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All-optical vestigial sideband carrier suppressed return-to-zero to non-return-to-zero format conversion based on spectral filtering from a cross-phase modulated signal

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An all-optical vestigial sideband carrier suppressed return-to-zero to non-return-to-zero format conversion is presented with the help of simulation using cross-phase modulation in a nonlinear dispersion shifted fiber. For comparative analysis, a semiconductor optical amplifier based conversion is also considered. Through the process of spectral filtering, the wavelength converted output signal is recovered from a broadened optical spectrum. Error-free conversion of vestigial sideband carrier suppressed return-to-zero pulses to non-return-to-zero format is presented at 10 Gb/s using a $2^{10} - 1$ bit sequence and is able to transmit the recovered data through a distance of 50 km having a power penalty of around 1.38 dB in the case of dispersion shifted fiber, whereas a semiconductor optical amplifier performs abysmally.

Keywords: cross-phase modulation, dispersion shifted fiber, return-to-zero, semiconductor optical amplifier, vestigial sideband carrier suppressed.

1. Introduction

The photonic subsystems at the interfaces with the capability of modulation format adaptation are the key for getting high capacity, low cost and energy efficient interconnections between different optical network segments. To overcome the problem of congestion or link failure, the interface node should also have the provision of wavelength conversion which allows wavelength reutilization and reconfiguration. For example, when the interfacing between optical time division multiplexing (OTDM) and wavelength division multiplexing (WDM) technologies is done, required conversion to non-return-to-zero (NRZ) format at these interfaces shows the significance of these subsystems.

Although shaping and compressing of optical signal by pseudo-multilevel signaling or correlative coding are prevalent, there are some modulation formats which can provide spectrum compression up to half of their spectral content using proper optical filtering. Even after filtration of redundant half spectrum (*i.e.*, one of the two spectral sidebands), the information remains intact because the spectrum of real-valued baseband signals is symmetric around zero frequency. In case of vestigial sideband (VSB) signaling this is accomplished by using an optical filter offset from carrier frequency and gradually rolled off to provide suppression of major parts of one sideband and some filter action on the other. As an important directive, it was observed that most of the optical receivers use square-law detection instead of coherent detection. After conversion into VSB, a real-valued modulation format has to sustain square-law detection ability for achieving favorable VSB filtering. Optical VSB has been manifested on NRZ-OOK [1–3], RZ-OOK [4], and CSRZ-OOK [5]. In a WDM system, VSB filtering is accomplished at the transmitter (*i.e.*, before or in combination with multiplexing the WDM channels) or at the receiver (*i.e.*, after or in combination with demultiplexing). To achieve huge amount of spectral compression and a highly spectral efficient WDM data transmission in VSB-CSRZ, filtering at the transmitter end is recommended. In case of non-uniform WDM channel spacing, curtailed WDM channel crosstalk for the desired sideband is achieved by VSB filtering at the receiver.

Therefore, all-optical format conversion between VSB-CSRZ and NRZ is desirable in interfacing OTDM and WDM networks. The applicability of this code in optical communication has been explored by the researchers due to its advantages such as in [5]. But the conversion between VSB-CSRZ to NRZ in all-optical domain has not been reported yet. Several schemes have been reported related to conversions of RZ and NRZ formats, such as, employing cross gain modulation (XGM) and WDM-to-TDM conversion [6]; nonlinear optical loop mirror (NOLM) based on semiconductor optical amplifier (SOA) [7, 8]; an injection-locking scheme based on Fabry–Pérot laser [9, 10]; SOA-based interferometer structures [11]; optical filtering [12]; and four-wave mixing in SOA [13]. RZ-to-NRZ conversion with the scheme of NOLM is achievable by applying optical switching. The switching window of the optical switching process controls the shape of the NRZ data signal and in case when switching window is not rectangular, the obtained NRZ signal has large amplitude ripples in it. In case of a SOA-based approach, the data conversion is controlled by the data rate of the signal because of the limited carrier recovery time of the SOA. Injection locked Fabry–Pérot laser approach utilizes an external duplicator to generate multiple copies of the input RZ pulses within one bit.

In this paper we demonstrate an all-optical VSB-CSRZ to NRZ conversion based on cross-phase modulation (XPM). Simulations are performed based on the ideas presented in [14] (*i.e.*, in a nonlinear dispersion shifted fiber (DSF)) as well as in [15] (*i.e.*, in a SOA) for comparative analysis. By fine tuning the spectral content, the wavelength converted output signal is retrieved. Through simulations it is found that with the use of DSF the wavelength converted NRZ performs better compared to SOA.

2. Working principle and simulation setup

The optical nonlinear phenomenon, XPM, is frequently used in DSF since it facilitates all-optical signal processing due to its quick response. Here the working mechanism is based on the principal of change of phase of an optical signal due to input pump signal over a short duration of time as small as 10 fs. The expression for nonlinear phase change φ, due to input pump signal is given by [16]:

$$\varphi = 2\gamma L_{\mathrm{eff}} P$$

where γ corresponds to nonlinear coefficient of the fiber, L_{eff} corresponds to effective length of DSF, and P corresponds to power of the incident signal. Due to nonlinear change in phase, chirp is introduced into frequency along with reallocation of power, resulting in broadening of frequency spectrum. Different output waveforms can be extracted with the help of a tunable optical filter centered around different wavelengths which are functions of rate of change of input pump power.

Figure 1 shows the simulation setup. Initially a CW laser operating at 1.545 μm is modulated with the help of Mach–Zehnder modulator (MZM) to generate NRZ pulses at 10 Gb/s. A pseudorandom bit generator of length $2^{10} - 1$ is used as the input data. Another MZM and a clock signal operating at half the bit rate is used to generate carrier suppressed return-to-zero pulses (CSRZ). By properly filtering the spectrum of CSRZ by an optical Gaussian band pass filter (BPF), optical vestigial sideband carrier suppressed return-to-zero (VSB-CSRZ) format is produced. Then the modulated CW signal is amplified by a semiconductor optical amplifier (SOA) with gain of 20 dB with noise figure of 4 dB. Another CW laser operating at a wavelength of 1.554 μm is used in the above process as a probe signal. The light from the two sources is combined

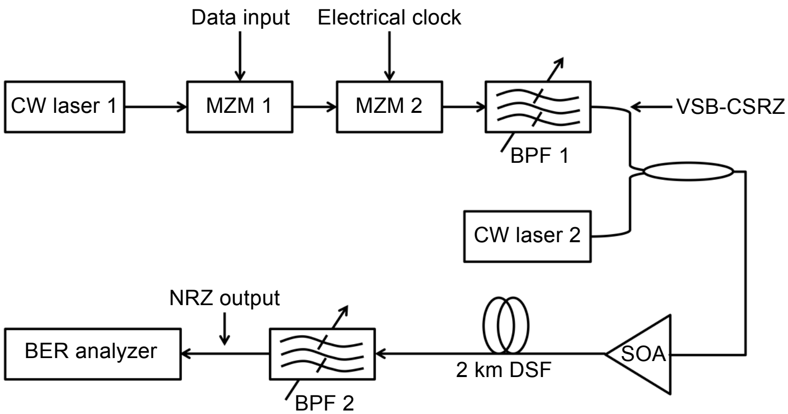

Fig. 1. Simulation setup of VSB-CSRZ to NRZ format conversion using cross-phase modulation in a dispersion-shifted fiber. CW laser 1, CW laser 2 – continuous wave laser diodes, MZM 1, MZM 2 – Mach–Zehnder modulators, SOA – semiconductor optical amplifier, DSF – dispersion-shifted fiber, BPF 1, BPF 2 – band pass filters, and BER analyzer – bit-error-rate analyzer.

together using a 3 dB coupler. Now the combined signal is launched into a 2-km DSF having nearly zero dispersion at 1.55 μm. Here DSF is used to alter the phase with the objective of obtaining broadened spectra. A tunable optical Gaussian BPF with a 3 dB bandwidth of 0.07 nm is laid at the output of the DSF. Now the filtered signal is detected by using a p-i-n photodiode. For time-domain and frequency-domain visualization, oscilloscope and spectrum analyzers are used. A resolution of 0.001 nm is used for spectral measurements in an optical spectrum analyzer.

3. Results and discussion

The optical spectrum obtained at different sections of the simulation is shown in Fig. 2. Both the VSB-CSRZ signal and input pump signal is denoted by a solid line curve centered at around 1.545 and 1.554 μm, respectively. The spectrum obtained after DSF is represented by a dash-dot curve and is distributed throughout the frequency region as can be visualized from the figure. The reason behind the broadening of spectrum of VSB-CSRZ signal is due to self-phase modulation whereas in pump signal it is due to the effect of XPM induced by VSB-CSRZ signal. Finally by filtering out the spectrum centered around input pump signal, NRZ signal is recovered. The filtered spectrum centered around 1.554 μm is represented by a dotted curve in Fig. 2.

Figure 3 shows the eye diagrams of input VSB-CSRZ and output recovered NRZ signal, respectively, for an arbitrary input laser power. A clear eye diagram can be observed in the case of VSB-CSRZ whereas for recovered NRZ signal, jitters can be observed. The asymmetric temporal profile of the recovered NRZ signal from VSB-CSRZ signal is due to the differences between the rising edge of the gain switched pulses and the falling edge, resulting in difference between red and blue chirps in the VSB-CSRZ signal. It is anticipated that the imbalance can be minimized by employing appropriate

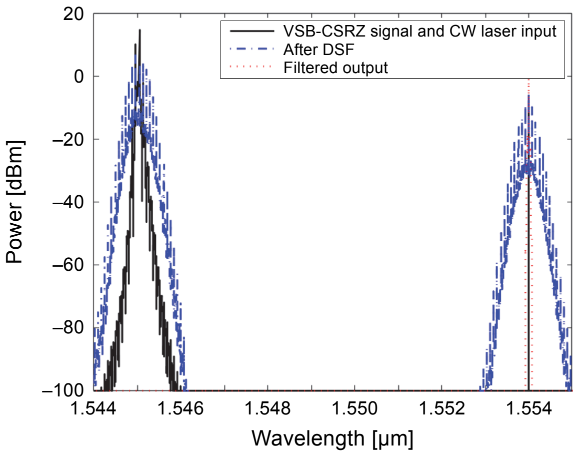

Fig. 2. Optical spectra of the input VSB-CSRZ signal (1.545 μm), CW laser input (1.554 μm) before coupling, after the DSF and filtered output.

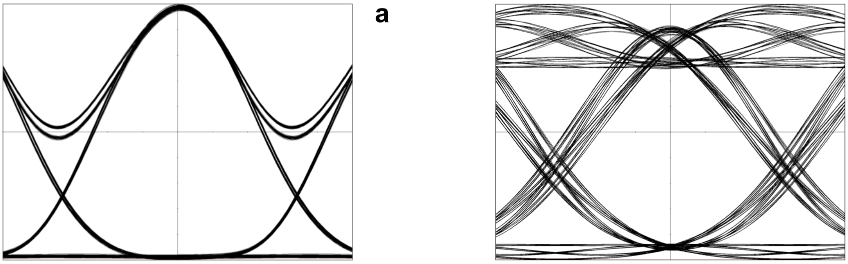

Fig. 3. Eye diagram of 10 Gb/s VSB-CSRZ signal (**a**), and recovered NRZ signal (**b**).

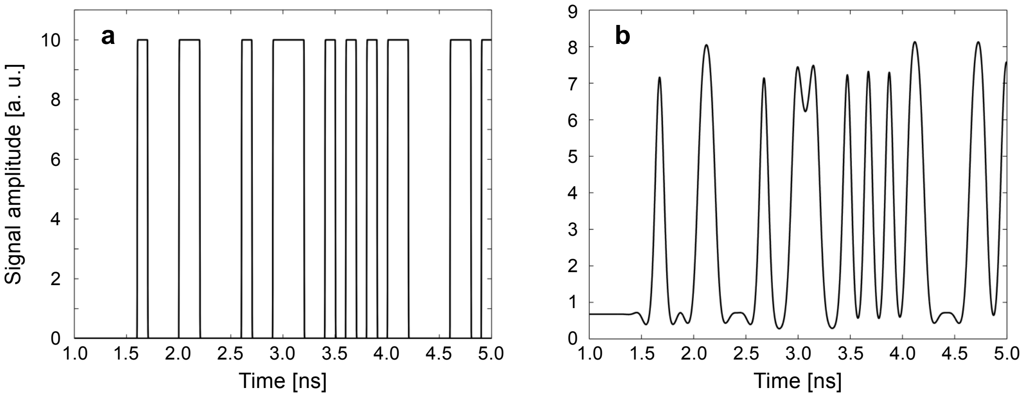

Fig. 4. Input NRZ signal (**a**), and recovered NRZ signal (**b**).

optical BPF having an optimized bandwidth [14]. Figure 4 shows the arbitrary input NRZ data that is considered at the initial stage before being converted to VSB-CSRZ and the recovered NRZ data after fine tuning the broadened spectrum at DSF due to the effect of XPM. The plot clearly indicates that a 10 Gb/s VSB-CSRZ signal has been fruitfully converted into NRZ output. The inter symbol interferences which are visible in Figs. 3**b** and 4**b** result in excess power penalty during the conversion procedure. The excess power penalty occurs due to attenuation of the signal at different stages of the circuits such as fibers as well as at an optical band pass filter which is an inherent property of optical devices. By fine tuning the optical band pass filter, the excess power penalty can be optimized but to a fractional value. The power loss can also be compensated by adding optical amplifiers at each stage. The later process is not followed as it increases the cost of the system.

Figure 5 shows the BER curves of NRZ, VSB-CSRZ, converted NRZ signal based on DSF and SOA measured under different received optical power. The back-to-back receiver sensitivity measured at BER of 10^{-9} of NRZ signal is about −21.62 dBm whereas for VSB-CSRZ it is about −22.69 dBm. Sensitivity degradation of 1.07 dB is observed due to narrowing of the spectrum by an optical band pass filter while converting the NRZ to VSB-CSRZ signal. The back-to-back receiver sensitivities as observed from

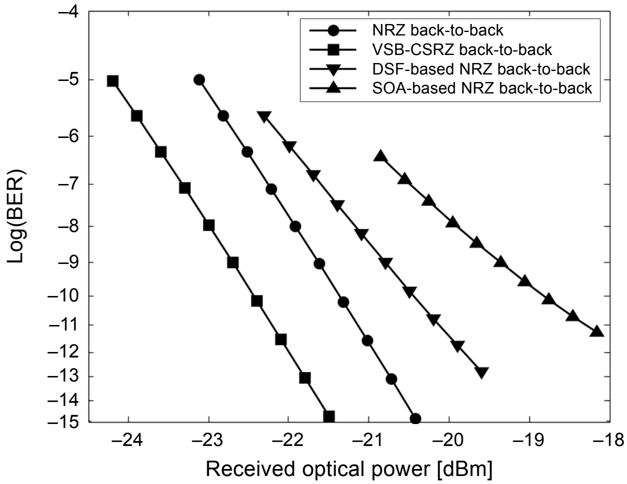

Fig. 5. BER of different signals back-to-back.

Fig. 5 of the converted NRZ signal based on DSF and SOA are −20.79 and −19.35 dBm, respectively. Power penalty of about 0.83 dB is observed in case of DSF compared to 2.27 dB in SOA with respect to original NRZ signal. A large decrease in sensitivity which is observed in case of SOA is due to unwanted pattern effects that are caused by the SOAs intrinsic slow gain recovery time which in turn slows down the speed of operation, whereas it is less in DSF due to ultrafast response time of Kerr-based nonlinear effects.

Figure 6 shows another BER curve of NRZ, converted NRZ signal based on DSF under different received optical powers after transmission through 50 km SMF. It can

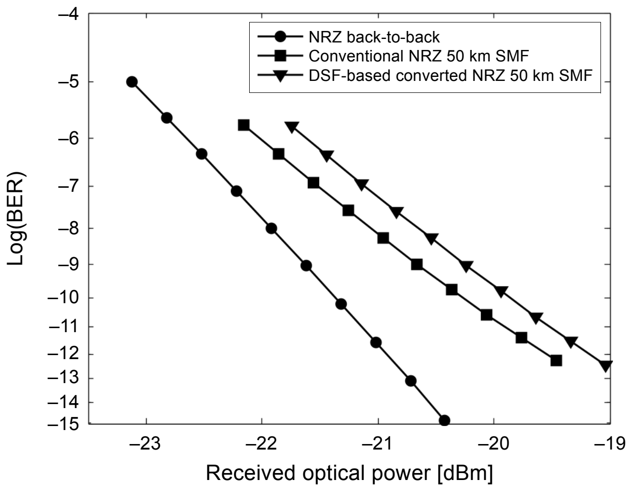

Fig. 6. BER of NRZ signal along with converted NRZ after a distance of 50 km.

be observed that the receiver sensitivity for NRZ signal after traversing 50 km SMF is about −20.65 dBm thereby resulting in a power penalty of 0.96 dB. This degradation in sensitivity is due to inherent properties that are associated with transmission of signal through optical fiber. Figure 6 also shows the BER curve of converted NRZ signal based on DSF after traversing 50 km SMF having a power penalty of 1.38 dB with respect to NRZ signal. Here BER curve of converted NRZ signal based on SOA is not included as it performs abysmally and also is not able to traverse 50 km SMF.

4. Conclusions

An all-optical VSB-CSRZ to NRZ format has been implemented at 10 Gb/s through simulation by exploring XPM in a DSF. By fine tuning the broadened optical frequency spectra, desired data format is retrieved at appropriate wavelength. Clear eye diagram has been obtained at the output of the converter and error-free conversion of VSB-CSRZ pulses to NRZ format is presented using a $2^{10} - 1$ bit sequence. A power penalty of around 1.38 dB is observed in the case of DSF after traversing a distance of 50 km SMF. This wavelength converter can be used for higher bit rates in future all-optical networks.

References

[1] Bigo S., *Multiterabit/s DWDM terrestrial transmission with bandwidth-limiting optical filtering*, IEEE Journal of Selected Topics in Quantum Electronics **10**(2), 2004, pp. 329–340, DOI: 10.1109/JSTQE.2004.826573.

[2] Idler W., Bigo S., Frignac Y., Franz B., Veith G., *Vestigial side band demultiplexing for ultra high capacity (0.64 bit/s/Hz) transmission of 128 × 40 Gb/s channels*, [In] *OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171)*, Vol. 1, 2001, article ID MM3.

[3] Bigo S., Frignac Y., Charlet G., Idler W., Borne S., Gross H., Dischler R., Poehlmann W., Tran P., Simonneau C., Bayart D., Veith G., Jourdan A., Hamaide J.-P., *10.2 Tbit/s (256 × 42.7 Gbit/s PDM/WDM) transmission over 100 km TeraLight™ fiber with 1.28 bit/s/Hz spectral efficiency*, [In] *OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171)*, Vol. 4, 2001, article ID PD25, DOI: 10.1109/OFC.2001.927567.

[4] Tsuritani T., Agata A., Morita I., Tanaka K., Edagawa N., *Performance comparison between DSB and VSB signals in 20 Gbit/s-based ultra-long-haul WDM systems*, [In] *OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171)*, Vol. 1, 2001, article ID MM5, DOI: 10.1109/OFC.2001.927921.

[5] Agarwal A., Chandrasekhar S., Essiambre R.-J., *42.7 Gb/s CSRZ-VSB for spectrally efficient meshed networks*, [In] *Proc. Eur. Conf. Optical Communication (ECOC)*, 2004, article ID We3.4.4.

[6] Norte D., Willner A.E., *Experimental demonstrations of all-optical conversions between the RZ and NRZ data formats incorporating noninverting wavelength shifting leading to format transparency*, IEEE Photonics Technology Letters **8**(5), 1996, pp. 712–714, DOI: 10.1109/68.491604.

[7] Hyuek Jae Lee, Yoo S.J.B., Chang Soo Park, *Novel all-optical 10 Gbp/s RZ-to-NRZ conversion using SOA-loop-mirror*, [In] *OFC 2001. Optical Fiber Communication Conference and Exhibit. Technical Digest Postconference Edition (IEEE Cat. 01CH37171)*, Vol. 1, 2001, article ID MB7, DOI: 10.1109/OFC.2001.927829.

[8] CHUNG GHIU LEE, YUN JONG KIM, CHUL SOO PARK, HYUEK JAE LEE, CHANG-SOO PARK, *Experimental demonstration of 10-Gb/s data format conversions between NRZ and RZ using SOA-loop-mirror*, Journal of Lightwave Technology **23**(2), 2005, pp. 834–841, DOI: 10.1109/JLT.2004.838851.
[9] CHOW C.W., WONG C.S., TSANG H.K., *RZ to NRZ data format and wavelength conversion using an injection locked laser diode*, [In] *The 16th Annual Meeting of the IEEE Lasers and Electro-Optics Society, 2003. LEOS 2003.*, Vol. 2, 2003, pp. 475–476, DOI: 10.1109/LEOS.2003.1252880.
[10] CHOW C.W., WONG C.S., TSANG H.K., *All-optical modulation format conversion and multicasting using injection-locked laser diodes*, Journal of Lightwave Technology **22**(11), 2004, pp. 2386–2392, DOI: 10.1109/JLT.2004.836808.
[11] LEI XU, WANG B.C., BABY V., GLESK I., PRUCNAL P.R., *All-optical data format conversion between RZ and NRZ based on a Mach–Zehnder interferometric wavelength converter*, IEEE Photonics Technology Letters **15**(2), 2003, pp. 308–310, DOI: 10.1109/LPT.2002.806105.
[12] CHO P.S., MAHGEREFTEH D., GOLDHAR J., *10 Gb/s RZ to NRZ format conversion using a semiconductor-optical-amplifier/fiber-Bragg-grating wavelength converter*, [In] *24th European Conference on Optical Communication. ECOC'98 (IEEE Cat. No.98TH8398)*, Vol. 1, 1998, pp. 353 – 354, DOI: 10.1109/ECOC.1998.732588.
[13] REALE A., LUGLI P., BETTI S., *Format conversion of optical data using four-wave mixing in semiconductor optical amplifiers*, IEEE Journal of Selected Topics in Quantum Electronics **7**(4), 2001, pp. 703–709, DOI: 10.1109/2944.974242.
[14] LEE S.H., CHOW K.K., SHU C., *Spectral filtering from a cross-phase modulated signal for RZ to NRZ format and wavelength conversion*, Optics Express **13**(5), 2005, pp. 1710–1715, DOI: 10.1364/OPEX.13.001710.
[15] DURHUUS T., MIKKELSEN B., JOERGENSEN C., DANIELSEN S.L., STUBKJAER K.E., *All-optical wavelength conversion by semiconductor optical amplifiers*, Journal of Lightwave Technology **14**(6), 1996, pp. 942–954, DOI: 10.1109/50.511594.
[16] AGRAWAL G.P., *Nonlinear Fiber Optics*, Academic Press, 2001.

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