Pulsed-ASE-seeded DWDM optical system with interferometric noise suppression

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Abstract: We propose and demonstrate a 10-Gb/s dense wavelength-division-multiplexing (DWDM) optical system based on a pulsed-seed-light source employing a fiber-based Mach-Zehnder interferometer (F-MZI) as an intensity noise suppressor. The transmission results show that the required injection power into a reflective modulator was as low as −18 dBm. The F-MZI can accommodate the polarized seed-light with superior noise characteristics so that the supported DWDM systems double using a single conventional unpolarized seed-light. In addition, an allowable length of the drop fiber is investigated to show the system flexibility.

OCIS codes: (060.4510) Optical communications; (060.4250) Networks.

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1. Introduction

The wide variety of advanced real-time applications have been driving the demand of the gigabit sustained bit-rate in access as well as metro networks [1]. In order to handle these bandwidth requirements, dense wavelength division multiplexing passive optical networks (DWDM-PONs) have been studied intensively [2–9]. In particular, a high-speed connection over 10 Gb/s-per-channel should be supported to accommodate diverse services in a single platform. Although a lot of novel technologies have been proposed, a massive deployment of a WDM-PON is still questionable, since those methods are rather complex and expensive [2–4]. However, a seeded DWDM optical system based on an amplified spontaneous emission (ASE) seed light has been regarded as an affordable solution due to its cost-effective implementation of color-free (or colorless) operation [5–9]. Each transmitter was equipped with a colorless reflective modulator (RM) such as an anti-reflection coated Fabry-Perot laser diode (FP-LD) and reflective semiconductor optical amplifier (RSOA). Thanks to a great feasibility of the field-deployable system, the seeded DWDM system has been approved as the international standard by ITU-T [10,11]. Unfortunately, it was difficult to increase the data-rate up to 10-Gb/s due to the relative intensity noise (RIN) arising from the ASE-ASE beating, narrow modulation bandwidth of the RM, and chromatic dispersion. To overcome these hurdles, the 10-Gb/s seeded DWDM system at 100 GHz grids has been demonstrated recently employing a forward error correction (FEC), high-speed SOA reflective electro-absorption modulators (SOA-REAMs) [12], and a dispersion compensating fiber (DCF) [13]. The 2nd generation FEC was mandatory. It may impose a non-acceptable latency. In addition, the RM should operate in the deep gain-saturation region with a high injection power to satisfy the required RIN.

In this paper, we propose and demonstrate a 10-Gb/s DWDM system based on pulsed-ASE-light seeding employing an interferometric noise suppressor that was simply realized by a fiber-based Mach-Zehnder interferometer (F-MZI) [14,15]. The proposed pulsed-seed-light source facilitates the 10 Gb/s signal transmission achieving a 1st generation FEC threshold at the low injection power of –18 dBm. Furthermore, the dynamic range of a drop fiber length is determined through the experimental analysis of a dispersion penalty.

2. Experimental setup

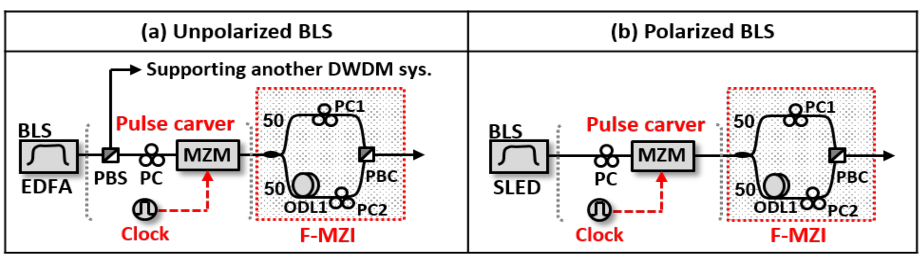

Fig. 1. Schematics of the pulsed-seed-light with (a) the unpolarized and (b) polarized BLS.

Figures 1(a) and 1(b) show the schematic configuration of the proposed pulsed-seed-light with the unpolarized and polarized broadband light source (BLS), respectively. An Erbium-doped fiber amplifier (EDFA) was used as the unpolarized BLS and a semiconductor based high power superluminescent diode (SLED) was used as the polarized one. In the case of the unpolarized BLS, two DWDM systems can be supported after passing through a polarization beam splitter (PBS). A MZ modulator (MZM) based pulse carver and F-MZI were also equipped for the pulse generation and the noise suppression, respectively. The broadband light output of the C-band BLS was modulated with a 10.7 GHz (corresponding to the bit-rate) clock signal by the MZM for the pulse generation. The pulsed-seed-light was then sent to the F-MZI composed of the two polarization controllers (PC1 and PC2), polarization beam

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combiner (PBC) and optical delay line (ODL1). The ODL1 of the lower branch was inserted to have a time delay of $\triangle t_d$ by one pulse period (93.5 ps) which yields the 1st low noise window at a center frequency of $1/(2\triangle t_d)$ in intensity spectrum [14]. Two orthogonally polarized pulse trains were then combined as depicted in Fig. 2. It should be noted that we use the F-MZI for noise suppression and it is not a transmission method with polarization multiplexing.

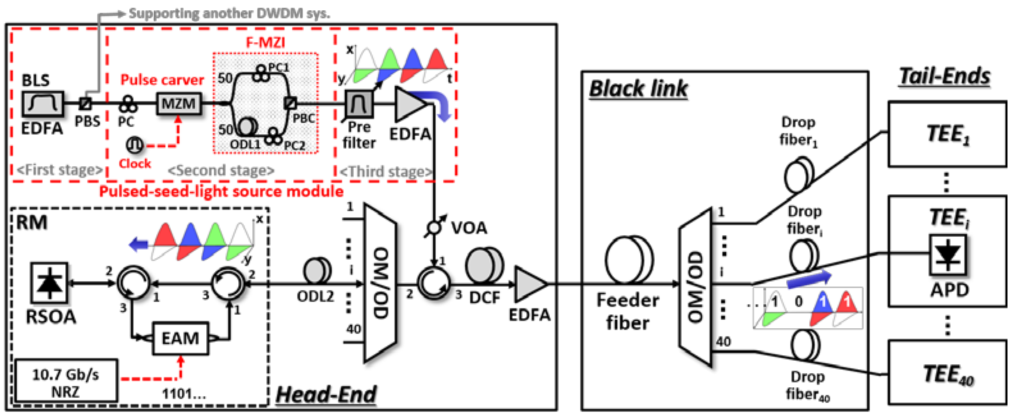

Fig. 2. Experimental setup of the 10-Gb/s DWDM system employing the pulsed-seed-light source based on the F-MZI.

The experimental setup for demonstrating the 10-Gb/s DWDM system is shown in Fig. 2. Two 1 × 40, 100 GHz spaced, and cyclic arrayed-waveguide gratings (AWGs) were utilized as an optical multiplexer and demultiplexer (OM/OD) at the head-end and black link, respectively. The AWGs have flat-top pass band with a 3-dB bandwidth of 80 GHz (0.64 nm).

The BLS and the F-MZI with the pulse caver was inserted into the first and second stage of the modular pulsed-seed-light source, respectively. Also, a pre-filter for alleviating the filtering effect [6] and an EDFA for acting as a booster amplifier were utilized at the third stage. A bandwidth-variable tunable filter was utilized to find the optimum bandwidth of the pre-filter. A 3-dB optimum bandwidth of the pre-filter was 60 GHz (0.48 nm) corresponding to 75% of the AWG bandwidth. It may be noted that a Fabry-Perot etalon can be used for a multi-channel pre-filter for real implementation and a cost-effective SLED can be an alternative to a commercial EDFA based BLS for the C-Band ASE generation as shown in Fig. 1(b). Furthermore, all optical devices of the three stages can be packaged into a single compact BLS module.

After passing through the AWG of the head-end, the pulsed-seed-light was injected into the RM. Each RM equipped with two circulators, polarization insensitive RSOA, and EAM functions as an optical amplifier, low frequency noise suppressor, and modulator simultaneously. Note that the RM can be replaced with a simple and compact SOA-REAM [12]. Since the pulsed-seed-light was inputted into the EAM driven by the non-return-to-zero (NRZ) signal, the optical return-to-zero (RZ) signal was generated. In this case, a high-speed modulator was not needed for the RZ signal generation [9]. An ODL2 was inserted for timing synchronization between the pulsed-seed-light and modulated NRZ signal. The optical RZ signal propagated through the AWG as an OM and a 20-km standard single mode fiber (SSMF) as a transmission fiber. A DCF module was used to compensate the chromatic dispersion. It was then demultiplexed by the AWG in the black link and delivered to each tail-end receiver based on an avalanche photo detector (APD) whose bandwidth was 6 GHz.

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3. Experimental results

3.1 Interferometric noise suppression

For the investigation of the noise characteristics according to the various seed-light sources, we measured the RIN at the tail-end equipment (TEE, the channel-18 (1543.3 nm) for this case) in the back-to-back configuration (no transmission fiber). Here, all RIN measurements were conducted with the continuous-wave (CW)-seed-light, i.e., without driving the clock and NRZ signal to the MZM and EAM of the RM, respectively. In the measurement, for compensating the limited bandwidth of the used APD, the average RIN was obtained by dividing the integrated RIN from 50 MHz to 10 GHz by a bandwidth of 6 GHz.

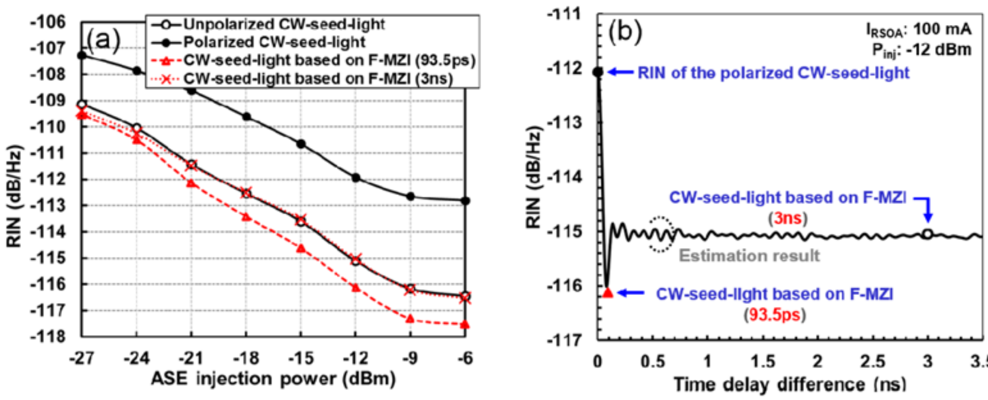

Fig. 3. (a) Measured average RIN and (b) estimated RIN as a function of the time delay difference of the F-MZI.

As shown in Fig. 3(a), we firstly measured the average RIN with the unpolarized CW-seed-light (○) used as a conventional BLS. The gain-saturation effect of the RSOA leads the RIN suppression with increasing the ASE injection power. In the case of the polarized CW-seed-light (●), the RIN was increased by a factor of two as expected. By employing the F-MZI (with delay time of 93.5 ps) into the polarized CW-seed-light, however, the RIN was suppressed by more than 4 dB (▲), when the injection power was larger than −18 dBm. Comparing the unpolarized CW-seed-light case, the F-MZI based seed-light gives 1 dB less noise. Thus, the required injection power could be reduced by 3 dB for the given RIN. For example, we have the RIN of −113.5 dB/Hz at −18 dBm injection power for the F-MZI based seed-light, while it was −15 dBm for the unpolarized one. This feature shows superiority of the proposed seed-light compared with a conventional unpolarized one. It should be noted here that the proposed seed-light uses a single polarization only. Therefore, we could realize two seed-lights with superior noise characteristics using a single unpolarized seed-light.

To study the effects of delay time between two arms of the F-MZI as a noise suppressor, we measured the RIN at injection power of −12 dBm as shown in Fig. 3(b). As mentioned before, the RIN suppression by the F-MZI was about 4 dB at the delay time of 93.5 ps. However, it converged to the 3 dB with increasing the time delay. In other words, the proposed seed-light source becomes a conventional unpolarized seed-light, when the delay time is much longer than the inverse of the bandwidth of the measurement.

To understand the RIN suppression by the F-MZI in the spectral domain, we measured the RIN spectra as illustrated in Fig. 4. Due to the limited carrier lifetime of the RSOA, the noise suppression (compared with the input RIN) by the gain-saturation effect dominantly occurs in low frequency region (dotted-black and solid-brown line). However, the F-MZI remarkably suppressed the RIN around 5.35 GHz corresponding to the half of the inverse of the delay time. This arises from the destructive interference in intensity spectrum. It should be noted

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here that the F-MZI with two orthogonal polarization forms the interference in optical intensity instead of the optical field. Thus, the gain-saturated RSOA and the F-MZI effectively suppressed the RIN in the low- and high-frequency region, respectively. Meanwhile, when the F-MZI has a long time delay difference of 3 ns corresponding to 32 period delay of the modulation signal, the low-noise windows repeat with short intervals of 167 MHz. Then, the constructive and destructive interferences cancel each other out. As a result, the average RIN (×) agrees well with the unpolarized CW-seed-light case (○) as seen in Fig. 3(a). Thus, this long period delayed interferometer can be considered as the regular unpolarized BLS [9].

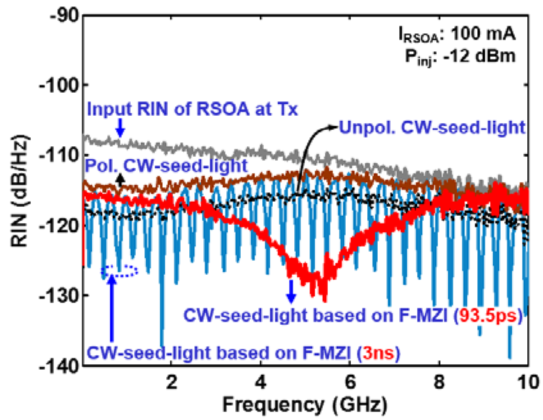

Fig. 4. Measured RIN spectra according to seed-light source.

3.2 Results of 10 Gb/s signal transmission

To investigate a transmission performance of the proposed pulsed-ASE-seeded DWDM system based on the F-MZI, we measured the bit error rate (BER) curves and eye diagrams. Then, we compared those with the conventional unpolarized CW-seed-light case. The received power was –22 dBm for the eye diagram measurement. It may be noted that the time delay difference of the F-MZI was one period delay (93.5 ps) of the modulated signal of the 10.7 Gb/s NRZ data. A pseudorandom bit sequence (PRBS) pattern length was 2^{31}-1.

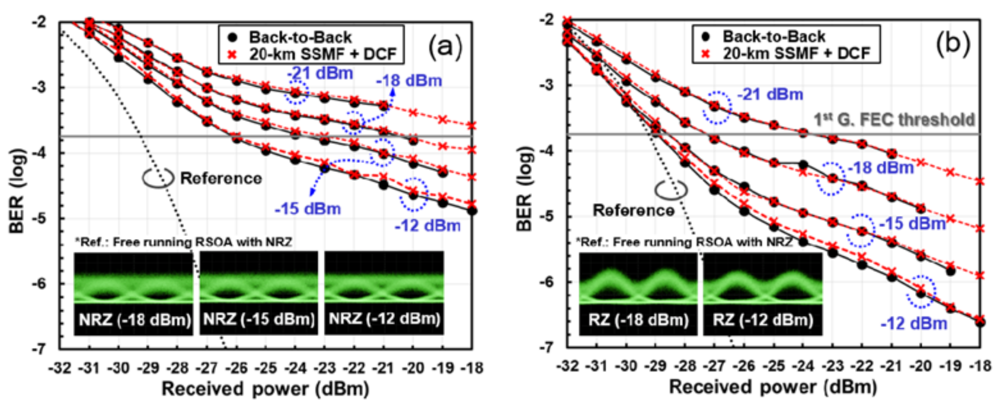

Fig. 5. Measured BER as a function of the injection power. (a) Unpolarized CW-seed-light source and (b) proposed pulsed-seed-light source based on the F-MZI (93.5 ps delayed).

As seen in Fig. 5(a), in the case of the unpolarized CW-seed-light, the FEC threshold of 1.8×10^{-4} was barely achievable at the –18 dBm injection power. A huge power penalty of 9 dB was imposed compared with the reference BER (In the case of the free-running RSOA with the NRZ modulation). Here, we used –18 dBm injection power as a reference, since it was defined as the minimum injection power in G.698.3 [11]. However, the pulsed-seed-light source (i.e., the RZ signal transmission case) satisfied the FEC threshold at –18 dBm injection power with 2 dB power penalty as shown in Fig. 5(b). Thus, the proposed pulsed-seed-light source based on the F-MZI significantly improves the receiver sensitivity by 7 dB compared with the conventional unpolarized CW-seed-light-source. Moreover, it even reduce the injection power as low as –21 dBm achieving the FEC threshold. The improvement of BER performance can be understood by the interferometric noise suppression and gains from the RZ signal modulation. Also, we discuss the transmission performance comparing the RZ modulated signals without the F-MZI in the following section.

In addition, we measured the dispersion tolerance of the pulsed-seed-light with various lengths of SSMFs as illustrated in Fig. 6(a). For the comparison, the unpolarized CW-seed-light case was also investigated. If we accept 2 dB power penalty induced by the dispersion, the allowable fiber length was extended from 3.3 km to 6.3 km at the injection power of –12 dBm. The main reason of this improvement was explained by a wide timing margin of the RZ signal compared to the NRZ signal as shown in eye diagrams. It should be noted that the spectral width of the RZ signal and NRZ signal are almost same, since these are determined by the ASE bandwidth. The length was decreased to 5 km at the low injection power of –18 dBm due to the increased RIN. Thus, the dynamic range of the drop fiber length can reach up to 10 km when the DCF at the head-end completely cancels out the accumulated dispersion of the feeder fiber.

By a simple calculation, we can estimate an effect of the dispersion slope of the transmission fiber. It was almost negligible, since the dispersion is big enough compared with the dispersion slope induced dispersion at a given channel. Nevertheless, the dynamic range was slightly reduced by 9.4 km at the injection power of –18 dBm for the channel-40, 1560.9 nm (worst case). In this estimation, the transmission fiber which has a dispersion slope of 0.0826 ps/nm^2/km was considered.

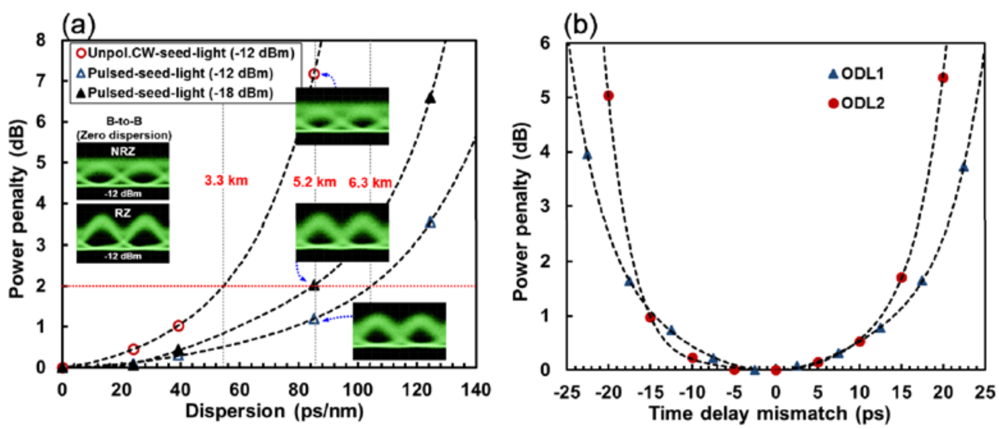

Fig. 6. Measured power penalty by (a) dispersion and (b) time delay mismatches.

As shown in Fig. 6(b), we also investigated an effect of the time delay mismatch between the two arms of the F-MZI by changing the time delay of the ODL1. The reference (zero mismatch) was in the case of that two orthogonally polarized pulsed-seed-lights have the time delay difference of 93.5 ps. If the 2 dB power penalty is permitted, the mismatch of ± 19 ps is allowable. Also, the mismatch of the timing synchronization between the pulsed-seed-light and the modulated NRZ signal at the RM was investigated by manipulating the ODL2. For this case, the allowable mismatch for 2 dB penalty was ± 16 ps. The results show that the system performance was more sensitive to the change of the ODL2 because it affects both the x- and y-polarized pulsed-seed lights simultaneously.

3.3 Performance comparison of 10-Gb/s RZ signals

To confirm advantages in the injection power for the proposed pulsed-seed-light, we also measured the BER curves with various pulsed-seed-lights (i.e., the RZ signal transmission cases) as shown in Fig. 7. To do that, we emulate the unpolarized pulsed-seed-light without the F-MZI by increasing the delay time from 93.5 ps to 3 ns, since the seed-light with 3 ns delay time was equivalent to the unpolarized seed-light in terms of the RIN as seen in Fig. 3(a). The results show that the BER curves which have a 3 dB injection power difference (denoted as C1 and C2) agree very well as seen in Fig. 7. It implies that if we utilize the proposed pulsed-light source, the injection power of 3 dB can be reduced compared to the pulsed-seed-light without the F-MZI.

We also evaluated transmission performance of the polarized pulsed-seed-light source for the comparison. Unfortunately, even at the high injection power of −12 dBm, it was hard to achieve the 1st generation FEC threshold (×) as seen in Fig. 7. It should be noted here that the proposed seed-light works with a polarized input light as shown in Fig. 1(a). Thus, it is possible to realize two proposed seed-lights by using a single unpolarized CW-seed-light such as an EDFA based seed-light to reduce the system costs.

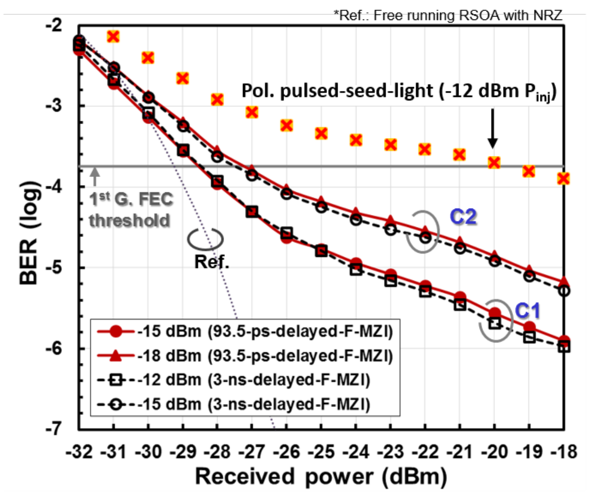

Fig. 7. Measured BER curves as a function of time delay difference.

4. Conclusion

In conclusion, we propose and experimentally demonstrate a 20-km transmission of a 10 Gb/s DWDM optical system employing a pulsed-seed-light source. To enhance the transmission performance, we introduce the fiber-based Mach-Zehnder interferometer (F-MZI) for the intensity noise suppression. A single F-MZI can be shared by all DWDM channels. The F-MZI based pulsed-light source enables the 1st generation FEC threshold to be satisfied at −18 dBm injection power. It is also possible to accommodate the polarized seed-light or unpolarized seed-light for doubling the supported systems. Moreover, the demonstrated DWDM system could have the dynamic range of the drop fiber length longer than 10 km at the low injection power.

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