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NRZ to Manchester code conversion based on nonlinear optical fiber loop mirror

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An approach to convert NRZ signal to Manchester code at 20 Gbit/s based on nonlinear optical fiber loop mirror (NOLM) is demonstrated. Using 20 Gbit/s NRZ data and optical clock as external pumps of the NOLM, the conversion of NRZ to Manchester code is successfully realized. The eye diagrams, waveforms and optical spectra are presented. We investigated the extinction ratio (ER) penalty (5 dB) to evaluate the system performance and analyzed the method to improve it. The proposed scheme is potential for applications in future networks.

1. Introduction

The symbol time of Manchester code comprises two slots, exactly one of which contains a pulse. Therefore, Manchester code is known as the simplest form of 2-ary pulse-position-modulation (PPM) which maps message bits to pulse position [1]. Manchester code has been shown to present many advantages. For example, this kind of code is self-clocking, which means that a clock can be recovered from the encoded data since it contains a transition in the middle of the symbol time [2]. Furthermore, its differential detection scheme exhibits high-level intensity fluctuation tolerance, verifying itself as a promising code for high-speed burst mode transmission links [3,4] and chaotic communication system [5]. Additionally, the technique to generate Manchester code can be used for optical code division multiple access (OCDMA) systems in secured optical communication networks with reduced multiple access interference [6–8]. It has also been employed as the downstream signal format in a wavelength re-modulated wavelength division multiplexed passive optical network (WDM-PON) to facilitate data re-modulation at the optical network unit (ONU) for upstream transmission [9,10] as well as to avoid the penalty caused by the loss of the low-frequency components [11].

Manchester encoding scheme involves the following: 1) Data and clock signals are combined to form a single self-synchronizing data stream. 2) Each encoded bit contains a transition at the midpoint of a bit period. 3) The direction of transition is determined by whether the bit is a “0” or a “1”. 4) The first half is the true bit value and the second half is the complement of the true bit value [6]. Therefore, the rules of Manchester encoding are as follows [12]: 1) if the original data is logic “0,” the Manchester code is a transition of “0” to “1” in one time period; 2) if the original data is logic “1,” the Manchester code is a transition of “1” to “0” in one time period. Since the only half time period will represent the true bit value; it could be either the first half-time period or the second half-time period.

Approaches to obtain Manchester code include: 1) costly XOR logic gates in electrical domain that needs OE/EO conversion [13]; 2) utilization of a push–pull type Mach–Zehnder intensity modulator [14] or nested Mach–Zehnder interferometers for differential Manchester code [15] that does not require any electrical logic gate; 3) fiber-based Kerr shutter in which two pumps induce birefringence in the highly nonlinear fiber(HNLF), leading to the state of polarization (SOP) of dummy channel rotation according to the instantaneous power of clock and NRZ data [16]. This approach has the potential application in ultrafast condition though it has just been demonstrated at 10 Gbit/s.

In this paper, we proposed and experimentally demonstrated an approach for 20 Gbit/s all-fiber amplitude-shift keying (ASK) Manchester code generation using nonlinear optical loop mirror (NOLM). Due to the cross-phase modulation (XPM), the input NRZ data and optical clock induce nonlinear phase shift to the probe, changing the intensity of the probe after interfering at the output of the NOLM. This scheme has many advantages, such as, all-fiber construction, high speed due to ultrafast nonlinear response time of Kerr effect in the fiber, and suppression undesired four-wave mixing (FWM) effect between two pumps. Furthermore, it is easy to choose the first half bit time or the second half bit time to represent the true bit value by tuning the tunable optical delay line (TODL). However, for practical application, one of the disadvantages of this approach is that it cannot be integrated due to long fiber structure.

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2. Principle of operation and experiment setup

The principle of operation is a well-known NOLM-based pump-probe structure with two pumps (NRZ data and optical clock). Here, the second pump acts as a "compensator" for the temporary phase shift induced by the first pump. That means if the two pumps with proper optical power are overlap in the time domain, the phase shift experienced by the probe will be canceled. Therefore, Manchester code can be produced at the output of NOLM as shown in Fig. 1(a). The output power can be written as:

$$P_{out} = P_{in} \sin^2[(\phi_{cw} - \phi_{ccw})/2] \tag{1}$$

Where, P_{in} is the optical power of probe light, ϕ_{cw} is the phase shift induced by optical clock (clockwise pump), and ϕ_{ccw} is the phase shift induced by NRZ data (counterclockwise pump).

Fig. 1(b) depicts the experimental setup of the NRZ data to Manchester code convertor which only uses commercially available fiber pigtailed components. External cavity laser (ECL1) at 1553.2 nm is modulated by a Mach–Zehnder modulator (MZM1) driven by a 2^{31}-1 pseudo-random binary sequence (PRBS) to form NRZ data. Then it is amplified by EDFA1 as pump-1 and launched into the loop via wavelength division multiplexer (WDM1). A TODL is used to synchronize the two pumps. ECL2 at 1548.4 nm is modulated by MZM2 to form a 20 GHz optical clock with the duty cycle of 49.6%, and then amplified by EDFA2 and launched into the NOLM through WDM2. Continuous wave at 1538.9 nm from ECL3 is acted as the probe on which the optical Manchester code will be carried. The length of the HNLF used in the NOLM is 1 km long with an insertion loss of 1.7 dB, a nonlinear coefficient of 12.5 W^{-1} km^{-1}, a chromatic dispersion of −0.69 ps/(nm·km), and a dispersion slope of 0.01 ps/(nm^2·km) at 1550 nm. Three isolators (ISOs) are placed in each channel to terminate the residual pump power. PC1 and PC2 serve to align the polarization for MZM1 and MZM2, respectively. Three PCs (PC3–PC5) are used to adjust the SOP of pumps and probe in the loop. A bandpass filter (BPF) with a 3-dB bandwidth of 0.8 nm is placed at the output to filter out the desired signal. Temporal waveforms, eye diagrams and ER are measured in the optical domain using an optical sampling module with 65 GHz bandwidth connected to digital communications analyzer (DCA). Optical spectra are monitored by an optical spectrum analyzer (OSA).

3. Results and discussions

Fig. 2 shows that the output extinction ratio (ER) changes as a function of the input optical power of the NRZ data when ECL2 is OFF. In this condition, the NOLM acts as a wavelength convertor. As the pump power is increasing, the ER of the output also increases showing an up-curved distribution of the data points that corresponds to the sin^2 characteristics of the output. This is consistent with the description of Eq. (1) mentioned above when $\phi_{cw}=0$. A maximum ER of 13.8 dB is obtained with a pump power of 15 dBm. If the power continues to increase, the nonlinear phase shift becomes larger than π and ER will gradually decrease. Note that the ER of the input NRZ data is 15.5 dB, therefore, the ER penalty of the NOLM as a wavelength convertor for NRZ signal is 1.7 dB. This value is useful for us to analyze the ER performance of the Manchester code consequently.

To obtain Manchester code output, we need to adjust the PC3, PC4 and PC5 carefully. Firstly, we turn off ECL2 and change PC3 and PC5 to

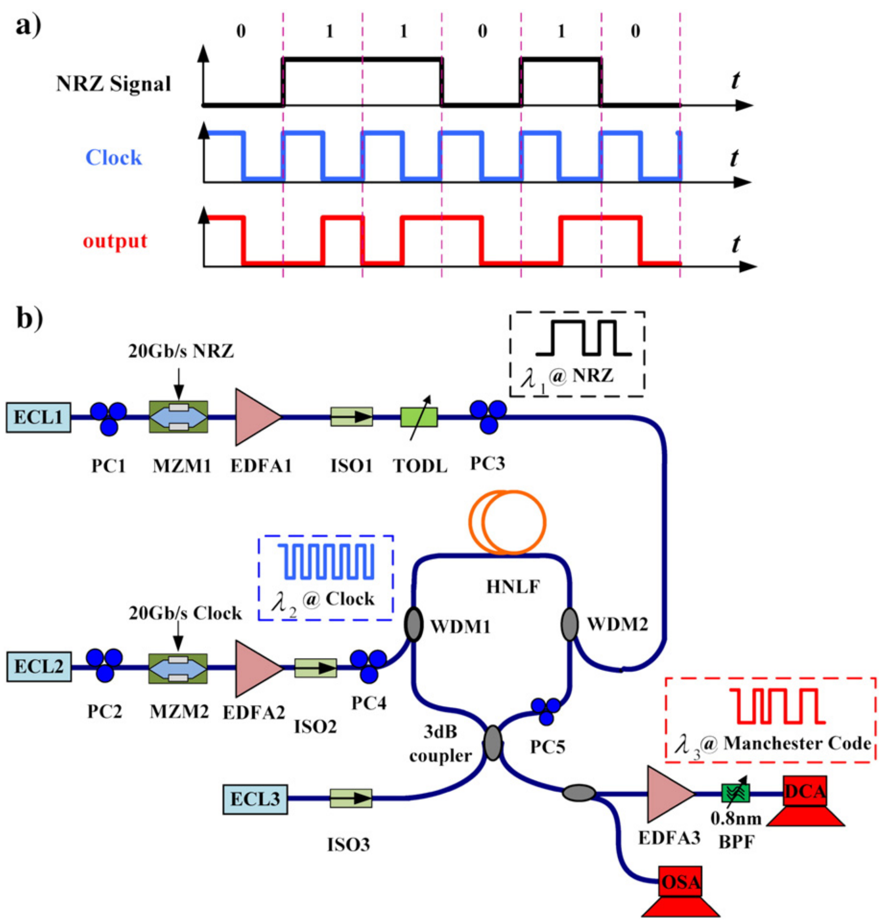

Fig. 1. (a) Waveforms of two input pumps (NRZ data and clock), and Manchester code output. (b) Experimental setup.

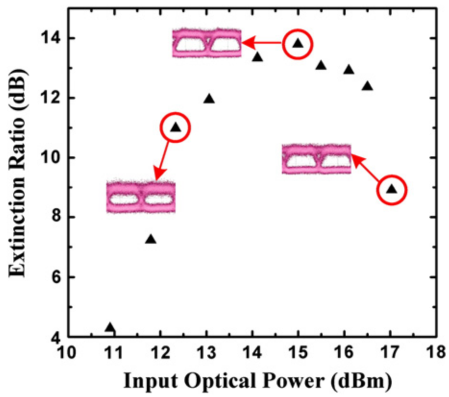

Fig. 2. ER of the NOLM output as a function of the input power of NRZ data when clock is OFF.

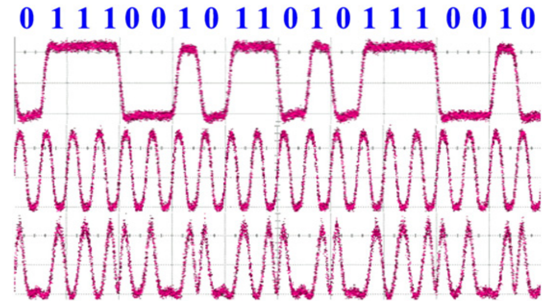

Fig. 4. Waveforms of (a) NRZ input, (b) clock input, and (c) Manchester code.

insure a good quality NRZ signal output. Then ECL2 is turned on and PC4 is adjusted to align a proper SOP for optical clock with PC3 and PC5 fixed. Finally, TODL is turned to choose the first half bit time or the second half bit time of the output Manchester code to present the true value of the input NRZ data.

In Fig. 3(a)–(d), we show that the optical spectra of the output of NOLM before the BPF when both input pumps (NRZ data and optical clock) are ON or OFF. Only when either pump is ON, there will be signal at the output, not vice versa. When both pump-1 and pump-2 are OFF, the output power of the NOLM is −32 dBm while increasing to −20 dBm when either pump is ON. As we can see in Fig. 3(d), FWM components involved with two pumps are successfully suppressed because of the bidirectional transmission structure of the pumps.

Fig. 4 shows the input NRZ patterns, optical clock and the converted Manchester code patterns at 20 Gbit/s. The second half bit time is chosen to present the true value of the input. However, when the pattern is '10' or '01', there is a dip or a small peak between the two bits in the output Manchester waveform. This is because it takes time for both clock and NRZ data to rise from low power level to high power level or fall from high power level to low power level, thus the phase shift induced to the probe caused by the rising edge of the clock and the falling edge of the NRZ data is inconstant. It will change with the time between bits "10" and "01". As a result, interference at the output of the NOLM is incomplete during this transition time and a dip will emerge. Similarly, a small peak caused by the rising edge of the two pumps will appear between bits "01" since the rising edges of them are not exactly the same. However, we believe this can be improved by using the pump signals with much more shorter rising or falling time such as super-Gaussian or rectangle waveforms.

In Fig. 5, we illustrate the eye diagrams and optical spectra of the input NRZ data, clock, as well as the output Manchester code which has the ER of 10 dB with respect to the input NRZ signal with ER of 15.5 dB. It means that the corresponding ER penalty compared to the input NRZ data is 5.5 dB, which could be caused by the reasons below. Firstly, since the duty cycle of the two pumps is high, the constant phase shift induced by counter-propagating signals can't be neglected

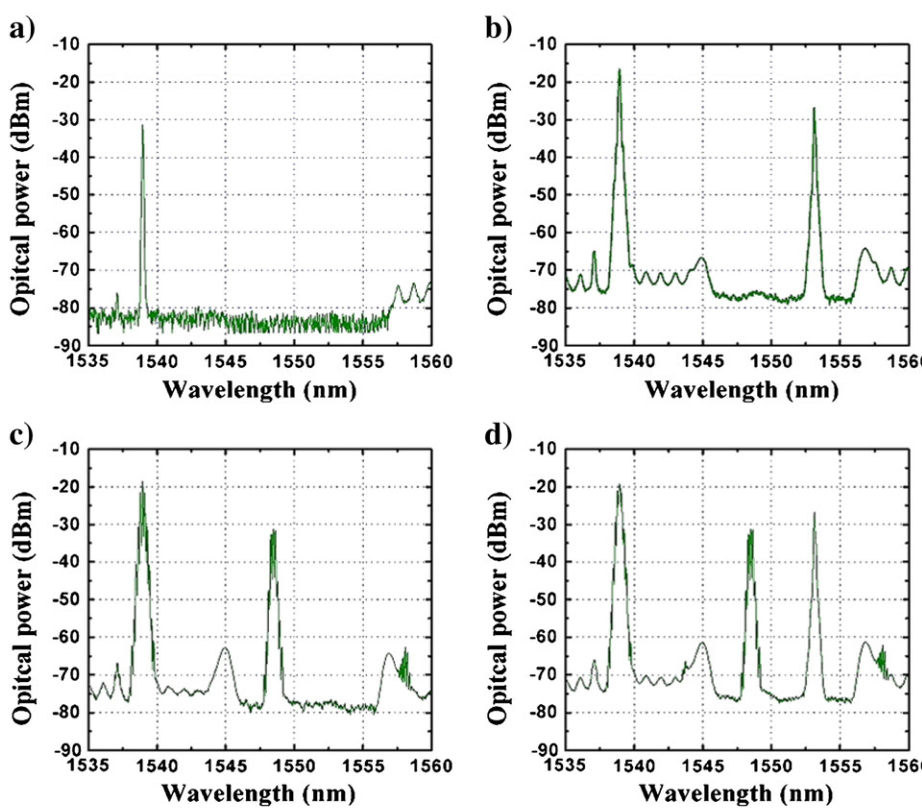

Fig. 3. Output optical spectra before the BPF, (a) pump-1 OFF and pump-2 OFF; (b) pump-1 ON and pump-2 OFF; (c) pump-1 OFF and pump-2 ON; (d) pump-1 ON and pump-2 ON.

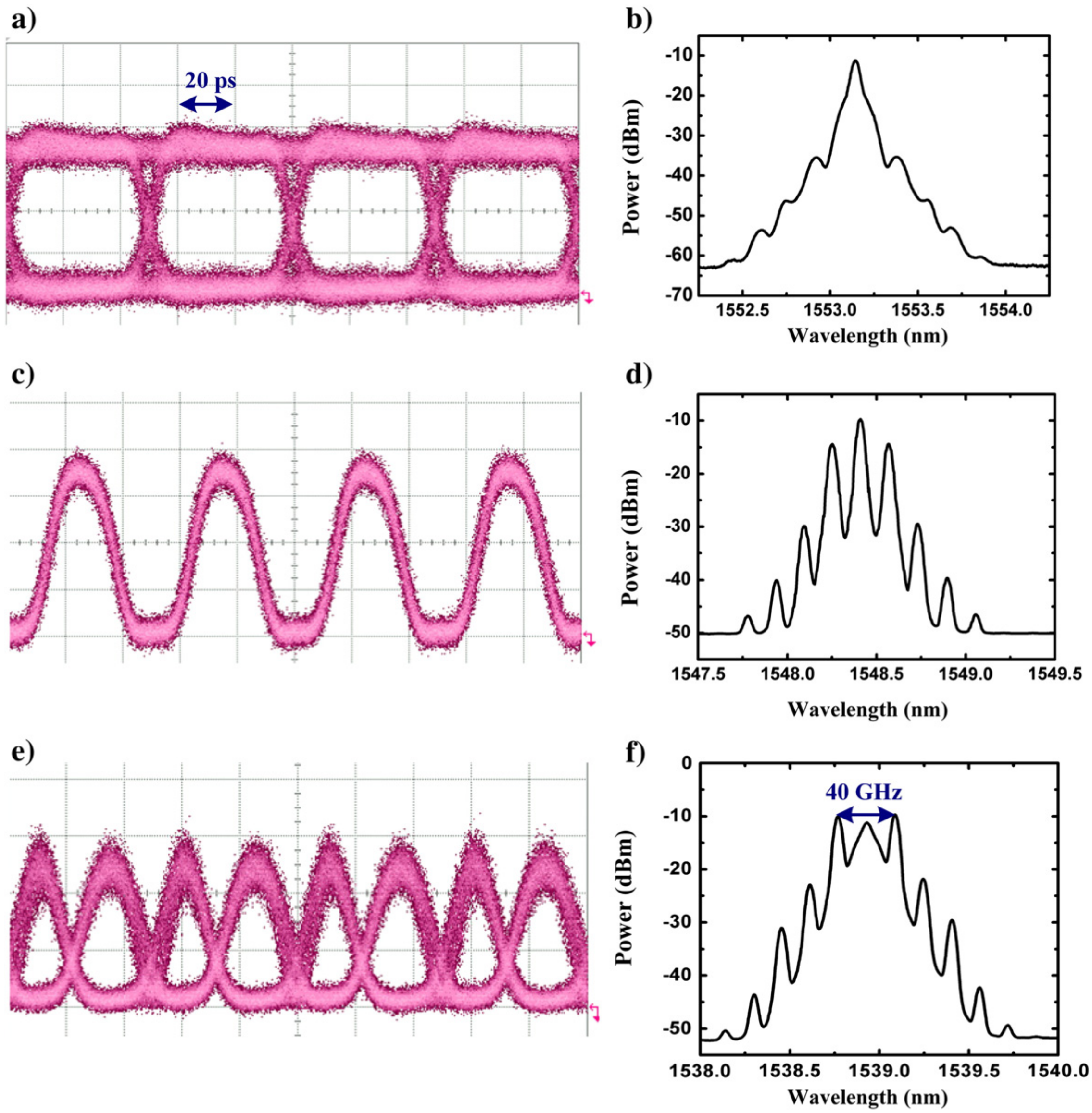

Fig. 5. Eye diagrams and optical spectra input NRZ data (a, b), clock (c, d), and converted Manchester code (e, f).

[17]. Therefore, the NOLM can't achieve full-swing operation in the experiment. On the other hand, the splitting ratio of the 3 dB coupler used in NOLM is not ideal and the SOP of pumps and probe in non-polarization maintaining HNLF may be influenced by environment. Both of the aspects may cause incomplete interference to degrade the ER. Therefore, the ER performance should be improved by introducing an "optical bias controller" [17] and polarization maintaining fiber. Note that the power of NRZ pump and clock pump for obtaining the Manchester code with the best ER performance in our experiment are 15.1 and 15.6 dBm, respectively. If we fix the power of input clock and change the power of NRZ data, obviously ER degradation of the output could be monitored because of the incomplete interference. However, if the power of input clock could follow the power changes of NRZ data properly, the ER performance can also be improved slightly since the net phase shift caused by the two pumps is closed to zero when they overlap. According to the experiment results, in order to obtain an ER higher than 8 dB, the power level of the NRZ pump should be in the range of 14 to 16 dBm with matched clock power. Fig. 5(f) shows the optical spectrum of the output Manchester code. Both the 20 GHz and 40 GHz frequency components can be found and optical carrier is suppressed to some extent compare to conventional NRZ spectrum.

4. Conclusion

We experimentally demonstrated an NRZ to Manchester code conversion technique based on bidirectional pumped NOLM. The scheme is based on the XPM effect between two pumps (the NRZ data and synchronized optical clock) and probe. The waveforms, eye diagrams and optical spectra of the output Manchester code are illustrated. We investigated the ER penalty (5.5 dB) to evaluate the system performance and analyzed the method to improve it. This kind of configuration can also be used in OCDMA and wavelength re-modulated WDM-PON system to greatly improve system performance. TODL can be tuned to choose the first half-bit time or second half-bit time to present the true data. Moreover, we believe that the bit rate can be significantly improved because of the ultrafast response time of Kerr effect. However, for practical application, integration is a problem that needs to be solved in the future.

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