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RESEARCH ARTICLE

Simulation for all-optical format conversion from NRZ-DPSK to RZ-DPSK

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Abstract We propose and simulate a simple scheme of all-optical format conversion from non-return-to-zero differential phase-shift keying (NRZ-DPSK) to return-to-zero differential phase-shift keying (RZ-DPSK) by using phase modulators and detuning filters. The operation principle is theoretically analyzed and simulated by exploiting spectra, temporal waveform and eye diagram with commerical optical design software VPI Transmission Maker 8.5. The use of electrical clock recovery and linear phase modulation in the conversion scheme may be potiental in practise use.

Keywords format conversion, differential phase-shift keying (DPSK), all-optical processing

1 Introduction

In prospective optical networks, different modulation formats may be selectively employed depending on network size and system settings [1]. Thus, optical format conversion is an essential technology, to which has been paid much attention in recent years. However, most previous works have focused on on-off keying (OOK) formats, such as conversions from non-return-to-zero OOK (NRZ-OOK) to return-to-zero OOK (RZ-OOK) formats [2–4]. Recent studies have presented that differential phase-shift keying (DPSK) format particularly exhibits better performance than that of OOK for long-haul transmission [5]. But only a few studies have focused on such NRZ to RZ format conversion in DPSK based on cascaded second-order nonlinearities in a periodically poled lithium niobate (PPLN) waveguide [6].

Compared with conventional OOK formats, phase modulated formats are suitable for long-haul transmission. More specifically, return-to-zero differential phase-shift keying (RZ-DPSK) formats have narrower pulse and thus have a potential for multiplexing in time domain, i.e., phase-shift keying (PSK) optical time divided multiplexed (OTDM) system. In this paper, we propose a format conversion scheme from non-return-to-zero differential phase-shift keying (NRZ-DPSK) to RZ-DPSK by using phase modulators and detuning filters. Generally, in conversional NRZ-RZ conversion for OOK formats, format conversion usually requires detuning filter [7], but the application of detuning filter in DPSK system may cause demodulation of the signal [8]. But there is no report that detuning filters used in demodulated alternate mark inversion (AMI) and duobinary (DB) of the DPSK signal. By the analysis of the instinct relationships among AMI, DB and DPSK signals, numerical and simulation results of the format conversion with the help of the VPI Transmission Maker 8.5 have been showed in this paper, and the paper is organized as below: In Sect. 2, the principle of the format conversion from NRZ-DPSK to RZ-DPSK is demonstrated by exploiting the instinct relations among AMI, DB and DPSK signals. In Sect. 3, the numerical model is provided and the simulation result is shown with the help of VPI. The scheme described in this study does not require high-order nonlinearity such as four waves mixing (FWM) or cascaded second-harmonic generation (cSHG), so the high efficiency conversion may be potentially available in next generation optical network. And the scheme may be potential in practical use by mature electrical clock recovery avoiding optical-electrical-optical (O-E-O) operation.

2 Principle of conversion from NRZ-DPSK to RZ-DPSK

The instinct relations of AMI, DB and DPSK are shown in

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Fig. 1. DPSK signal can be demodulated to AMI and DB signals by using demodulator such as 1 bit delay interferometer [9]. And such AMI and DB signals can also build up original DPSK signal by another 1 bit delay interferometer, as long as phase information of the AMI and DB signals remain as same as the original DPSK signal [10]. If the phase information of the AMI and DB signals has been changed by wavelength conversion scheme in semiconductor optical amplifier (SOA), the binary phase-shift keying (BPSK) signal will be built instead of DPSK signal [11]. The principle of the conversion from NRZ-DPSK to RZ-DPSK is indicated in Fig. 2. Normally, NRZ-DPSK signal, which is modulated by Mach-Zehnder modulator (MZM), has intensity dips due to limited bandwidth and the voltage of drive signal. These intensity dips may be cut out in two different ways: one is by RZ pulse carving in the transmitter, the other is by high-order nonlinearity such as FWM and cSHG in the middle of the transmission spans. But our scheme is to do the RZ pulse carving "operation" in the demodulated products of the NRZ-DPSK signal. The demodulated products of NRZ-DPSK signal are NRZ-DB signal and RZ-AMI signal. If the "operation" may preserve the phase information of the original signals, the converted RZ-DB and RZ-AMI signals may build up a converted RZ-DPSK signal.

The proposed setup of the format conversion from NRZ-DPSK to RZ-DPSK is shown in Fig. 3. The 20 Gbit/s NRZ-DPSK signals at 193.1 THz are modulated at the MZM based transmitter. 10% of the NRZ-DPSK signals are used as electrical clock recovery (CR) by a 10:90 tap. Remaining 90% are demodulated by a 1 bit delay interferometer. The demodulated products are transmitted to two arms of Mach-Zehnder interferometer (MZI), and there is a phase modulator and a detuning filter in each arm. Both the same phase modulators (PMs) are driven by an electrical clock which is recovered from the CR. The filters are first-order Gauss shape with a bandwidth of 30 GHz, the center frequency of the filters is 193.180 THz, which is 80 GHz detuned from the frequency of the signals. After the MZI, a 1 bit delay interferometer is used to build up a new RZ-DPSK signal.

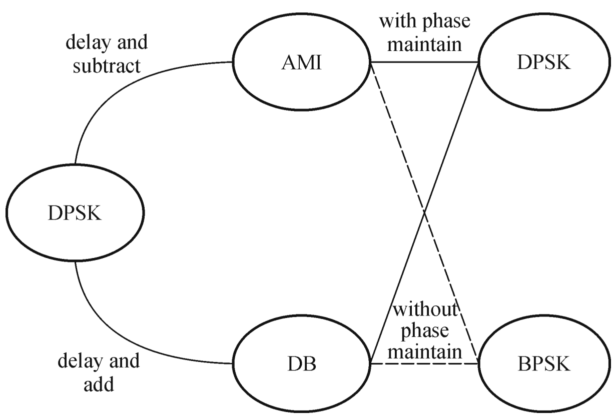

Fig. 1 Relations among DPSK, AMI, DB and BPSK formats

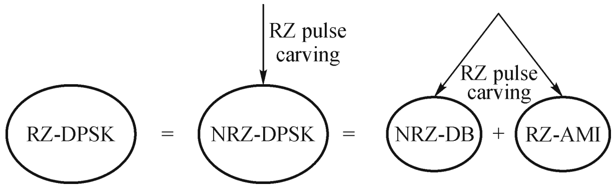

Fig. 2 Principle of format conversion from NRZ-DPSK to RZ-DPSK

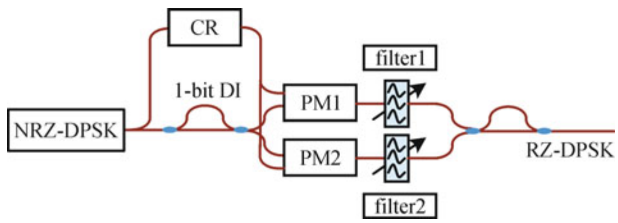

Fig. 3 Proposed setup of format conversion from NRZ-DPSK to RZ-DPSK

3 Theoretical model and simulation result

The NRZ-DPSK signal field E_s can be expressed as

$$E_s = A_s \exp\left(\mathrm{i}(\omega_0 t - \phi_s)\right), \tag{1}$$

where A_s is the complex amplitude of the signal, ω_0 is the center frequency, and ϕ_s is the phase information of the signal. After 1 bit delay interferometer (DI), the demodulated products can be expressed as [12]

$$E_{DB} = A_s \exp(\mathrm{i}\omega_0 t)\exp\left(\mathrm{i}\frac{\phi_{s1}+\phi_{s2}}{2}\right) \times \cos\frac{\phi_{s1}-\phi_{s2}}{2}, \tag{2}$$

$$E_{AMI} = A_s \exp(\mathrm{i}\omega_0 t)\exp\left(\mathrm{i}\frac{\phi_{s1}+\phi_{s2}}{2}\right) \times \sin\frac{\phi_{s1}-\phi_{s2}}{2}. \tag{3}$$

E_{DB}, E_{AMI} are the electrical fields of DB and AMI signals, respectively, $\phi_{s1}(t)$, $\phi_{s2}(t)$ are the phases of the adjacent bit sequence in the two arms of the DI. The AMI and DB signals may build up original DPSK signals, because the phase information term $\pm\exp\left(\mathrm{i}\frac{\phi_{s1}(t)+\phi_{s2}(t)}{2}\right)$ is maintained during the interference. On the other hand, by wavelength conversion scheme, only PSK signal will be built up, because only the amplitude term can be maintained, and the phase information can not.

After phase modulators, the DB and AMI signals may have a phase shift, which is related to the recovered clock of the NRZ-DPSK signal. The phase modulated DB and AMI signals E'_{DB}, E'_{AMI} can be expressed as

$$E'_{DB} = A_s \exp\left(i\frac{\phi_{s1}+\phi_{s2}}{2}\right) \times \cos\frac{\phi_{s1}-\phi_{s2}}{2} \times \exp\left(i\theta(t)\right), \quad (4)$$

$$E'_{AMI} = A_s \exp\left(i\frac{\phi_{s1}+\phi_{s2}}{2}\right) \times \sin\frac{\phi_{s1}-\phi_{s2}}{2} \times \exp\left(i\theta(t)\right), \quad (5)$$

where $\theta(t)$ is the phase shift related to the recovery clock of the NRZ-DPSK signal.

The frequency response $H(\omega)$ of the Gauss shaped filter can be expressed as

$$H(\omega) = \exp\left[-\frac{1}{2}\left(\frac{\omega-\omega_f}{B_0}\right)^2\right], \quad (6)$$

where ω_f is the center frequency and B_0 is 3-dB bandwidth of the filter, and the related time domain response can be expressed as

$$h(t) = \frac{B_0}{\sqrt{2\pi}}\exp\left[-\frac{1}{2}(B_0 t)^2\right]\exp(i\omega_f t). \quad (7)$$

The output signal fields E_{DBout} and E_{AMIout} after the filter are the convolutions of the input signal field and the time domain response of the filter, which can be expressed as

$$E_{DBout} = E'_{DB} \times h(t) = \int E'_{DB}(\tau)h(t-\tau)d\tau, \quad (8)$$

$$E_{AMIout} = E'_{AMI} \times h(t) = \int E'_{AMI}(\tau)h(t-\tau)d\tau. \quad (9)$$

By first-order Taylor expansion, Eqs. (8) and (9) can be further expressed as [13]

$$E_{DBout} = E'_{DB}\exp\left[-\frac{1}{2}\left(\frac{\omega_f-\omega_0+\frac{d\theta(t)}{dt}}{B_0}\right)^2\right], \quad (10)$$

$$E_{AMIout} = E'_{AMI}\exp\left[-\frac{1}{2}\left(\frac{\omega_f-\omega_0+\frac{d\theta(t)}{dt}}{B_0}\right)^2\right]. \quad (11)$$

From Eqs. (10) and (11), it can be seen that, first, the phase information is maintained, so E_{DBout} and E_{AMIout} may build up the original DPSK signal. Second, new DB and AMI signals have a new amplitude term which comes from the phase modulators and filters. The phase modulators give the DB and AMI signals an RZ shaped clock related phase shift, and detuning filters acts as a phase shift to amplitude conversion. Because the phase shift is related to the clock, so the converted amplitude is also clock related, and this results in an NRZ-DPSK to RZ-DPSK format conversion.

It should be noticed that, using detuning filter in DPSK signal may cause demodulation while in DB and AMI signals may not. The reasons can be found in Eqs. (1)–(3). Equation (1) is the field of the DPSK signal, once there is phase change in the DPSK signal, the detuning filter will convert this phase shift to amplitude output. But in DB and AMI signals, once there is a phase change, unlike the constant amplitude of DPSK, the amplitude of the DB and AMI signals will also change due to the cosine and sine terms in Eqs. (2) and (3). Once there is a phase shift in the AMI and DB signals, the detuning filter still convert this phase shift to amplitude output, but in the mean time, the cosine or sine term is zero, the total output amplitude is zero. So using detuning filter will not cause the demodulation of the DB and AMI signals.

Numerical analysis is used to explain the theory of the scheme, so we neglect high-order term in the Taylor expansion. Next, more exactly simulation results have been shown by using commercial optical design software VPI Transmission Maker 8.5. In the simulation, no such approximation mentioned above is used.

In the following simulation, the input signal is considered as 20 Gbit/s $2^{31}-1$ pseudo-random binary sequence (PRBS) NRZ-DPSK signal, the recovered clock has sine pulse type, the phase modulators are just get a 180° phase change when driven by the clock signal, sample rate is set to 640 GHz to achieve high accuracy. The power, center frequency, and the time widows of the signal are set to 1 dBm, 193.1 THz and 6.4 s, respectively.

The simulation results shown in Fig. 4(a1) are the spectra of the original NRZ-DPSK signal, and Fig. 4(a2) is the spectra of the converted RZ-DPSK signal. The main band of the converted RZ-DPSK signals is smooth and broader than NRZ-DPSK signal. And the conversion efficiency is about -10 dB, which is more effective than 20 dB efficiency in FWM. Figures 4(b1) and 4(b2) are the temporal waveforms of the NRZ-DPSK signal and the demodulated products of the NRZ-DPSK signal, respectively, Figs. 4(b3) and 4(b4) are the waveforms of the electrical clock and the converted RZ-DPSK signal, respectively, Fig. 4(b5) is the waveform of the demodulated products of the RZ-DPSK signal. It can be seen from Figs. 4(b1) to 4(b5) that the format conversion from NRZ-DPSK to RZ-DPSK is obtained and the demodulated products of NRZ-DPSK and RZ-DPSK are identical. The bit pattern in Fig. 4(b2) is "10111101100111010101" and

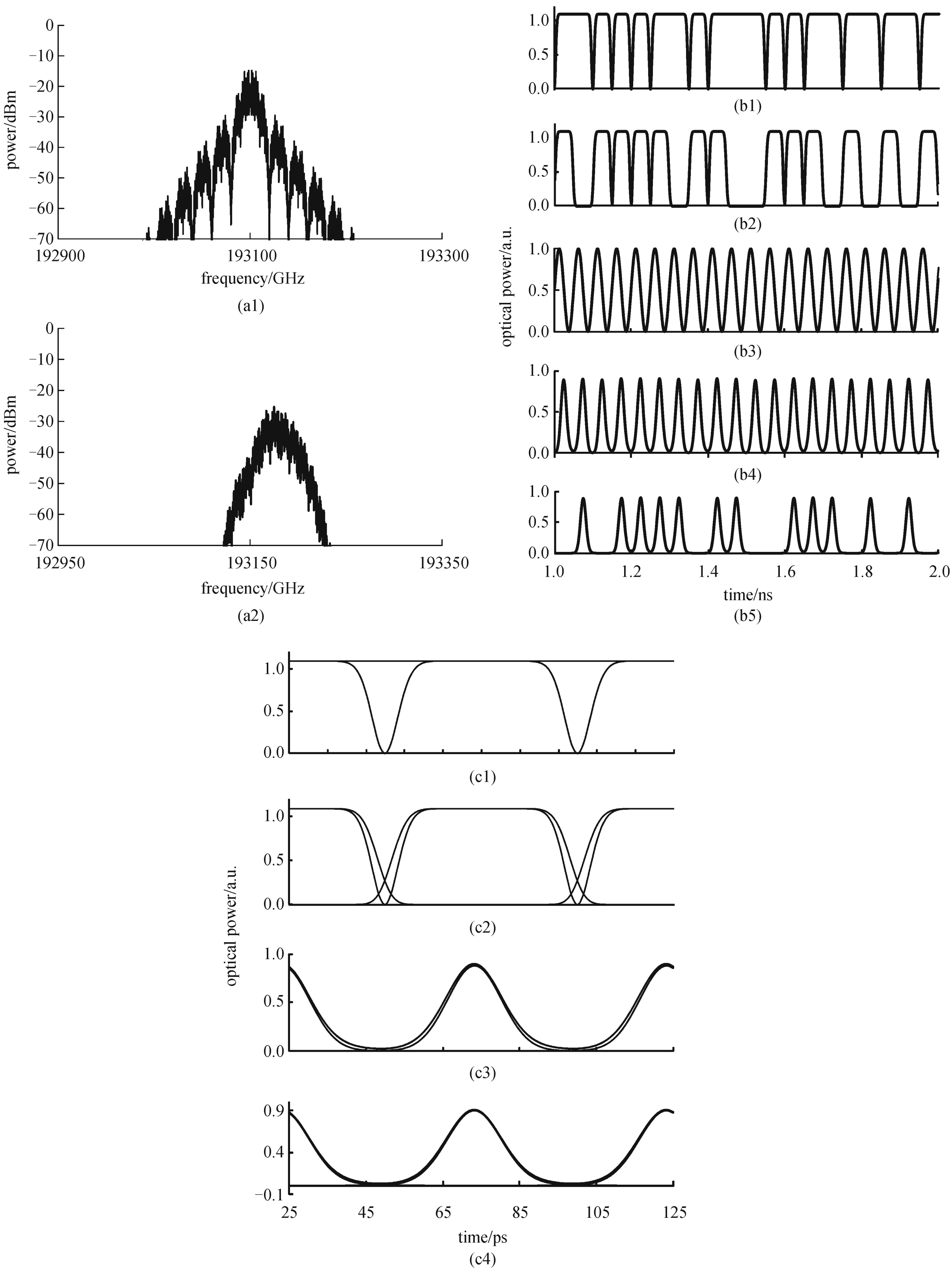

Fig. 4 Experimental results of 20 Gbit/s NRZ-DPSK to RZ-DPSK. (a1) and (a2) Optical spectra of NRZ-DPSK and converted RZ-DPSK signal; (b1)–(b5) temporal waveforms of NRZ-DPSK, demodulated NRZ-DPSK, clock signal, RZ-DPSK, demodulated RZ-DPSK, respectively; (c1)–(c4) eye diagrams of NRZ-DPSK, demodulated NRZ-DPSK, RZ-DPSK and demodulated RZ-DPSK, respectively

so is the bit pattern in Fig. 4(b5), Fig. 4(b2) is the NRZ form and Fig. 4(b5) is the RZ form. So the phase information is preserved. It should be noticed that the converted RZ-DPSK signal in Fig. 4(b5) is 1 bit duration later than the NRZ-DPSK signal in Fig. 4(b2). It is because every time a “delay and add” or “delay and subtract” operation happen, the first and the last of the bit sequence are lost, the first bit and the last bit do not have a “delay bit” to add or subtract. But it will not affect transmission. Figures 4(c1)–4(c4) are the eye diagrams of NRZ-DPSK signal, demodulated NRZ-DPSK signal, RZ-DPSK, and demodulated RZ-DPSK signal, respectively. According to our simulation, a clearly eye open can be expected in the format conversion from NRZ-DPSK to RZ-DPSK signal.

In the conversion, high-order nonlinearity such as FWM is avoided. Although the detuning filter may induce some power loss, which is also an issue in FWM scheme. Our scheme does not suffer from the limited condition which is very common in high-order nonlinearity scheme.

In our scheme, the electrical clock is used because the electrical clock recovery is more mature and preferable in real practice, and there is no optical-electrical-optical (O-E-O) conversion in our scheme, the signal’s transmission paths are all-optical paths. So the scheme is considered as all-optical format conversion. On the other hand, if an optical clock is preferred, nonlinearity device such as semiconductor optical amplifier (SOA) can be used to replace the phase modulator, but the amplified spontaneous emission (ASE) and self phase modulation (SPM) in the SOA may degenerate the conversion performance.

4 Conclusion

In conclusion, a new kind of all-optical format conversion from NRZ-DPSK to RZ-DPSK signal is proposed and simulated by using phase modulators and detuning filters. The optical spectra, temporal waveforms and eye diagrams are studied in detail to confirm the successful realization of NRZ-DPSK to RZ-DPSK format conversion. The use of mature electrical clock recovery avoiding O-E-O operation may be potential in practical use.

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