A Novel Return-to-Zero FSK Format for 40-Gb/s Transmission System Applications

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Abstract—In this paper, we present the generation, the detection and the performance evaluation of a novel return-to-zero frequency shift keying (RZ-FSK) format for 40 Gb/s transmission. Non-return-to-zero (NRZ) FSK signal is generated by using two continuous-wave (CW) lasers, one Mach–Zehnder modulator (MZM) and one Mach–Zehnder delay interferometer (MZDI). A RZ-FSK signal is successfully generated by cascading a dual-arm MZM, which is driven by a sinusoidal voltage at half of the bit rate. The demodulation can be simply achieved on one bit rate through one MZDI or an array waveguide grating (AWG) demultiplexer with balanced detection. By numerical simulation, two types of frequency modulation schemes using MZM or PM, and impact of the frequency tone spacing (FTS) of the generated FSK signal are discussed. The proposed scheme shows that the novel frequency modulation format offers a few transmission advantages comparing with than that of the other traditional modulation formats, such as RZ and differential phase-shift keying (DPSK), under varying dispersion management. The performance analysis of RZ-FSK signal in a 4 × 40 Gb/s WDM transmission system is introduced. We experimentally demonstrate, transparent wavelength conversion based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) and in a highly nonlinear dispersion shifted fiber (HNDSF) for a 40 Gb/s RZ-FSK signal, clearly validating the feasibility of all optical signal processing of high-speed RZ-FSK signal. Moreover, we investigate the receiver power penalty for the RZ-FSK signal after a 100 km standard single-mode fiber (SMF) transmission link with matching dispersion compensating fiber (DCF), under the post-compensation management scheme. Since the frequency modulation format is orthogonal to intensity modulation and vector modulation (polarization shift keying), it can be employed in the context of the combined modulation format to decrease the data rate or enhance the symbol rate. It can also be utilized in the orthogonal label-switching as the modulation format for the payload or the label.

Index Terms—Chromatic dispersion, Mach–Zehnder delay interferometer, Mach–Zehnder modulator (MZM), optical communication, return-to-zero frequency shift keying (RZ-FSK), wavelength conversion.

I. INTRODUCTION

Over the past few years, a number of advanced modulation formats have attracted increased attention in order to enhance the optical signal robustness to chromatic dispersion and fiber nonlinear effects, and looser requirement for bandwidth of electrical circuits [1]–[6]. In many different modulation formats, frequency shift keying (FSK) modulation format enables differential detection scheme, and simulations have shown that it has a comparable gain of OSNR sensitivity to DPSK in a 10 Gb/s transmission system [5]. Furthermore, the orthogonal modulation of amplitude shift keying (ASK) and FSK has recently attracted much attention for its high-spectral advantages comparing with the other traditional modulation formats [6]–[10]. One example is the combination of ASK and FSK, which is driven by a sinusoidal voltage at half of the bit rate through one MZDI or an array waveguide grating (AWG) demultiplexer with balanced detection. By numerical simulation, two types of frequency modulation schemes using MZM or PM, and impact of the frequency tone spacing (FTS) of the generated FSK signal are discussed. The proposed scheme shows that the novel frequency modulation format offers a few transmission advantages comparing with the other traditional modulation formats, such as RZ and differential phase-shift keying (DPSK), under varying dispersion management. The performance analysis of RZ-FSK signal in a 4 × 40 Gb/s WDM transmission system is introduced. We experimentally demonstrate, transparent wavelength conversion based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) and in a highly nonlinear dispersion shifted fiber (HNDSF) for a 40 Gb/s RZ-FSK signal, clearly validating the feasibility of all optical signal processing of high-speed RZ-FSK signal. Moreover, we investigate the receiver power penalty for the RZ-FSK signal after a 100 km standard single-mode fiber (SMF) transmission link with matching dispersion compensating fiber (DCF), under the post-compensation management scheme. Since the frequency modulation format is orthogonal to intensity modulation and vector modulation (polarization shift keying), it can be employed in the context of the combined modulation format to decrease the data rate or enhance the symbol rate. It can also be utilized in the orthogonal label-switching as the modulation format for the payload or the label.

Index Terms—Chromatic dispersion, Mach–Zehnder delay interferometer, Mach–Zehnder modulator (MZM), optical communication, return-to-zero frequency shift keying (RZ-FSK), wavelength conversion.

In this paper, we propose a novel scheme for generation of a RZ-FSK signal that can reach the bit rate at 40 Gb/s and above. The RZ-FSK transmitter and receiver’s configuration and the detailed operational principle of RZ-FSK generation and detection are presented in Sections II. In Section III, based on numerical simulation, we will compare the performance of FSK, DPSK and RZ modulation formats at 40 Gb/s for 12 spans of 80 km SMF in terms of the tolerance to nonlinear effects and chromatic dispersion, and demonstrate RZ-FSK signal has a few advantages than that of the other modulation formats. The performance analysis of RZ-FSK signal in a 4 × 40-Gb/s WDM transmission system is introduced. In Section IV, we experimentally demonstrate, 40-Gb/s RZ-FSK signal over 100 km SMF with
full dispersion compensation, and also experimentally compare transparent wavelength conversion based on four-wave mixing (FWM) in a semiconductor optical amplifier (SOA) and in a highly nonlinear dispersion shifted fiber (HNDSF), clearly validating the feasibility of all optical signal processing of 40-Gb/s RZ-FSK signal. Section V concludes the paper.

II. RZ-FSK TRANSMITTER AND RECEIVER

The schematics of the RZ-FSK generation and detection are illustrated in Fig. 1(a) and (b). Low speed FSK signal can be produced by directly modulating DFB lasers by driving them with a bias current far above threshold and adding a relatively small modulation current. To generate a FSK signal at 40 Gb/s and above, two continues-wave (CW) lasers with carefully selected are combined by a 3 dB coupler and input to the Mach–Zehnder modulator (MZM1) or the phase modulator (PM), which is modulated by NRZ data, and then demodulated to intensity modulation by the subsequent Mach–Zehnder delay interferometer (MZDI). The MZDI is imbalanced by introducing one-bit time delay line. Note that the wavelengths of the two beams are carefully selected so that one beam is at the maximum transmission of the MZDI (constructive interference) while the other at the minimum (destructive interference), thus the tone spacing is \((N+1/2)/T_b\) Hz, \((N = 1, 2, 3, \ldots)\), where \(T_b\) is one bit period. Assuming the center frequencies of the two beams are \(f_1\), \(f_2\) respectively, the optical field exiting a phase modulator is given by

\[
E_1(t) = E_0 \cdot \exp\left(\frac{j2\pi f_1 T_b + \Phi_1 + \Phi_2}{2}\right) \cdot \cos\left(\frac{2\pi f_1 T_b + \varphi}{2}\right) \quad (1)
\]

\[
E_2(t) = E_0 \cdot \exp\left(\frac{j2\pi f_2 T_b + \Phi_1 + \Phi_2}{2}\right) \cdot \cos\left(\frac{2\pi f_2 T_b + \varphi}{2}\right) \quad (2)
\]

where \(\Phi_1, \Phi_2\) are the phase of the neighboring bits, and the data information is reflected in the phase difference \(\varphi\). Using the fact that

\[
f_1 = \frac{m}{T_b}, \quad m = 0, 1, 2, 3, \ldots M \quad (3)
\]

\[
f_2 = f_1 + \frac{2n + 1}{2T_b}, \quad n = 0, 1, 2, 3, \ldots N. \quad (4)
\]

However, in a real transmitter, we should consider the rise time and the fall time of the input signal. According to the (3), \(1/f_1 = T_b/m, \quad m = 0, 1, 2, 3, \ldots M\). \(T_b/M\) must be larger than the rise time of the input signal pulse-width. If \(T_b/M\) is too small, the phase information generated by the MZM1, or the PM, could not be transferred to the intensity signal in the MZDI. Even if the phase information is accurately transferred to the amplitude information, however, the difference between
Having learned that the bandwidth of the transmitted signal is a function of the carrier’s rise and fall times, we should wonder whether the generated FSK signal is normal. In our model, an electrical rectangular NRZ pre-shaped input data (Data) pulse with symbol duration \( T_b \) is filtered by a linear time-invariant filter with a normalized Gaussian shaped impulse response:

\[
h(t) = \frac{2}{\sqrt{\pi T_e}} e^{-(2t/T_e)^2} \quad (5)
\]

where \( T_e \) denotes the 1/\( e \)-pulse duration. The output pulse \( y(t) \) is given as convolution of \( h(t) \) with the rectangular input time function:

\[
y(t) = \frac{1}{2} \left( \text{erfc} \left( \frac{2(t - T)}{T_e} \right) - \text{erfc} \left( \frac{2t}{T_e} \right) \right) \quad (6)
\]

The 10%-90% amplitude values of \( y(t) \) was defined as the rise time, and the 90%-10% amplitude values of \( y(t) \) was defined as the fall time. Provided that the pulse duration \( T_b \) is long compared with the filter time (the constant \( T_e \)), the rise time is approximately \( \Delta t = 3T_e/4 \). In this case, for \( T_b = 3T_e/2 \), the approximation error is less than 10%. Furthermore, in the frequency domain, the filter is also Gaussian shaped. The 1/\( e \)-bandwidth \( \Delta f_e \) is given by

\[
\Delta f_e = \frac{4}{\pi \cdot T_e} \quad (7)
\]

Such that for all rise times \( \Delta t \leq T/2 \), the 1/\( e \)-bandwidth is approximately

\[
\Delta f_e \leq \frac{3}{\pi \cdot \Delta t} \quad (8)
\]

Considering the above discussion, the rise-fall time of the input signal (\( \Delta t \)) should not exceed \( T_b/M \), the (9) should be expressed as

\[
\Delta f_e \leq \frac{3M}{\pi \cdot T_b} \quad (9)
\]

Assuming the edge of the generated FSK signal is not sharp, the DL-MZ interferometer, \( L \) should be smaller than a certain number, and the value of \( T_b/(L+1/2) \) could be introduced to ensure the process of phase-to-intensity transform is perfect. Hence, in order to more accurately describe the bandwidth limitation of the transmitter, similar to the previous derivation, the (10) should be modified and expressed as

\[
\Delta f_e \leq \frac{3}{\pi \cdot T_b} \left( L + \frac{1}{2} \right) \quad (12)
\]

Finally, the maximal 1/e-bandwidth of our proposed transmitter, is \( \Delta f_{e\text{max}} = 3/\pi \cdot T_b(L + 1/2) \).

Based on the above (3) and (4), the frequency tone spacing (FTS) of the generated FSK signal should be expressed as

\[
\text{FTS} = \frac{2n + 1}{2T_b} \quad (n = 0, 1, 2, 3\ldots N) \quad (13)
\]

While the coupling ratios of the MZDI’s two couplers are both 50:50, the output at constructive port of MZDI can be described by

\[
P_o = P_i \cdot \left\{ -\frac{1}{2} \cos \left( 2\pi f_1 + 2\pi f_2 \right) \cdot \text{FTS} + \Delta \varphi + \frac{\pi}{2} + \frac{1}{2} \right\} \quad (14)
\]

where \( P_i \) and \( P_o \) are the input and output optical power, \( \Delta \varphi \) is the phase difference between the two arms of MZDI. According to the (14), if the central frequency of the laser locates at such a position so that one of the generated FSK tones \( f_1 \) locates exactly at maximum transmission point of the MZDI while the other \( f_2 \) locates at minimum transmission point, as depicted in Fig. 1(c), two logically inverted data streams can be achieved at each MZDI output. In this way, an optical FSK signal is generated at the output of MZDI. The FSK signal with an optical pulse existing at every bit slot is generated. It should be noted that the constructive wavelength carries duobinary (DB) modulation, whereas the destructive carries alternate-mark inversion (AMI) [2]. Hence, the FSK signal can be regarded as a combination of two intensity modulated (IM) signals with non-information-bearing phase modulation.

In practice, the frequency modulation format with RZ shape is widely used in long-haul optical communication systems due to its superior performance. The RZ pulse carver can be implemented cascading a MZM2 after MZDI. In our scheme, the MZM2 driven by a sinusoidal voltage at half of the bit rate is employed. As a result, the generated FSK signal passes through the MZM2 to generate a RZ-FSK signal. Fig. 1(b) shows the configuration of the RZ-FSK receiver. The optical bandpass filter (OBPF) provide more than 25 dB suppression ratio between the two FSK tones. An array waveguide grating (AWG) demultiplexer is used to separate the FSK two tones and demodulate the FSK into intensity modulation. As we discussed before, the data obtained in one output is identical to the original data, but in another output, the detected data is logically inverted. Hence, these two outputs can be detected by a differential receiver. A low pass filter is applied after the differential electrical amplifier to remove the high-frequency pulses induced by the beating of the two modes. Through experiment, Fig. 2 shows the measured waveforms and optical spectra for
FSK and RZ-FSK signal. Clear waveforms powerfully demonstrate the feasibility of the proposed FSK and RZ-FSK generation schemes, as shown in Fig. 2(a)–(f). From Fig. 2(g) with conventional spectra, two non-symmetrical FSK components and RZ-FSK components can be observed, which are generated with the proposed scheme. It can be well explained by the fact that the FSK signal is obtained by demodulating two DPSK signals. According to the position of the two RZ-FSK tones shown in Fig. 2(g), the low frequency RZ-FSK component carries the spectrum of RZ-DB modulation format and the high frequency one represents the spectrum of RZ-AMI modulation format. The degree of overlapping of these two spectral components will be increased with the decrease of tone spacing.

III. NUMERICAL SIMULATION AND RESULTS

The tolerance of RZ-FSK to some transmission impairments is evaluated through numerical simulations using commercial software. A comparison with currently used modulation formats, such as RZ and DPSK, is performed. As shown in Fig. 1(a), two CW lasers with carefully selected central frequency are utilized as the transmitter’s source. The central frequencies of two light beams are selected as 193 and 193.1 THz. One beam is at the maximum transmission of the MZDI (constructive interference) while the other is at the minimum (destructive interference). At the transmitter, the data stream from 40-Gb/s pattern generator, with NRZ binary sequence, is pre-coded and drive a phase modulator. The phase shift in the phase modulator is $\pi$. The flowing one bit delay MZDI is used demodulate the two DPSK signals into two IM signals. Assuming that the coupling ratios of the MZDI’s two couplers are both 50:50, a high-speed FSK signal can be obtained and can be regarded as a combination of two logically inverted intensity modulated signals with phase modulation in no information bearing way. On the other hand, for RZ carving, one MZM driven by a sinusoidal voltage at half of the bit rate is employed. The schematic modulation of 40-Gb/s RZ-FSK signal clock is also shown in Fig. 1(a). At the receiver, an OBPF and an AWG demultiplexer are used as the frequency discriminator to demodulate the received FSK signal, or RZ-FSK signal, into IM signal for direct detection.

A. Comparison of two Frequency Modulation Schemes Using MZM and PM

In terms of implementation, there are two methods to realize phase change by using: PM or MZM, as shown in Fig. 3. The difference between the two modulator options is shown as follows. PM keeps the optical intensity constant and modulates the phase subject to its bandwidth limitations. However, as we know, using a PM will induce significant chirp on the signal. It introduces imperfect phase modulation in data transition region, which would cause additional power penalty. In contrast, MZM is usually used for phase modulation for this particular reason. MZM produces instantaneous phase jumps but at the expense of some residual intensity modulation. Through such difference of the two methods is not critical when the center frequencies of the two beams are properly aligned, the impairment from timing misalignment strongly depends on this effect. That is because when timing is misaligned, the data transition region of some or other beam center frequency is located in the midpoint of data time slot of FSK signal. Therefore, by using MZM, the data-related dips inevitably lead to inter-symbols interference to F signal. For PM, if the bandwidth of the optical bandpass filters (OBPF) is sufficiently large so that the signal...
can keep its constant intensity after filtering, such ISI can be effectively avoided. But, in strongly optical filtering systems or the for sharp-edged input data pulses, dips would also be introduced after filtering. Therefore, comparison of two phase modulation schemes using MZM and PM schemes should also be taken into account.

Monte-Carlo numerical simulation is performed to investigate the dependence of frequency modulation between PM+MZDI and MZM+MZDI. As shown in Fig. 4(a), it is found that about 0.51 dB improvement in the receiver sensitivity can be achieved after substituting PM with MZM as the phase modulator. The improvement is due to the fact that the upward overshoots could be partly pre-compensated by downward intensity dips with MZM modulation, which can be clearly seen by comparing the corresponding temporal waveforms given in Fig. 4(b) and (c). Hence, the frequency modulation signal using MZM+MZDI is more suitable to be adopted, if only referring receiver sensitivity, since it has higher receiver sensitivity than using PM+MZDI.

**B. Impact of Different FTS**

In the optical FSK generating technique, especially with the center frequencies of the two beams, the FTS should be well preserved to ensure one beam is at the maximum transmission of the MZDI, while the other at the minimum. It is important to note that using different FTS to generated FSK signal, the transmission performance is different. We must be careful that the value of FTS is satisfied with the (13). By using Monte Carlo numerical simulation, the BER performances for two FSK signals are shown in Fig. 5(a). For 40-Gb/s FSK with 60-GHz FTS, 100-GHz FTS, the observed power penalties after transmission over 80-km SMF is 0.58 and 0.46 dB, respectively. The bandwidth of the discrimination filter is set at 60 and 100 GHz for the two FSK signals, respectively. Fig. 5(b)–(e) describe the eye diagrams at BER = 10^{-3} for the two FSK signals in back-to-back case and after 80-km transmission link. Clear and opening eyes powerfully demonstrate the feasibility of the generated FSK scheme. It is also shown that larger pulse timing jitter can be
observed with larger spectral overlapping between the two FSK components. Hence, the FSK signal with 100 GHz FTS is more suitable to be adopted, if referring power penalties, and the sampling and decision are easier in the receiver.

### C. Comparison of Transmission Properties of FSK, DPSK and RZ

As shown in Fig. 6, one erbium-doped fiber amplifier (EDFA) was set at the beginning of each span to compensate signal attenuation in the SMF and DCF, respectively followed by a variable optical attenuator (VOA) to adjust the span launch power. As we know, for long-distance transmission, the dispersion compensation is always compensated in each amplifier span. Each fiber span consists of 80-km SMF with dispersion matching DCF. The transmission optical fiber parameters are shown in Table I.

<table>
<thead>
<tr>
<th>Fiber parameters</th>
<th>SMF</th>
<th>DCF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dispersion D (ps/nm/km)</td>
<td>16</td>
<td>-90</td>
</tr>
<tr>
<td>Fiber loss (dB/km)</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Nonlinear coefficient $(W \cdot km)^{-1}$</td>
<td>2.6</td>
<td>4</td>
</tr>
<tr>
<td>Dispersion slope $dD/dl$, (ps/nm2/km)</td>
<td>0.08</td>
<td>-0.21</td>
</tr>
</tbody>
</table>

The system performances with different dispersion compensation schemes are studied by simulation. It is found that 1 dB tolerance range of the compensation ratio is between 98% to 102%, corresponding to a residual dispersion of 26 ps/nm, which is almost half of the dispersion tolerance of RZ and DPSK. In this simulation, the DPSK signal is produced by a phase modulator and the RZ signal is generated by push-pull RZ modulation followed by the NRZ modulation. Due to the relatively large signal bandwidth, the dispersion should be carefully managed for the transmission of FSK signal.

Fig. 7 shows examples of how the dispersion compensation scheme and the span input power affect the system performance over 11 spans of 80-km transmission link. Multi-span transmission over 880 km SMF is achieved for FSK. If the receiver sensitivity is defined as the received optical power at BER of $10^{-9}$, given the same sensitivity penalty, DPSK has the maximum reach whereas RZ the minimum. For FSK and DPSK, post-compensation scheme has better performance than pre-compensation. But for RZ, pre-compensation is preferred. The tolerance to nonlinear effects is demonstrated in Fig. 7 where the sensitivity penalty is calculated from each span input power. At low powers, the performance is degraded by the amplified spontaneous emission (ASE) noise from the amplifiers. If the power is increased, self-phase modulation in conjunction with dispersion will degrade the signal. Between two extremes the optimized range of input power is around 5–8 dBm for FSK. It is clear to see that the generated FSK signal shows high fiber input power tolerance for long distance transmission link with post-compensation.

### D. Performance Analysis of FSK Under Different Dispersion Compensation

Here, we will show how dispersion compensation schemes affect the FSK transmission system performance. At present, several techniques, including dispersion compensating fiber (DCF) and Fiber Bragg Grating (FBG), can be used to compensate the accumulated dispersion in the fiber [19], [20]. In the following examples, we will show three different schemes, pre-, post-, and hybrid-compensation, to compensate the fiber dispersion. In various dispersion compensation schemes, we will use the ideal DCF, which is placed at different point in each transmission span, as the dispersion compensator to show our scheme.

Pre-, post-, and hybrid-compensation configurations are shown in Fig. 6. In each scheme, we have used two erbium-doped fiber amplifiers (EDFAs) before and after fiber link to compensate and adjust the input power. For pre-compensation, DCF is placed before SMF. In the post-compensation, DCF is located after SMF. In the hybrid-compensation case optical fiber placement follows the sequence of DCF, SMF, and DCF. For three cases, the transmission span length is 80 km. The receiver sensitivity of the FSK signal in the pre-, post- and hybrid-compensation cases depending on SMF length and input power as shown in Fig. 8. The optimum span input power of each cases is around 10 dBm. The post-compensation shows the best tolerance to the residual dispersion, while the receiver sensitivity is below 1 dB. Especially, while the sensitivity power exceeds $-20$ dBm, the post-compensation can tolerate about 60 ps/nm residual dispersion more than the other ones. The optimized compensation ratio in three cases is found less than 100%, and the dispersion compensation ratio will degrade if the input power in each span is increased. Moreover, post-compensation scheme shows a considerable power level resilience. Very low receiver penalty and considerable resilience of input power up to 25 dB are demonstrated in the post-compensation scheme. Thus, the FSK signal by post-compensation has better transmission performance than the FSK signal by the pre-compensation or hybrid-compensation.

Fig. 9(a)–(c) shows that the dispersion tolerance value with the employment of the post-compensation scheme is the highest with the value of 95 ps/nm, compared with pre-compensation or hybrid-compensation scheme. The optimized dispersion...
compensation ratio in each dispersion compensation scheme is found to be less than 100%. Either full compensation or overcompensation will cause pulse broadening. Hence, the transmission performance of the FSK signal will be degraded, if the compensation configuration is full compensation and overcompensation. Typical examples with input power of 1, 5, 10, and 15 dBm are also investigated in Fig. 9. When the input power is between 5–10 dBm, the best performance of the system can be obtained. Furthermore, in different schemes the dispersion tolerance reaches the maximum at the input power of 10 dBm. When the value of input power is relatively small, the power penalty becomes higher. On the contrary, if the input power is relatively high, the effect of optical fiber nonlinearity will cause power loss. The lowest penalty of the FSK signal is obtained in the post-compensation scheme, which means that, when the input power is constant, the post-compensation scheme provides the largest eye-opening. Hence, in practice, we should transmit the FSK signal in a long distance optical transmission link with post-compensation.

E. Performance Analysis of RZ-FSK Under Different Dispersion Compensation

As shown in Fig. 1, the transmitter configuration of the generated RZ-FSK can be divided into three differently functional units, which include transmitter unit, fiber link unit and receiver unit. In our simulation, the signal bit rate is fixed at 40 Gb/s, and the tone spacing of RZ-FSK is defined to be 100 GHz. Each transmission span consists 80 km of SMF in different dispersion compensation scheme.

Fig. 10 shows how in three dispersion compensation schemes the fiber input powers affect the receiver sensitivity performance. The value of optimized fiber input power in three cases is from 5 to 15 dBm. All the dispersion compensation schemes show a low receiver penalty and considerable resilience of the fiber input power. Furthermore, the RZ-FSK signal with post-compensation scheme has the best better transmission performance.

The comparison of transmission performance between FSK and RZ-FSK formats is shown in the composite chart of Figs. 8 and 10. We can find that the transmission performance of the RZ-FSK format is preferable for the FSK format with NRZ shape under the three dispersion compensation schemes. Firstly, the receiver power penalty of the RZ-FSK format is lower than the FSK format. Secondly, the resilience of input power level is considerable for the RZ-FSK format. Finally, the RZ-FSK modulation format also has the good dispersion tolerance. The comparison between FSK and RZ-FSK formats is studied for attempting to find the optimum frequency modulation format for high bit rate optical transmission systems. Fig. 11 shows the measured receiver sensitivity (at a BER of $10^{-9}$) for RZ-DPSK...
Fig. 9. Sensitivity power as a function of residual dispersion at different input power for (a) post-compensation, (b) pre-compensation and (c) hybrid-compensation.

Fig. 10. Contour plot of receiver sensitivity for the RZ-FSK signal as a function of input power and fiber length for (a) post-compensation, (b) pre-compensation, and (c) hybrid-compensation.

and RZ-FSK signals after different compensation versus different input powers into SMF-28 with 80-km distance. It is clearly shown that the receiver sensitivity is higher for the RZ-DPSK than for the RZ-FSK. But, for two types of signals, RZ-DPSK and RZ-FSK, the pre-dispersion compensation has lower receiver sensitivity than post-dispersion compensation. Moreover, the hybrid compensation has the highest receiver sensitivity for RZ-DPSK or RZ-FSK signal transmission. Since post-compensation has higher receiver sensitivity than pre-compensation which is similar to the hybrid-compensation, and it is easily implemented in practice, we choose dispersion post-compensation scheme in our experimental for RZ-FSK signal transmission.

F. Performance Analysis of RZ-FSK Signal in a 4 × 40-Gb/s WDM Transmission System

Research on 40-Gb/s/ch wavelength-division multiplexing (WDM) transmission systems is a hot topic in the high speed optical transmission area. The main aims are to achieve high spectral efficiency and to overcome the limited transmission distance due to interaction between fiber nonlinearity and chromatic dispersion. Here, we will analyze the RZ-FSK signals with different FTS, concentrating on their advantages and disadvantages in terms of spectral efficiency, tolerance against fiber nonlinearity, and chromatic dispersion in the 4 × 40-Gb/s WDM transmission system. We evaluate the linear cross penalty with both signals formats in a 4-channel WDM configuration as a function of channel spacing. We use flat-top AWGs for wavelength multiplexing and demultiplexing. The optical bandwidth of the AWGs is set to 0.75 of the channel spacing. The PRBS pattern length is $2^{23} - 1$. The PRBS patterns in the neighboring optical channels are offset by 25% of the total pattern length for de-correlation. The WDM optical spectra diagrams of two RZ-FSK signals (one is the RZ-FSK signal with 100 GHz FTS, and the other is the RZ-FSK signal with 60-GHz FTS) with double FTS channel spacing, are shown at the top of Fig. 12(a) and (b). The crosstalk penalties obtained at the center channel (the second channel) as a function of channel spacing are shown at the bottom of Fig. 12(a) and (b). As the channel spacing is reduced, the linear crosstalk penalty gradually increased. For the same channel spacing, the eye-opening penalties (EOP) of the RZ-FSK signal with 100 GHz FTS has the lower EOP value than the RZ-FSK signal with 60 GHz FTS. Kerr nonlinearity and chromatic dispersion of the fiber are essential deteriorating issues of WDM systems, causing EOP. As we know, ITU G.692 proposal has three channel spacing values for WDM application, which include 50, 100, and 200 GHz. It is important to note that the spectral efficiency limit of the RZ-FSK format, if it is intended for WDM transmission, is the value of channel spacing must be greater than or equal to the value of FTS, otherwise, crosstalk between channels will be introduced. To avoid linear crosstalk penalty as much as possible, in our proposed configuration, the WDM source includes four distributed feedback (DFB) lasers that are combined
Fig. 11. Measured receiver sensitivities versus different input powers into SMF-28 for various dispersion compensation schemes for (a) RZ-DPSK and (b) RZ-FSK.

Fig. 12. Measured eye opening penalty versus channel spacing for RZ-FSK with (a) 100-GHz FTS and (b) 60-GHz FTS in 4 × 40-Gb/s WDM transmission system.

Fig. 13. Measured receiver sensitivities versus different input powers into SMF-28 for RZ-FSK with (a) 100-GHz FTS and (b) 60-GHz FTS in 4 × 40-Gb/s WDM transmission system.

with a frequency spacing of 200 GHz. The center frequencies of the generated RZ-FSK signals are 193, 193.2, 193.4, and 193.6 THz, respectively, in compliance with ITU-standardized proposal. In a 4 × 40-Gb/s WDM transmission system, two RZ-FSK signals with 100 GHz or 60 GHz FTS over 4 × 80 km spans of SMF followed by DCF are transmitted and received. The receiver sensitivity versus input power is show in Fig. 13(a) and (b). The RZ-FSK modulation with 100 GHz FTS is more durable for Kerr nonlinear distortion than 60-GHZ FTS. Integrating the above discussion, RZ-FSK format with 60-GHz FTS has compacter optical spectra than 100 GHz, but RZ-FSK with 100 GHz is more suitable to be adopted in WDM transmission system since it has better transmission performance.

IV. EXPERIMENTAL SETUP AND RESULTS

The experimental setup is shown in Fig. 14. The signal sources include one external cavity lasers (ECL) at 1557.64 nm and a tunable laser made by Agility Inc. at 1558.46 nm, i.e., with 100 GHz FSK tone spacing. In this experiment,
we launch RZ-FSK signal with 100 GHz FTS, because the previous simulation shows that it has better transmission performance than RZ-FSK signal with 60 GHz FTS. It is noted that two beams can be generated by a MZM driven by 50 GHz clock. The data at 40-Gb/s (PRBS $2^{23} - 1$, ITU-T G.709 FEC) is generated by SHF BPG44E BT pattern generator and added onto the MZM. The phase modulated signal is then demodulated by the subsequent MZDI with 25-ps delay, thus realizing a 40-Gb/s FSK signal. A following MZM is driven by 20 GHz clock and used to generate RZ-FSK signal. It should be noted that the output power of two lasers has to be fine tuned so that an approximately constant optical pulse can be achieved by the RZ-FSK transmitter. The transmission span consists of 100 km of SMF with a matching length of DCF for post-compensation. We choose post-compensation in the experimental scheme, because the above simulations prove that this compensation has good receiver performance and it is easily implemented in practice. The dispersion at 1550 nm of the SMF and DCF is 16.9 and $-100$ ps/nm/km, respectively. In each span, the SMF input power is 6 dBm, and the DCF input power is 0 dBm.

Optical wavelength conversion technology (OWC) on the development of large-capacity optical networks is significant, because it can reduce blocking probability, and is conducive to achieving interconnection between links and distributed network management. To realize wavelength conversion for a high-speed RZ-FSK signal, the interferometer devices based on cross-phase modulation (XPM) in the semiconductor optical amplifier (SOA) cannot be applied, and instead some transparent wavelength conversion scheme must be considered to preserve the frequency information. By using FWM in fibers, it is possible to implement a modulation transparent wavelength converter. Recent FWM wavelength conversion experiments also indicate that using highly nonlinear dispersion shifted fiber (HNDSF) can result in large spectral and dynamic ranges. Therefore, wavelength conversion using SOA or HNDSF can be chosen as an ideal solution to transparent wavelength conversion for a RZ-FSK signal.
Fig. 16. Measured BER curves for (a) SOA and (b) HNDSF.

Fig. 17. Measured eye diagrams (10 ps/div) for (a) original RZ-FSK, (b) converted by SOA, (c) converted by HNDSF, and (d) converted and transmitted.

The pump source is ECL working at 1554.8 nm. The RZ-FSK signal is amplified and combined with the pump after polarization alignment. FWM takes place in the 300 m long HNDSF with a nonlinear coefficient $\gamma = 10$ W$^{-1}$km$^{-1}$. The zero dispersion wavelength of the HNDSF is 1556 nm and the dispersion slope is 0.022 ps/nm$^2$/km. The SOA used in the experiment is 500 $\mu$m long with 200 mA driving current. An OBPF$_1$ with 1-nm bandwidth is used to filter out the converted signal.

Fig. 15 shows the optical spectra at the output of the HNDSF and the SOA. A conversion efficiency of the FWM process up to $\alpha$ dB could be achieved in SOA and $\beta$ dB in HNDSF. The BER performance of the RZ-FSK signal for back-to-back and wavelength conversion are measured as shown in Fig. 16. Because the FWM effect in fibers can be exploited to achieve all-optical reshaping, it can be predicted that the ER of the converted FSK signal will be enhanced due to this reshaping characteristics. This is verified in our experiment. 2R regeneration is observed in HNDSF.

Fig. 18 shows the measured optical spectra by experiment. The inset figure shows CW light signal, after DPSK modulation, FSK signal, demodulated FSK signal, RZ-FSK signal and demodulated RZ-FSK signal. We can find that an improved transmission characteristic for the RZ-FSK signal compared to the FSK signal can be achieved.

We also measured bit-error ratio (BER) performance of RZ-FSK transmission. The measured BER curves before and after the transmission link is shown in Fig. 19(a), where error-free transmissions for RZ-FSK and FSK can be obtained. The power penalty against the FSK at BER = $10^{-9}$ about 5.0 dB were observed. The transmission penalties for the tone1 and tone2 of the RZ-FSK are both less than 5 dB. Fig. 19(b)–(e) shows eye-diagrams of FSK and RZ-FSK for back-to-back, and after transmission through a 100 km SMF transmission link with matching DCF. Because FSK is orthogonal to intensity modulation and vector modulation (polarization shift keying), it can be employed in the context of the combined modulation format to decrease the data rate or enhance the symbol rate. It can also be utilized in the orthogonal labeling as the modulation format for the payload or the label.
Fig. 18. Measured optical spectra for (a) CW light signal, (b) After DPSK modulation, (c) FSK signal, (d) demodulated FSK signal, (e) RZ-FSK signal, (f) demodulated RZ-FSK signal.

Fig. 19. Measured BER curves for (a) back-to-back RZ-FSK and after 100-km SMF+DCF link, the eye diagram of demodulated FSK (10 ps/div) for (b) back-to-back (c) after 100-km SMF+DCF link, the eye diagram of demodulated RZ-FSK for (d) back-to-back and (e) after 100-km SMF+DCF link.

V. CONCLUSION

In this paper, we propose and demonstrate a new optical modulation transmitter, which transmit the RZ-FSK signal by using two CW lasers, one MZM, one MZDI and another MZM driven by a sinusoidal voltage at half of the bit rate. The demodulation can be simply achieved on 1 bit rate through one MZDI or an array waveguide grating (AWG) demultiplexer with balanced detection. Through numerical simulation, two frequency modulation schemes using MZM and PM, and impact of different frequency tone spacing (FTS) of the generated FSK signal are discussed. The important advantage of the proposed frequency modulation scheme over existing ones is that the FTS of the generated signal can be tunable by changing the center frequencies of two used lasers. Especially for high speed transmission, it is useful while we adjust the value of FTS to achieve higher receive sensitivity. Moreover, this proposed scheme is simple and potentially inexpensive. We also experimentally demonstrate and compare transparent wavelength conversion based on four-wave mixing (FWM) in an SOA and in a highly nonlinear dispersion shifted fiber (HNDSF) for a 40-Gb/s RZ-FSK signal. We experimentally investigate 40-Gb/s RZ-FSK signal transmission over 100 km SMF link with matching DCF. Our experimental results suggest that RZ-FSK modulation scheme could be a promising candidate for future high-speed transmission system and optical label switching networks.
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