Wavelength domain switching using electro-optic single-sideband modulation

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Abstract

We investigated an optical wavelength shifter using electro-optic modulators. A single-sideband modulator consisting of a pair of Mach-Zehnder modulators can generate wavelength-shifted output lightwaves. We can agilely control the output wavelength by changing the rf-signal frequency or dc-bias voltages fed to the modulator. A WDM system with the wavelength shifter was numerically analyzed by using a lightwave network simulator, to discuss the distortion and cross-talk due to the nonlinearity of the modulator.

1 Introduction

In wavelength-domain-multiplexing (WDM) optical networks, wavelength conversion is a key technology for cross-connection at switching nodes [1]. Nonlinear effect between lightwaves whose wavelengths are different, such as four-wave-mixing in optical fibers, cross phase modulation in semiconductor optical amplifier, and so on, are often used to obtain wavelength conversion, by which bit-stream data on a WDM channel can be copied to the other channel [2]. Pumping light sources are used in these techniques, so that the switching time from one WDM channel to the other channel is dominated by that of the pumping light source. The wavelength from the light source can be tuned by changing temperature or current density of the light source. But, it is difficult to switch the wavelength in a few nano seconds without losing stability of the source. Recently, we reported wavelength conversion by using an optical single-sideband (SSB) modulator consisting of four optical phase modulators [3, 4, 5]. It requires no optical pumping, so that its switching time is not limited by that of the light source. The wavelength of the output lightwave depends on rf-signal frequency and dc-bias voltage fed to the modulator, which can be electronically controlled. In this paper, we investigated a WDM system with the wavelength shifter by using a lightwave network simulator, to discuss the distortion and cross-talk due to the nonlinearity of the modulator. The conversion efficiency of the shifter can be increased by feeding large amplitude rf-signals, however the cross-talk due to the third order undesired optical harmonics causes the deformations of the optical signals.

2 Optical SSB modulator

The SSB modulator consists of parallel four optical phase modulators as shown in Fig.1. The electric field of the output can be expressed by

$$E = \frac{\mathrm{e}^{\mathrm{i}\omega_0 t}}{4} \sum_{n=-\infty}^{\infty} \mathrm{e}^{\mathrm{i}n\omega_m t} \sum_{j=1}^{4} J_n(A_j^{\mathrm{RF}}) P_{n,j} A_j^{\mathrm{LW}}, \tag{1}$$

where

$$P_{n,j} \equiv \exp \mathrm{i} \Big[(T - Sn) j \frac{\pi}{2} + \Delta\phi_j^{\mathrm{LW}} + n\Delta\phi_j^{\mathrm{RF}} \Big] \tag{2}$$

$$\phi_j^{\mathrm{LW}} = T\frac{j\pi}{2} + \Delta\phi_j^{\mathrm{LW}} \tag{3}$$

$$\phi_j^{\mathrm{RF}} = -S\frac{j\pi}{2} + \Delta\phi_j^{\mathrm{RF}} \tag{4}$$

$$S = \pm 1, \quad T = \pm 1. \tag{5}$$

J_n expresses the first kind n-th order Bessel's function. ϕ_j^{RF} and ϕ_j^{LW} denote the phases of rf-signal and lightwave in Path j. $\Delta\phi_j^{\mathrm{RF}}$ and $\Delta\phi_j^{\mathrm{LW}}$ are the deviations of the phases from the ideal condition for the SSB modulation. A_j^{RF} is the induced optical phase due to the rf-signal in Path j, and is proportional to the amplitude of the rf signal applied to the electrode. A_j^{LW} denotes the amplitude of lightwave in Path j. When $\Delta\phi_j^{\mathrm{RF}} = \Delta\phi_j^{\mathrm{LW}} = 0$, the phases are 0, $\pi/2$, π and $3\pi/2$ (0, 90, 180 and 270 degrees). The SSB modulator has a pair of Mach-Zehnder structures on an x-cut lithium niobate (LN) substrate, so that we can apply rf-signals of 0, 90, 180 and 270 degrees by feeding a pair of rf-signals with 90 degrees phase difference at two rf-ports ($\mathrm{RF_A}$, $\mathrm{RF_B}$). The rf-signals can be obtained by using an rf 90 degrees hybrid coupler, as shown in Fig. 2. The optical phase differences are also set to be 90 degrees, by using dc-bias ports ($\mathrm{DC_A}, \mathrm{DC_A}, \mathrm{DC_A}$). The output optical spectrum defined by Eq. (1) for $S \times T = 1$ can be approximately expressed by

$$E \simeq A^{\mathrm{LW}} \mathrm{e}^{\mathrm{i}\omega_0 t} \left[J_1(A^{\mathrm{RF}}) \mathrm{e}^{\mathrm{i}\omega_m t} - J_3(A^{\mathrm{RF}}) \mathrm{e}^{-\mathrm{i}3\omega_m t} \right], \tag{6}$$

when the intensity of the electric field is so small that we can neglect high-order harmonic generation at the optical phase modulation. Because $J_1 > J_3$, the dominant component in the output is the first order upper sideband, which corresponds to the wavelength shifted component. On the other hand, in the case of $S \times T = -1$, the lower sideband can be obtained instead of the upper sideband. We can easily switch the polarity of T, by changing the dc-bias voltage applied on the port $\mathrm{DC_C}$. The signal-to-noise-ratio (SNR) and conversion efficiency of the wavelength shift by the modulator are given by $J_1(A^{\mathrm{RF}})/J_3(A^{\mathrm{RF}})$ and $J_1(A^{\mathrm{RF}})$, respectively (see Fig. 3). The conversion efficiency has a maximum of 0.582 (-5.36 dB) when the induced phase A^{RF} is equal to 1.84 rad. The wavelength of the output lightwave can be easily changed by controlling the dc-bias voltages and the rf-signal frequency. Thus, the wavelength shifter consisting of an SSB modulator, as shown in Fig. 2, has very high-speed switching time and can be applied for high-speed WDM switching in optical packet systems.

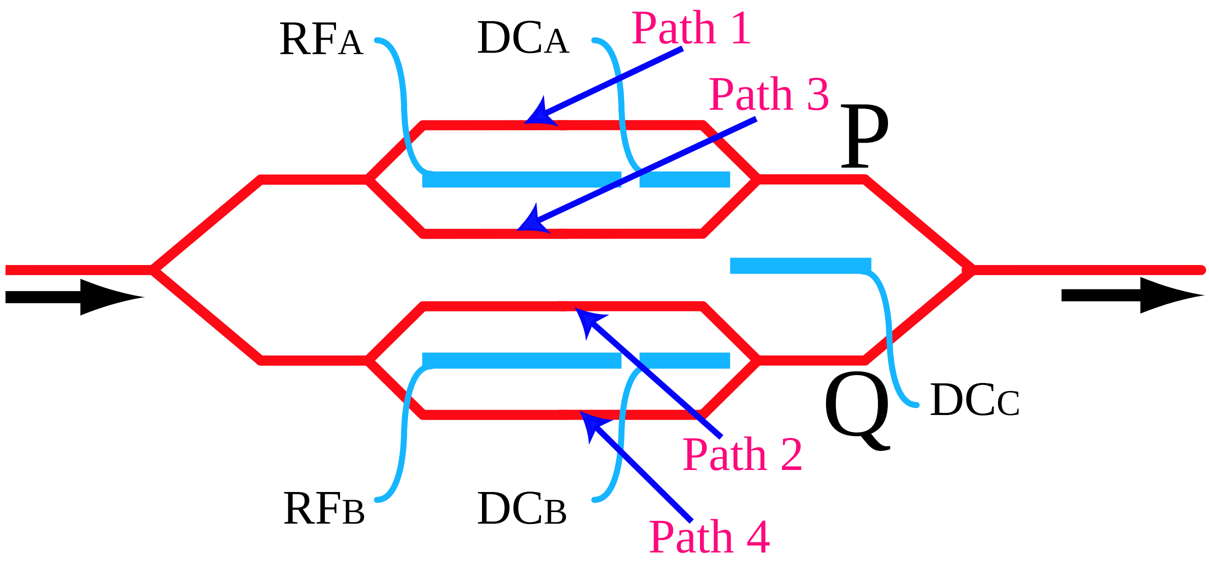

Figure 1: Optical SSB modulator

3 Numerical analysis of wavelength shift in WDM systems

We investigated the wavelength shifter in WDM systems by using a lightwave network simulator, *Optisystem*™ 2.2. As shown in Fig. 4, the WDM system has 9 channels with 25 GHz spacing. The bit rate and the optical

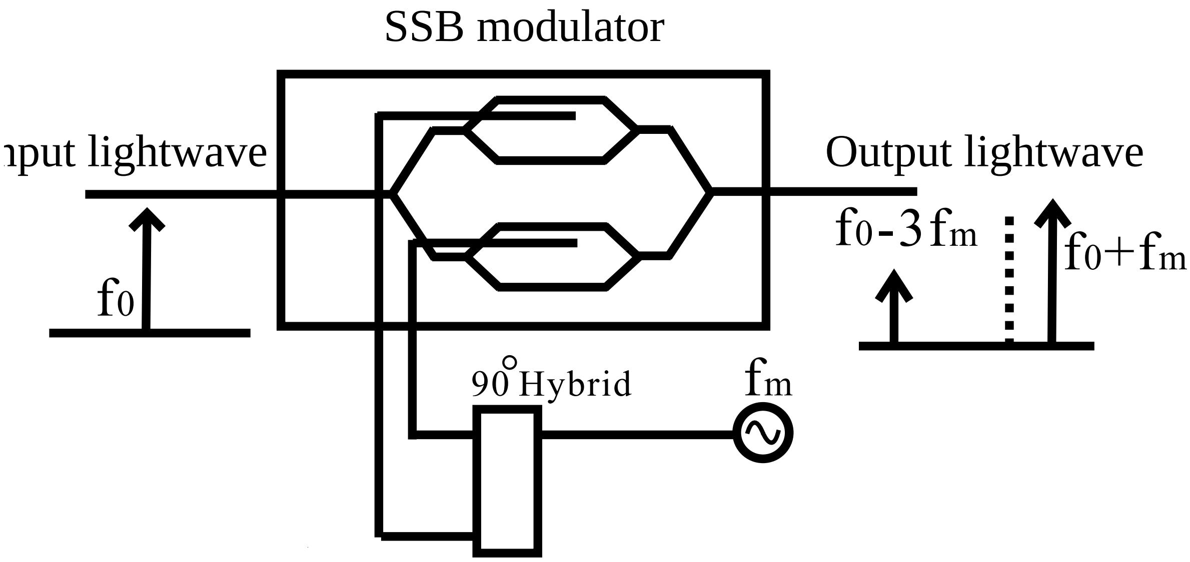

Figure 2: Wavelength shift using SSB modulation. A pair of rf-signals are fed to the modulator through a 90 degree hybrid coupler. The dominant component in the output is the upper sideband whose optical frequency is $f_0 + f_m$. The output contains undesired components such as the third order harmonics.

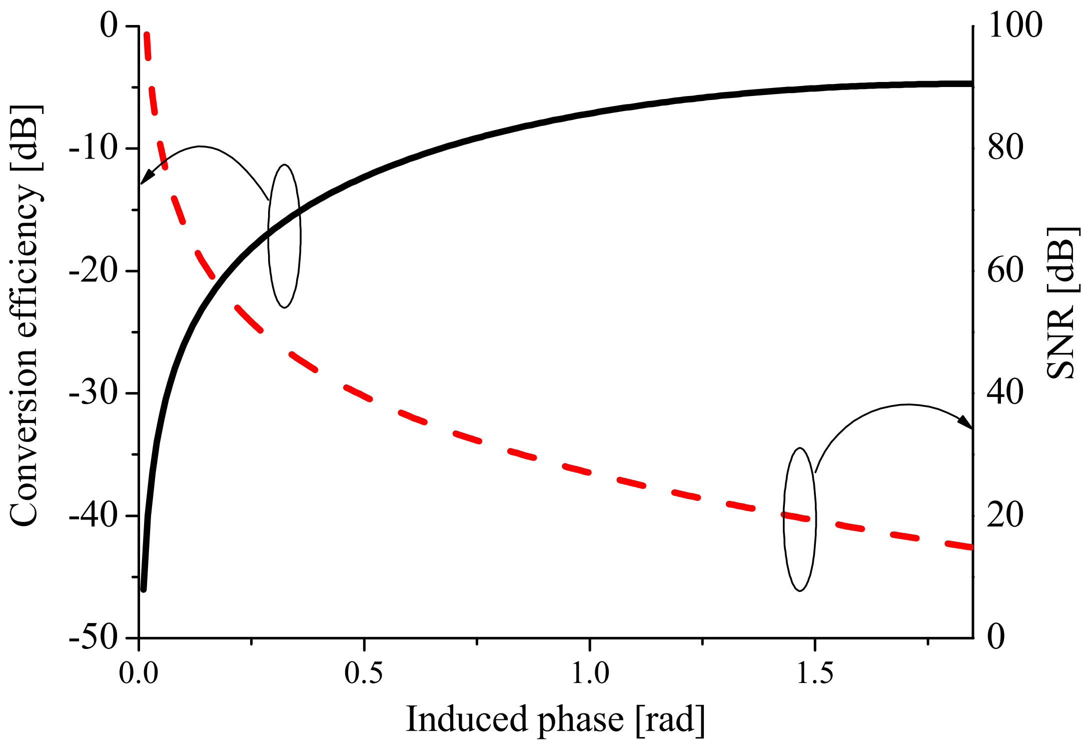

Figure 3: Conversion efficiency and SNR of wavelength shifter using SSB modulation.

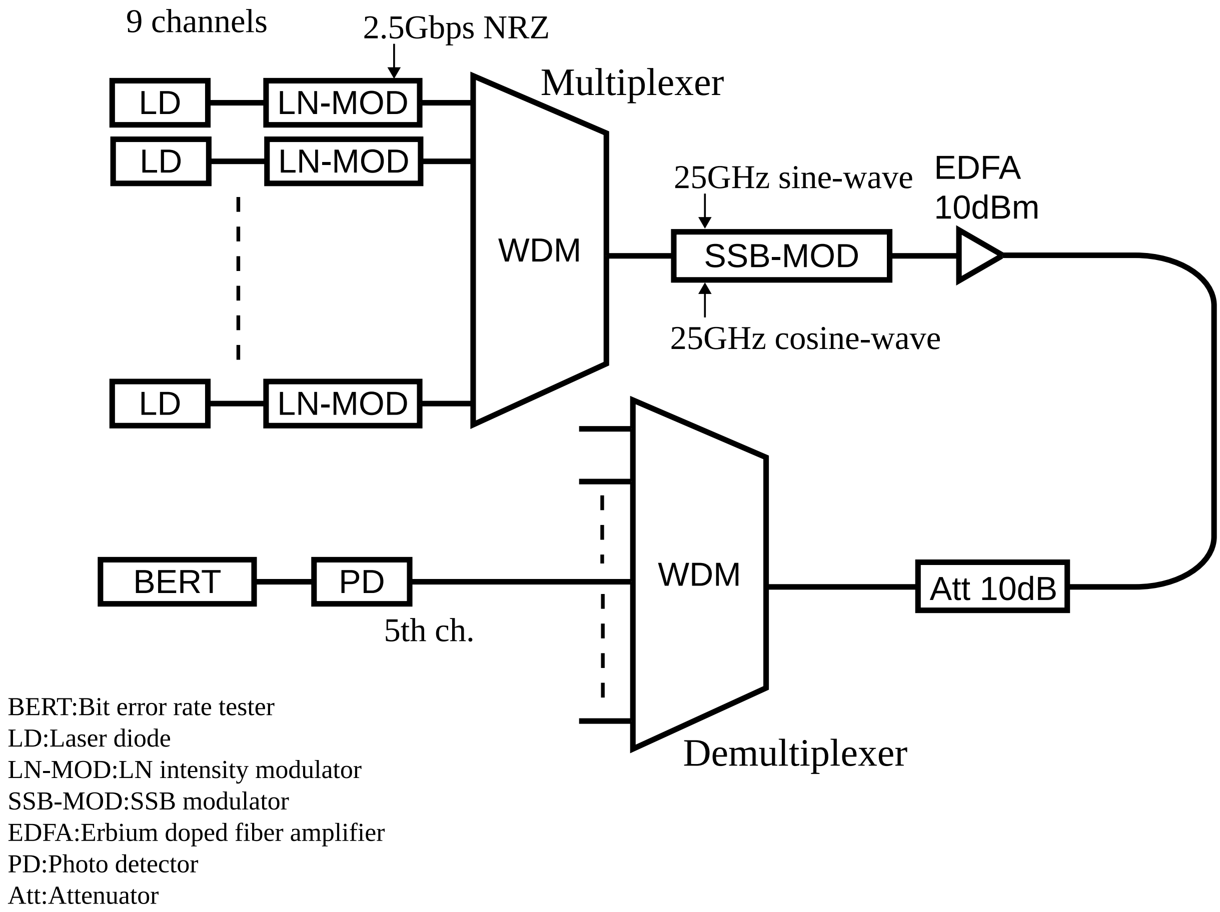

Figure 4: Model for a 2.5 Gbps WDM system with a wavelength shifter using SSB modulation.

frequency of the n-th channel were, respectively, $2.5 \times [(n-5) \times (r/100+1)]$ Gbps and $193.5 + (n-5) \times 0.025$ THz, where $r = 2.0$. Thus, the bit rate of the fifth channel was 2.5 Gbps. Those of neighboring channels were 2% higher or lower than that of the fifth, in order to suppress unphysical cross-talks which are due to the finite time windows in this simulation. The sampling rate in the simulator was 160 Gbps, while the time window was 40.96 ns, which was limited by the memory size and the processor speed of the computer we used. The NRZ signals were generated by LN optical intensity modulators. We used a model for the SSB modulator consisting of four optical phase modulators as shown in Fig. 1. The lightwave signals were fed to the SSB modulator via a WDM multiplexer. In order to compensate the loss at the wavelength shift, an EDFA which was put at the output lightwave port of the modulator, where the output power was controlled to be 10 dBm by tuning the pump laser power. The noise figure of the EDFA was assumed to be 4 dB. We calculated the optical spectra at the input and the output port of the SSB modulator by using optical spectrum analyzer components in the simulator where the resolution was assumed to be 0.01 nm. As shown in Fig. 5, optical wavelength shift (25 GHz) was successfully demonstrated in this simulation. There were undesired high-order optical harmonics in the output spectra. In the case of $A^{\mathrm{RF}} = 1.84$, the fifth order harmonics were also generated, in addition to the third order harmonics which were dominant in undesired components. Fig. 6 shows Q-factors of the fifth channel measured by a bit-error-rate-tester (BERT), and the total optical power at the output port of the SSB modulator. The electric output of the photo detector was fed to the BERT via a transimpedance amplifier whose impedance was 600Ω and noise figure was 6 dB. Q-factor of the reference signal, where an attenuator was placed at the output port of the WDM multiplexer instead of the SSB modulator, was also shown in Fig. 6. The output power was an increasing function of the induced phase A^{RF}. However, the SNR of the output signal was an decreasing function as shown in Fig. 3. Due to this trade-off relations, the Q-factor had a peak around $A^{\mathrm{RF}} = 1.0$. Figs. 7 and 8 show the eye-diagrams of the reference signal and the fifth channel. In the wavelength

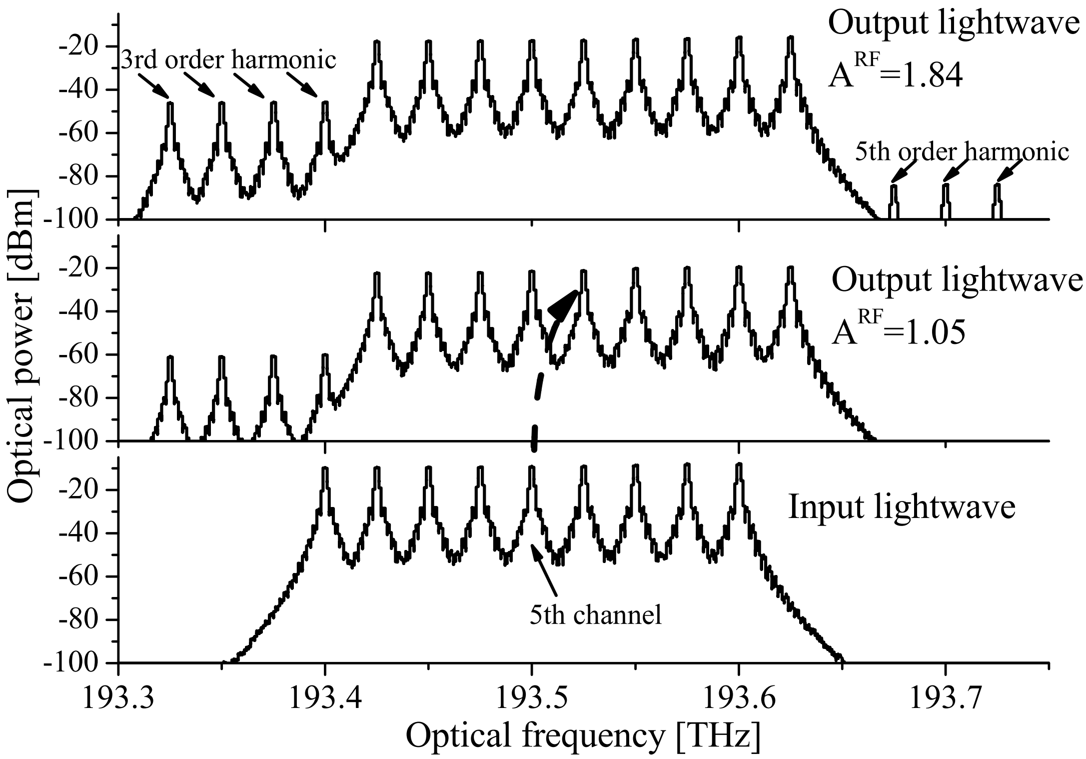

Figure 5: Input and output optical spectra of the SSB modulator.

shifted signal, the deviation of the mark level was larger than that of the reference. We deduce that this is due to interference between the desired channel and the high-order harmonic components of the other WDM channels.

4 Conclusion

By using numerical calculations, we investigated the wavelength shifter consisting of an optical SSB modulator. The WDM channel can be switched by changing the rf-signal frequency or the dc-bias voltages. When the induced phase at the modulator is equal to 1.84, we get the lowest conversion loss. However, the optical signal was distorted due to undesired optical harmonics generated at the SSB modulator.

References

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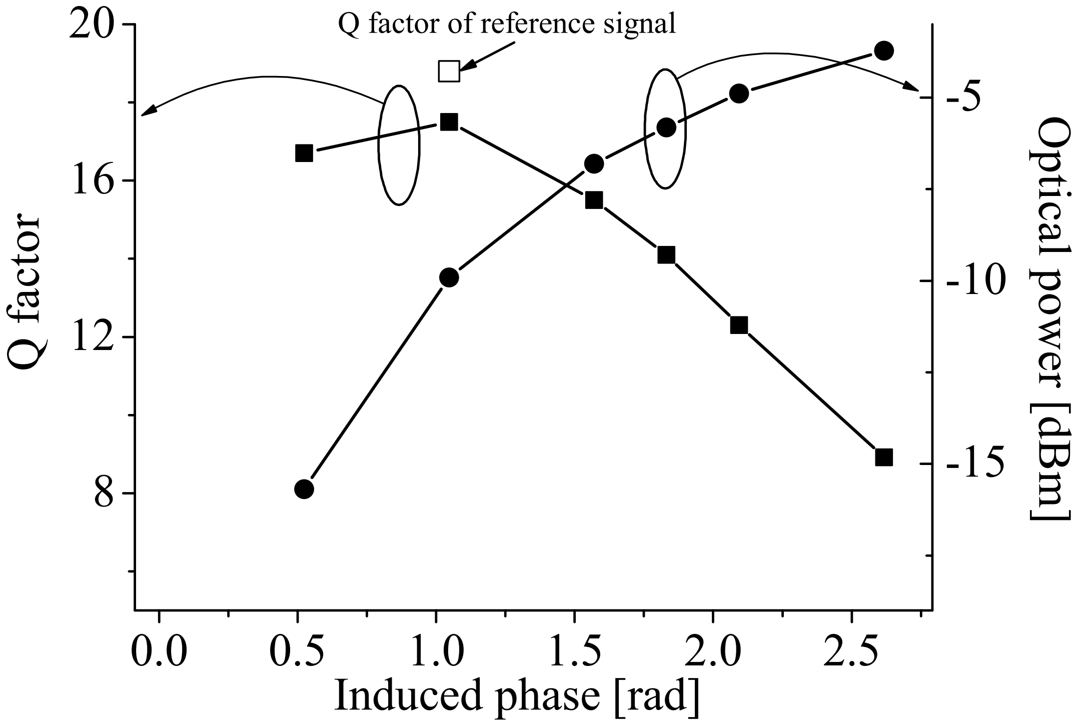

Figure 6: Q-factor of the fifth channel measured by a BERT, and the total optical power at the output port of the SSB modulator. Q-factor of the reference signal was 18.8, where an attenuator was placed at the output port of the WDM multiplexer instead of the SSB modulator.

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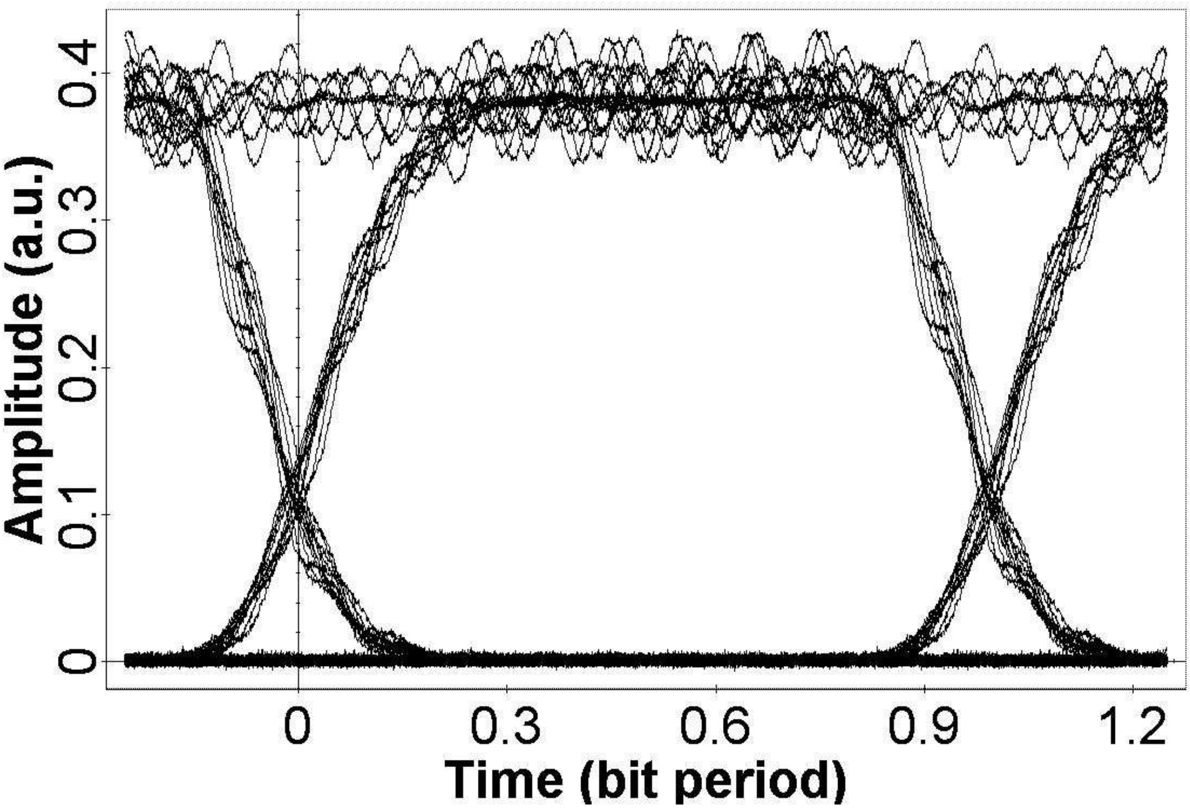

Figure 7: Eye-diagram of the reference signal.

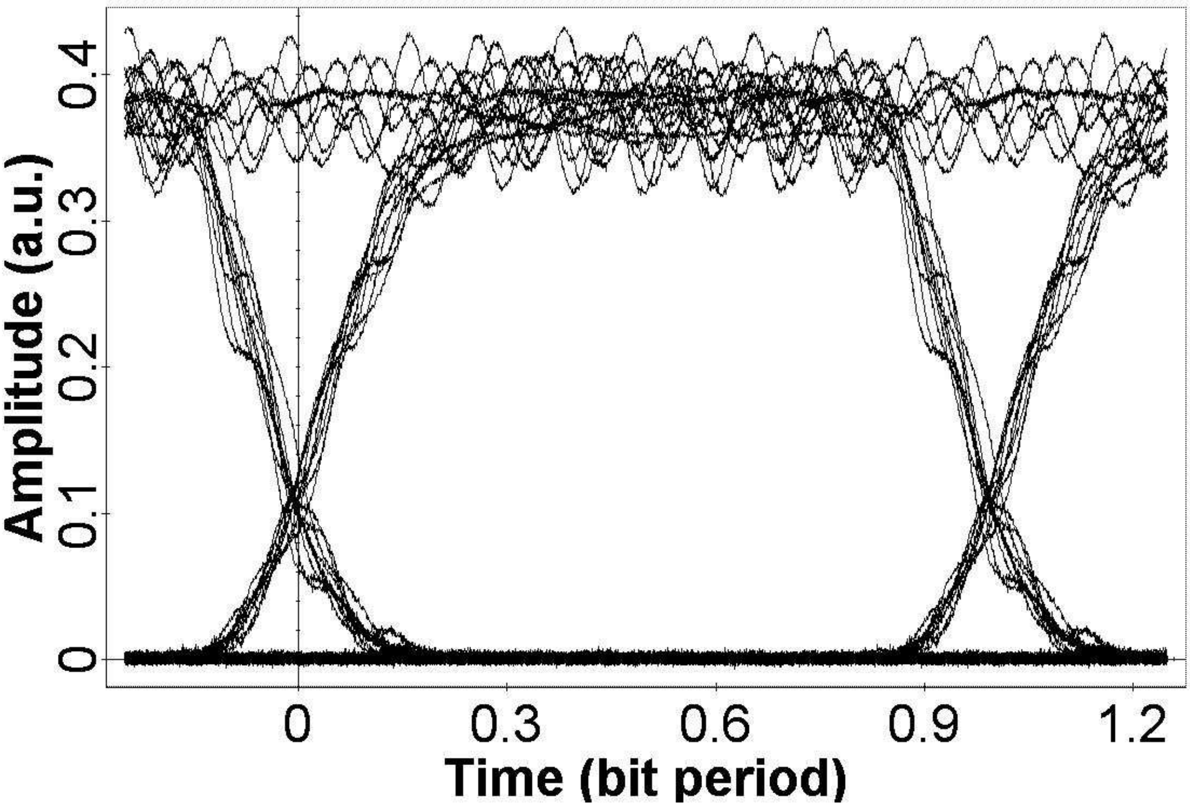

Figure 8: Eye-diagram of the wavelength-shifted fifth channel. Induced phase was 1.84 rad.