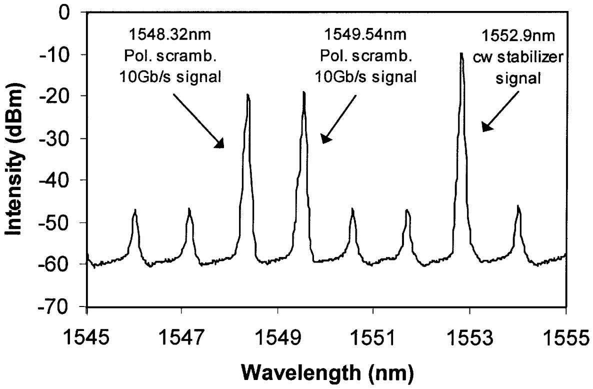



Fig. 6. The spectrum of an FP-LD after it is mutual injection locked by two polarization scrambled 10-Gb/s signals at 1548.32 and 1549.54 nm.

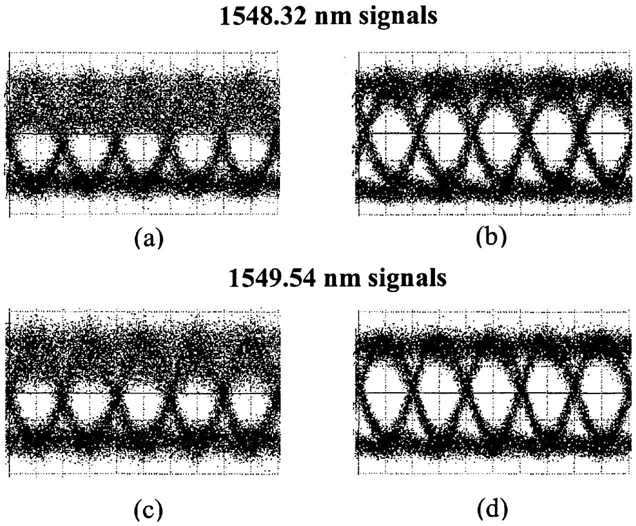



Fig. 7. Eye diagrams of the 1548.32 nm and 1549.54 nm signals before [(a) and (c)] and after [(b) and (d)] they are simultaneously polarization stabilized using MILD.

The side-mode suppression ratio of the polarization compensated signal is over 30 dB. The output of the MILD is TE polarized. Specific SOP can be obtained using a segment of polarization maintaining fiber or a slow polarization controller at the output of the MILD.

Next, we demonstrate that a single MILD can be used to simultaneously repolarize two polarization-scrambled 10-Gb/s signals. The wavelengths of the two DFB lasers in Fig. 3 are 1548.32 nm and 1549.54 nm. The DFB outputs are externally modulated with the same pseudo-random bit sequences (PRBSs) to produce two 10-Gb/s NRZ signals. The results will be the same for independently modulated signals provided that the CW stabilizer signal is chosen such that the CW signal locks the FP-LD only when the inputs of both 10-Gb/s signals are "0." The two 10-Gb/s signals are then polarization-scrambled at 152 kHz and injected into the MILD for polarization stabilization. The CW stabilizer signal is generated from a tunable laser operated at 1552.9 nm with a power of $-4.14$ dBm. The FP-LD current required to stabilize the polarization of two wavelength channels is $2.2I_{\rm th}$, which is higher than the $1.5I_{\rm th}$ required for a single channel. Fig. 6 shows the spectrum of the FP-LD output when it is simultaneously mutual injection locked by two polarization-scrambled 10-Gb/s signals at wavelengths 1548.32 nm and 1549.54 nm with incident powers $-10.8$ dBm and $-9.5$ dBm, respectively. Fig. 7(a) and (c) depict the eye diagrams for the polarization scrambled signals and Fig. 7(b) and (d) show the repolarized signals using a single MILD measured after a polarizer and a bandpass filter. Significant eye openings are observed in both signals.

## IV. Discussion and Conclusion

An all-optical polarizer constructed from a mutually injection-locked laser diode is used to simultaneously repolarize two 10-Gb/s polarization-scrambled signals without amplitude jitter penalty. No SOP characterization and feedback control process is used. For optimal performance, the maximum number of signals that can be repolarized with a single MILD depends on the number of modes in which the TE and TM modes overlap in the spectrum (mode spacing difference between TE and TM modes is about 0.038 nm in our case). If the SOPs of the injected signals are aligned with the TM polarization of the MILD such that the power of the TE components is lower than the injection-locking threshold, the MILD will attenuate the injected signals without repolarization. We note that since the random birefringence of buried optical networks typically causes only 2° to 10° fluctuations in the polarization angles of the propagating signals [8], one can use a slow polarization controller to avoid the alignment of the SOP of the injected signal with the TM polarization of the MILD.

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