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2.5 Gb/s transmission of a spectrum-sliced incoherent light source with 0.92 nm bandwidth over 80 km of dispersion-shifted fiber

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We present a spectrum broadening technique to improve the signal-to-noise ratio of spectrum-sliced incoherent light sources using the fiber four-wave mixing effect which occurs in a nonlinear loop mirror located at the receiver. The initial transmission channel bandwidth of 0.92 nm was increased to 1.62 nm in the nonlinear loop mirror at the optical receiver, which enhances the signal-to-noise ratio to a desired value. Using this technique, we have demonstrated the transmission of a 2.5 Gb/s NRZ signal with the 0.92 nm bandwidth through a 80 km dispersion-shifted fiber. The measured transmission penalty was less than 0.2 dB at 1×10^{-10} BER.

I. INTRODUCTION

Developments of high-power optical fiber amplifiers and narrow bandwidth optical filters make it possible to use spectrum-sliced incoherent light sources in wavelength division multiplexed (WDM) systems [1,2]. Erbium-Doped Fiber Amplifiers (EDFA's) can launch a high-power signal into the optical fiber with negligible stimulated Brillouin scattering [3] and passive optical filters can allocate WDM channels at desired positions. In contrast to the light source using DFB laser diodes, the optical bandwidth required for the spectrum-sliced incoherent light transmission grows linearly with the bit rate in order to maintain high signal-to-noise ratio (SNR) [2]. Thus, the application area of the incoherent light source was focused mainly on local-loop networks unlimited by the optical fiber dispersion. Recent experiments, however, show that the bit-rate distance product of the spectrum-sliced incoherent light can be increased beyond the local-loop applications [4,5]. The spectrum-sliced channels have been transmitted over 40 km of non-dispersion-shifted fiber at 2.5 Gbit/s with 0.23 nm bandwidth [4], and over 200 km of dispersion-shifted fiber (DSF) at 2.5 Gbit/s with about 1.8 nm bandwidth [5].

In the spectrum-sliced incoherent light transmission, the spontaneous-spontaneous beat is the dominant noise source in the optical receiver. Recently, the beat noise limited SNR of the spectrum-sliced channel has been analyzed [6], showing that the optical bandwidth of the spectrum-sliced channel should be increased to obtain enough SNR as the transmission bit rate increases. In the case of a high-speed transmission using spectrum-sliced incoherent light, however, we cannot increase the bandwidth of optical signals owing to the increase of the transmission penalty caused by chromatic dispersion.

In this paper, we present a spectrum broadening technique to improve SNR of the spectrum-sliced incoherent light signals using the fiber four-wave mixing (FWM) effect which occurs in a nonlinear optical loop mirror (NOLM) located at the receiving end.

II. EXPERIMENT

The method we used for broadening the optical bandwidth uses a nonlinear optical loop mirror (NOLM) operating near the zero-dispersion wavelength of DSF where the nonlinear effect occurs most strongly. The experimental setup is shown in Fig. 1. Three erbium-doped fiber amplifiers were used (EDFA1, EDFA2, EDFA3). The amplified spontaneous emission light from EDFA1 was spectrum-sliced using a tunable optical bandpass filter denoted as OBPF, which was tuned at 1557.4 nm with a 3 dB channel bandwidth of 0.92 nm. The output power of OBPF was -4.8 dBm, which was modulated with a 2.5 Gb/s PRBS $2^{23} - 1$ NRZ signal and then amplified up to +10 dBm using EDFA2. The amplified signal was transmitted over 80 km of DSF. The zero-dispersion wavelength and the dispersion slope of DSF were 1554.4 nm and 0.067 ps/km.nm^2, respec-

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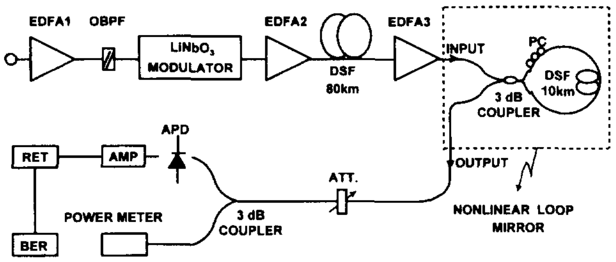

FIG. 1. Experimental setup. EDFA: erbium-doped fiber amplifier, OBPF: optical bandpass filter, DSF: dispersion-shifted fiber, PC: polarization controller, ATT: optical attenuator, RET: retiming circuit, BER: bit-error rate measurement system.

tively. The total fiber loss was about 19.8 dB including splicing losses. The EDFA3 has a low noise figure of less than 5.5 dB including input coupling losses and a high gain of larger than 31 dB at -15 dBm input. The +16 dBm output signal using EDFA3 is split into two counter-propagating fields at the 3 dB optical coupler. The center wavelength of the spectrum-sliced signal (1557.4 nm) is aligned to the zero-dispersion wavelength of the 10 km DSF in the NOLM. The counter-propagating signals undergo spectral-broadening due to FWM effects in DSF. The bandwidth-broadened signal components due to FWM effects appear at the output port of the NOLM. The signal is then attenuated and detected using an avalanche photo diode (APD) preamplifier with a 3 dB bandwidth of 1.7 GHz.

III. RESULTS AND DISCUSSIONS

We measured the spectral-broadening efficiency in the NOLM. The channel bandwidth of a spectrum-sliced incoherent light source was controlled by using an angle-tuned Fabry-Perot filter and a double-stage EDFA [7]. We changed the input channel bandwith of the NOLM from 0.25 nm to 0.92 nm with the same output power of 16 dBm. As shown in Fig. 2, the output spectral bandwith was linearly proportional to the input channel bandwidth and the output spectral bandwidth was about 1.84 times that of the input channel bandwidth.

Spectrum-sliced incoherent light sources have thermal-like properties since they emit light through spontaneous emission processes and consequently have an intrinsic intensity noise, spontaneous-spontaneous beat noise. The SNR of a spectrum-sliced channel is proportional to its optical bandwidth and inversely proportional to electrical bandwidth of optical receiver [6]. Thus, the beat-noise-limited SNR determines the bit-error rate (BER) at the optical receiver. The BER can only be improved, for a given bit rate, by increasing a channel bandwidth of the spectrum-sliced incoherent light source. The BER curves for the different input channel bandwidth are shown in Fig. 3. When the input channel bandwidth of 0.25 nm expanded to 0.46 nm, an error floor occurs at 1 $\times 10^{-5}$ BER. If we increase the input channel bandwidth up to 0.92 nm, the BER improved to 1 $\times$ 10^{-12} owing to the bandwidth expansion.

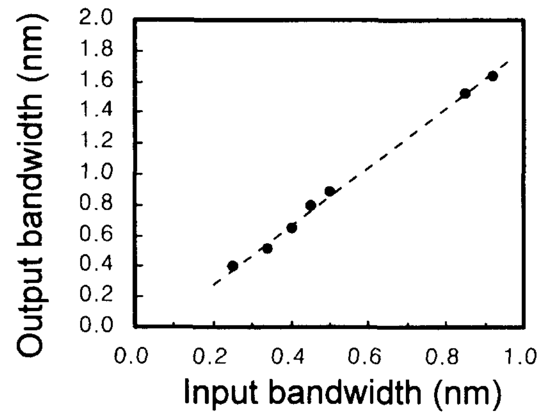

FIG. 2. Spectral-broadening efficiency of the nonlinear optical loop mirror (NOLM).

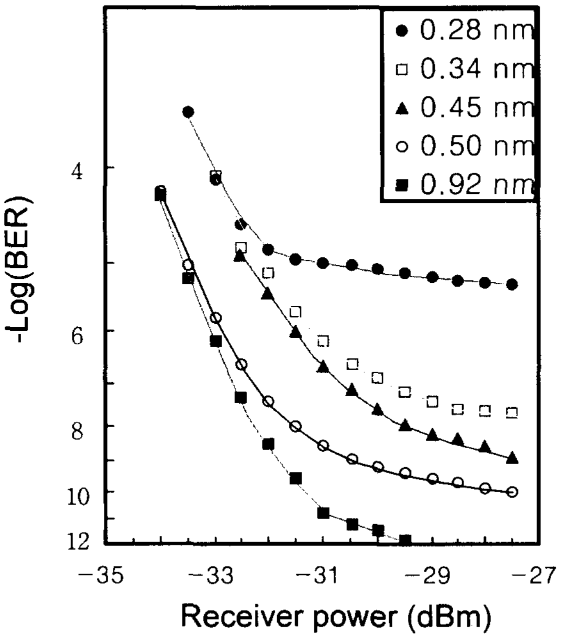

FIG. 3. Bit-error-rate curves with different input spectral bandwidth of the NOLM.

The normalized optical spectrum before and after the NOLM are shown in Fig. 4. The spectral shape is close to the Gaussian distribution with a 3 dB bandwidth of 0.92 nm after OBPF. After passing through the NOLM, the optical bandwidth of the spectrum-sliced channel increased to 1.62 nm due to the fiber FWM. Without the NOLM, as shown in Fig. 5 (a), the noise at the "mark" level caused by the spontaneous-spontaneous beat noise is significant. With the NOLM, however, as shown in Fig. 5 (b), the eye diagram has

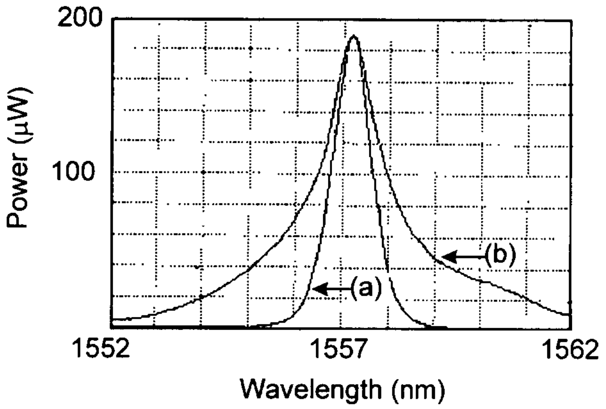

FIG. 4. Normalized spectrum-sliced incoherent signal. (a) without the NOLM, (b) with the NOLM.

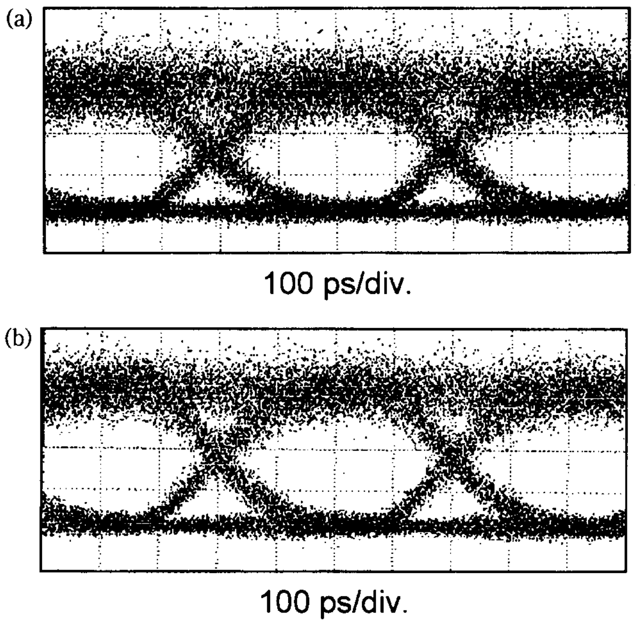

FIG. 5. Measured eye diagrams at 2.5 Gb/s modulation (a) without the NOLM (0.92 nm channel bandwidth), (b) with the NOLM(1.62 nm channel bandwidth).

a wider opening and the noise at the "mark" level is reduced even after the transmission of 80km DSF.

The measured BER curves are shown in Fig. 6. When the channel bandwidth was 0.92 nm without NOLM, an error floor occurs at 3 x 10^{-10} BER with a received power of -27 dBm. When the channel bandwidth increased to 1.62 nm with NOLM, the received power decreased by over 5 dB at 1 x 10^{-9} BER. The total power penalty due to the fiber dispersion was as low as 0.2 dB for the channel centered at 1557.4 nm which is +3 nm misalignment from the zero-dispersion wavelength of DSF used for the 80 km transmission. The slope change in BER curves for the received optical power greater than -33 dBm shows that the dominant noise is the spontaneous-spontaneous beat noise.

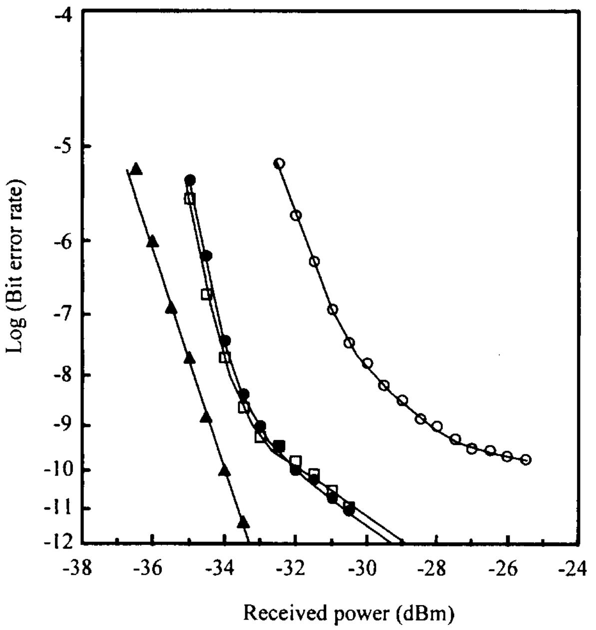

FIG. 6. Measured BER curves. ▲ : after 80 km DSF with the 1548 nm DFB-LD, ○ : Back-to- Back without the NOLM, ● : Back-to-Back with the NOLM, □ : after 80 km DSF with the NOLM.

We also include the results of transmitting over an 80 km DSF with a coherent 1548 nm distributed feedback laser diode (DFB-LD). The sensitivity enhancement was about 2.5 dB at 1 x 10^{-10}BER.

IV. CONCLUSION

The minimum optical bandwidth for the 2.5 Gbit/s transmission has been decreased to 0.23 nm using a feed-forward noise reduction technique [4]. The noise reduction, however, was performed opto-electronically at the $LiNbO_3$ modulator. It needed the additional O/E conversion circuits at the transmitter and an additional critical timing control.

In this paper, we have presented a simple all-optical method to reduce the dispersion penalty of the high-speed spectrum-sliced incoherent light signal. During the transmission, the optical bandwidth is kept to a narrow value . Although the SNR of the transmitted signal is poor, the SNR can be restored at the receiver using the fiber FWM in the NOLM. The experiment results with NOLM at a bit rate of 2.5 Gb/s showed a negligible dispersion penalty which is less than 0.2 dB over a transmission distance of 80 km DSF. In contrast, the results without the NOLM showed more than 5 dB penalty. This new technique will enable the spectrum-sliced incoherent light to be used in high-bit rate WDM systems.

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