All-optical modulation format conversion from frequency-shift-keying to phase-shift-keying

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Abstract: We have realized a novel optical modulation format conversion using double-sideband suppressed-carrier modulation. An optical wideband frequency-shift-keying (FSK) signal, generated by an external FSK modulator, can be directly converted into an optical phase-shift-keying (PSK) signal, where the FSK signal having two spectral components was fed to an optical intensity modulator followed by an optical bandpass filter. Optical frequency of the FSK signal was mapped into optical phase of the bandpass filter output whose phase deviation depends on a chirp of the FSK signal. We demonstrated modulation format conversion from FSK to PSK at 10 Gbps, by using a high-speed optical FSK modulator and a dual electrode Mach-Zehnder intensity modulator.

OCIS codes: (060.4080) Modulation; (060.2630) Frequency modulation; (070.6020) Signal processing;

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1. Introduction

Advanced optical modulation formats, such as phase-shift-keying (PSK) and frequency-shift-keying (FSK), are very attractive for high-density optical transmission and all-optical label

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processing [1, 2, 3, 4]. Recent studies have shown that in long-haul transmission systems differential phase-shift-keying (DPSK) turns out to be superior compared to on-off-keying (OOK) [1]. High-speed optical FSK transmission systems using direct or external modulation were also reported [5, 6]. We recently proposed an external optical FSK modulator consisting of two Mach-Zehnder (MZ) optical modulators, which provides high-speed and stable FSK modulation, while FSK bit rate of the direct modulation is limited by the response of the laser. The FSK modulator is based on optical single sideband modulation technique, where the output has only one of the sideband components: lower sideband (LSB) or upper sideband (USB)[3]. In optical packet systems, a simultaneous modulation scheme of wideband FSK and OOK (FSK/OOK, henceforth) is a promising technique for label switching [2, 3]. DPSK/OOK simultaneous modulation was also investigated to obtain high throughput optical packet nodes [4]. The frequency deviation in wideband FSK is larger than that of data bit rate, so that there are two separate spectral components in the FSK signal. Thus, we can easily demodulate the FSK signal by using an optical filter which can discriminate the two spectral components. However, this method has a drawback that it requires double the spectral bandwidth of the data. The spectral efficiency of the DPSK/OOK format can be better than FSK/OOK, but we need an optical interferometer for DPSK demodulation. Several types of modulation formats would be used in advanced optical networks to optimize the performance. Thus, the functionality of optical modulation format conversion will be a key technology in next-generation photonic routers or gateways. In this paper, we propose a novel technique for optical modulation format conversion from FSK to PSK, where a wideband optical FSK signal can be converted into an optical PSK format signal, by using an optical MZ modulator and a bandpass filter. First we describe the operation of the optical FSK modulator, and we detail the principle of the modulation format conversion from FSK to PSK. We also present an experimental result of conversion from FSK to PSK at 10 Gbps.

2. Optical FSK modulator

The FSK modulator consists of two MZ structures ($\mathrm{MZ_A}$ and $\mathrm{MZ_B}$) as shown in Fig. 1 [3]. A pair of rf-signals, which are of the same frequency f_m and have a 90° phase difference, are applied to the electrodes $\mathrm{RF_A}$ and $\mathrm{RF_B}$. The optical signals at the points P and Q can be respectively expressed by

$$P = \frac{\mathrm{e}^{\mathrm{j}\omega_0 t}}{2\sqrt{2}}\left[\mathrm{e}^{\mathrm{j}A_m\cos\omega_m t} + \mathrm{e}^{-\mathrm{j}A_m\cos\omega_m t}\mathrm{e}^{\mathrm{j}\phi_\mathrm{A}}\right] \tag{1}$$

$$Q = \frac{\mathrm{e}^{\mathrm{j}\omega_0 t}}{2\sqrt{2}}\left[\mathrm{e}^{\mathrm{j}A_m\sin\omega_m t} + \mathrm{e}^{-\mathrm{j}A_m\sin\omega_m t}\mathrm{e}^{\mathrm{j}\phi_\mathrm{B}}\right], \tag{2}$$

where the input lightwave is assumed to be $\mathrm{e}^{\mathrm{j}\omega_0 t}$. Induced optical phase retardation in an arm of $\mathrm{MZ_A}$ is described by $A_m\cos\omega_m t \quad (\omega_m = 2\pi f_m)$, and that of $\mathrm{MZ_B}$ is $A_m\sin\omega_m t$, due to the 90° difference in rf-signals. Induced phase in each arm assumed to have the same amplitude of A_m, so that $\mathrm{MZ_A}$ and $\mathrm{MZ_B}$ would comprise a pair of zero chirp intensity modulators. The optical phase differences (ϕ_A and ϕ_B) in the two MZ structures, which can be controlled by dc-bias voltages applied on the electrodes $\mathrm{RF_A}$ and $\mathrm{RF_B}$, are set to be π, to suppress the input component $\mathrm{e}^{\mathrm{j}\omega_0 t}$, so that $\mathrm{e}^{\mathrm{j}\phi_\mathrm{A}}$ and $\mathrm{e}^{\mathrm{j}\phi_\mathrm{B}}$ are equal to -1. The output lightwave signal of the FSK modulator can be described by

$$R = \mathrm{e}^{\mathrm{j}[\omega_0 t+\pi/4+\alpha F(t)]}J_1(A_m)\left[\cos F(t)\mathrm{e}^{\mathrm{j}\omega_m t} + \mathrm{j}\sin F(t)\mathrm{e}^{-\mathrm{j}\omega_m t}\right], \tag{3}$$

$$F(t) \equiv \frac{A_1+A_2}{2}\left[f(t)+\pi/4\right], \tag{4}$$

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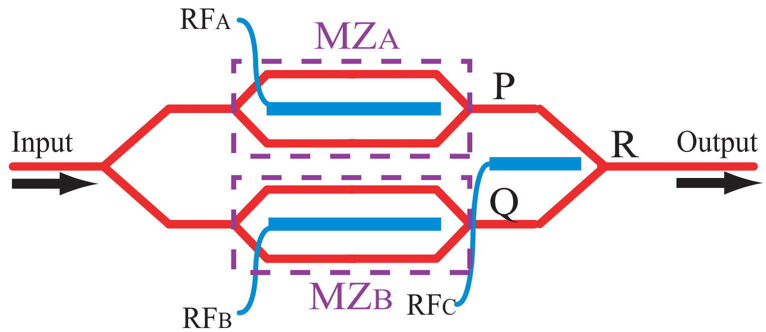

Fig. 1. Optical FSK modulator.

$$\alpha \equiv \frac{A_1 - A_2}{A_1 + A_2}, \tag{5}$$

where high order harmonic components are neglected. J_n expresses the first kind n-th order Bessel's function. The phase retardation on the path from P to R in Fig. 1 is $A_1 f(t)$, which can controlled by the voltage applied to $\mathrm{RF_C}$, while that of the path from Q to R is $-A_2 f(t)$. We note that α (FSK chirp parameter, henceforth) is an index of amplitude difference between the phase retardations of the two paths. When the two MZ structures are in the "on" state where $\mathrm{e}^{\mathrm{j}\phi_\mathrm{A}}$ and $\mathrm{e}^{\mathrm{j}\phi_\mathrm{B}}$ are equal to $+1$, and the amplitude of the rf-signals A_m is zero, the FSK modulator can be used as a conventional intensity modulator by feeding a baseband digital signal to $\mathrm{RF_C}$, where α describes the chirp parameter of this intensity modulator. When the electrode $\mathrm{RF_C}$ is in balanced push-pull operation, α is equal to zero. In this case, $F(t)$ denotes the induced optical phase difference between the two paths.

As shown in Eq. (3), when $F(t) = 0 \quad (0°)$, the amplitude of LSB becomes zero and the modulator generates USB. We call it "1" state in this paper. In "0" state where $F(t) = +\pi/2 \quad (+90°)$, the modulator generates LSB. Thus, we can select one of the sidebands (USB or LSB) by controlling the voltage on $\mathrm{RF_C}$. The optical phase of "0" state is $(\alpha+1)\pi/2$, while that of "1" state is zero. The switching speed depends on the bandwidth of $\mathrm{RF_C}$. Our fabricated FSK modulator has a traveling-wave electrode whose bandwidth is 18 GHz, so that we can generate high-speed optical FSK signal [3].

3. Modulation format conversion from FSK to PSK

Figure 2 shows the principle of modulation format conversion from FSK to PSK using double-sideband suppressed-carrier (DSB-SC) modulation technique. The FSK signal has a pair of optical carriers whose frequencies $f_0 - f_m$ and $f_0 + f_m$, where f_0 is the optical carrier frequency at the output port of the light source. When the FSK switching signal fed to $\mathrm{RF_C}$ is in "1" state the output carrier frequency is $f_0 + f_m$. That of "0" state is $f_0 - f_m$. The FSK signal is fed to an intensity modulator which is in null-bias point to obtain DSB-SC modulation. The modulating signal is a sinusoidal wave whose frequency is f_m. The output has three optical spectral components whose carriers are $f_0 - 2f_m$, f_0 and $f_0 + 2f_m$. When the FSK switching signal is in "1" state, the output of the intensity modulator has two carriers of f_0 and $f_0 + 2f_m$. On the other hand, the output of "0" has two carriers of f_0 and $f_0 - 2f_m$. The output always has the f_0 component regardless of the FSK switching signal. The DSB-SC modulation can be

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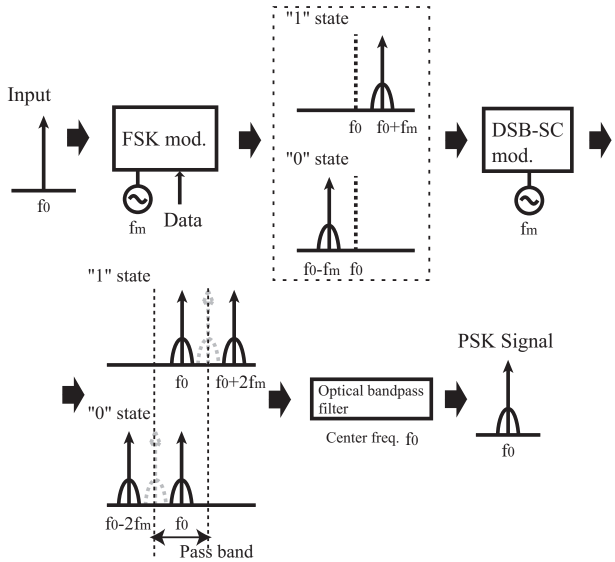

Fig. 2. Principle of modulation format conversion from FSK to PSK.

expressed by a simple mathematical model of

$$\mathrm{j}\sin[A'_m \sin(\omega_m t + \phi_m)], \tag{6}$$

where the phase retardation on each arm of the modulator is $A'_m \sin(\omega_m t + \phi_m)$. We used a dual-electrode Mach-Zehnder intensity modulator, to obtain zero-chirp modulation. By multiplying Eqs. (3) and (6), the output of the intensity modulator S can expressed as follows,

$$\begin{aligned} S &= -K\mathrm{e}^{\mathrm{j}\alpha F(t)}\left[\cos F(t)\mathrm{e}^{\mathrm{j}\omega_m t} + \mathrm{j}\sin F(t)\mathrm{e}^{-\mathrm{j}\omega_m t}\right] \\ &\times\left\{\mathrm{e}^{\mathrm{j}(\omega_m t+\phi_m)} - \mathrm{e}^{-\mathrm{j}(\omega_m t+\phi_m)}\right\}, \quad (7) \\ K &\equiv -\mathrm{e}^{\mathrm{j}(\omega_0 t+\pi/4)}J_1(A_m)J_1(A'_m) \quad (8) \end{aligned}$$

where high-order harmonic components are neglected. $f_0 + 2f_m$ and $f_0 - 2f_m$ components are eliminated by using an optical bandpass filter. The f_0 component T can be expressed by

$$T = K\Big[\cos[F(t)-\phi_m] - \mathrm{j}\sin[F(t)+\phi_m]\Big]\mathrm{e}^{\mathrm{j}\alpha F(t)}, \tag{9}$$

$$|T| = K\sqrt{1+\sin 2F(t)\sin 2\phi_m}. \tag{10}$$

When $\phi_m = n\pi/2 \quad (n = 0,1,2,3)$, the f_0 component can be expressed by

$$T = K\mathrm{e}^{-\mathrm{j}[(-1)^n-\alpha]F(t)}\mathrm{e}^{-\mathrm{j}n\pi/2}, \tag{11}$$

and $|T|$ would be constant. The optical phase of T is a linear function of $F(t)$, so that T is an optical PSK signal which can be demodulated by an one-bit delay MZ interferometer. On the other hand, when $F(t) = n\pi/2 \quad (n = 0,1,2,3)$, the amplitude $|T|$ does not depends on ϕ_m, and the optical phases of “1” state $(F(t) = 0)$ and “0” state $(F(t) = \pi/2)$ are, respectively, $-\phi_m$

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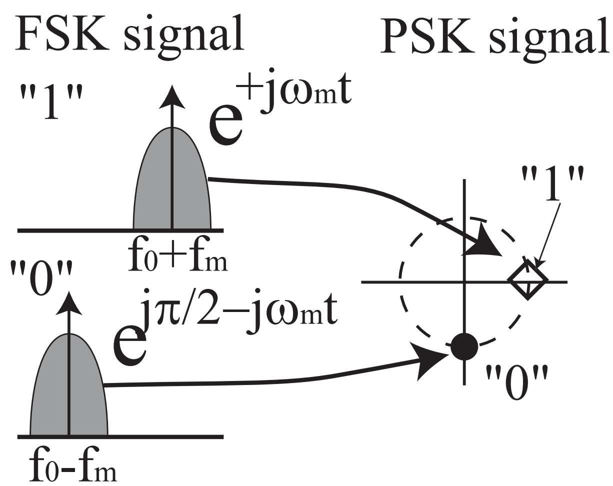

Fig. 3. Conversion from FSK to PSK ($\alpha = 0$).

and $\phi_m - (1-\alpha)\pi/2$. Thus, the optical signal T is also a PSK signal whose phase deviation is $(1-\alpha)\pi/2 - 2\phi_m$. However, the amplitude depends on $F(t)$ and would be changed during transient time of FSK where $F(t) \neq n\pi/2$.

To show the operation of modulation format conversion, we consider the case of $\phi_m = 0$, as shown in Fig. 3. The phase and frequency of "1" state are 0 and $f_0 + f_m$, respectively. On the other hand, the phase and frequency are $\pi/2$ and $f_0 - f_m$, respectively, in the case of "0" state. By using the DSB-SC modulation described by Eq. (6) and the bandpass filter, the FSK signal can be converted into a PSK signal whose frequency is f_0, where the FSK chirp parameter is assumed to be 0. The phase deviation of the PSK signal is $\pi/2$, where the phase is 0 for "1" state and $-\pi/2$ for "0" state. For arbitrary FSK chirp α, the deviation can described by $(1-\alpha)\pi/2$. Thus, when $\alpha = -1$, the deviation becomes π, which corresponds to an optimum condition for binary PSK. In the case of $\phi_m = \pi$, the chirp parameter α also should be equal to -1 for the optimum condition, while $\alpha = +1$ gives a PSK signal with the deviation of π, for $\phi_m = \pi/2$ and $3\pi/2$.

4. Experimental results

Figure 4 shows the experimental setup. An optical FSK signal was generated by an external FSK modulator. A pair of 12.5 GHz rf-signals were fed to the electrodes RF_A and RF_B via a 90 degrees hybrid coupler. A 10 Gbps non-return-to-zero (NRZ) signal of $2^{23}-1$ pseudo-random-bit-sequence (PRBS) was applied to RF_C, where the FSK chirp parameter was zero. The output of the FSK modulator had two peaks corresponding to USB and LSB, where the carrier suppression ratio was 17.4 dB. The FSK signal was fed to a dual-electrode intensity modulator, where modulating frequency was also 12.5 GHz. For simplicity, we used the same signal source both for FSK modulation and format conversion. In an actual system, we need a clock recovery setup to generate a phase-locked modulation signal of f_m at a remote location. We can extract the modulation signal of f_m applied on RF_A and RF_B from a tapped FSK signal or an optical beat signal between USB and LSB. The output had three spectral components of f_0, $f_0 + 2f_m$ and $f_0 - 2f_m$, where the power ratio between f_0 and $f_0 + 2f_m$ components (or $f_0 - 2f_m$) was

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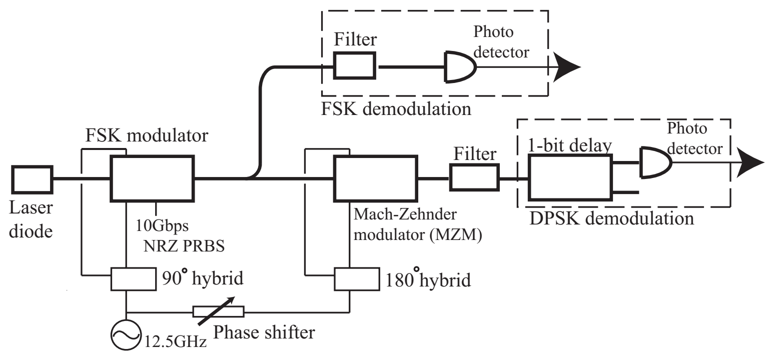

Fig. 4. Experimental setup.

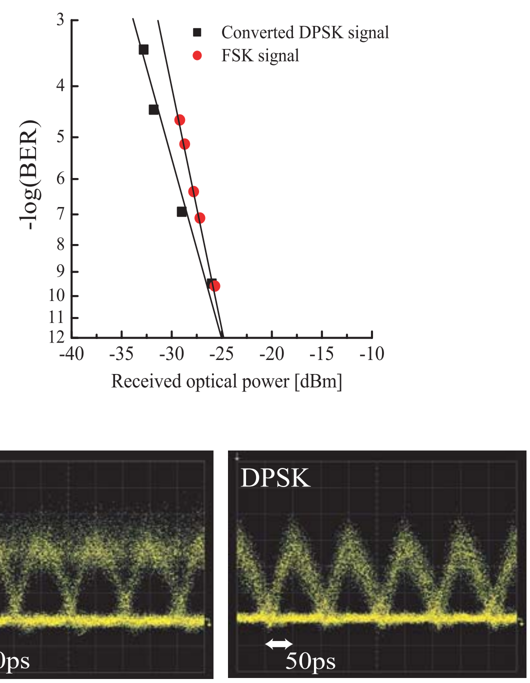

Fig. 5. BER curves and eye diagrams.

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3.0 dB. An optical PSK signal was extracted from the output of the intensity modulator by using an optical bandpass filter (25-50 GHz interleaver). We confirmed error-free conversion from FSK to PSK, where the PSK signal was demodulated by DPSK demodulation scheme with an optical one-bit delay. For comparison, we also demonstrated FSK demodulation by using an optical bandpass filter. Figure 5 shows bit-error-ratio (BER) curves and eye-diagrams. Clear eye-openings were obtained both for FSK and DPSK. Power penalty of the conversion technique was 0.8dB at BER $= 10^{-9}$.

5. Conclusion

In conclusion, we proposed a novel modulation format conversion technique without FSK signal detection, by using DSB-SC modulation. 10 Gbps optical FSK signal, generated by an integrated external modulator, was converted into an optical PSK signal. The setup is very simple and inline, so that our technique can be easily applied to FSK/OOK signals. In addition, by using an optical filter having plural passbands, FSK/OOK signals bundled in wavelength-domain can be also converted to bundled DPSK/OOK signals, because the DSB-SC modulation acts on all spectral components simultaneously.

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