Quaternary Optical ASK-DPSK and Receivers With Direct Detection

Michael Ohm and Joachim Speidel, *Member, IEEE*

***Abstract*—In this letter we present a novel quaternary optical-modulation scheme based on the combination of amplitude and phase modulation. The modulator has a simple structure and can be realized by using standard components. We present two simple receivers, each one using photodiodes for direct detection. The performance of the modulation scheme will be investigated.**

***Index Terms*—Amplitude modulation, direct detection (DD), optical modulation, phase modulation.**

I. Introduction

THE MODULATION format in most optical fiber transmission systems is binary intensity modulation with direct detection (IM/DD). Recently, differential phase-shift keying (DPSK) has been suggested for dense wavelength-division multiplexing (DWDM) systems because of higher robustness in the case of fiber nonlinearities, e.g., [1]. In both formats, only one bit per symbol is transmitted, leading to poor spectral efficiencies. A variety of higher order modulation schemes has been proposed, but most rely on rather complicated receivers [2], [3].

We introduce a new quaternary optical-modulation scheme, with simple modulator and demodulator structures, which allows us to transmit two bits per symbol, doubling the spectral efficiency as compared to conventional systems. The modulation scheme is a combination of amplitude-shift keying (ASK) and DPSK with DD and will therefore be called ASK-DPSK/DD.

The modulation scheme is presented in Section II. Demodulation is explained in Section III. The performance of ASK-DPSK is discussed in Section IV.

II. Modulation Scheme and Transmitter

Basically, we want to realize an ASK-DPSK scheme in the optical domain represented by four signal points on the real axis of a constellation diagram as shown in Fig. 1, which have two different magnitudes, $b > a > 0$ and two possible phase angles, 0 and π. Fig. 2 shows the transmitter, that produces the desired optical signal according to Fig. 1.

In the first stage, the electrical drive signal $u_A(t)$ modulates the amplitude of the light from a continuous-wave (CW) laser. $u_A(t)$ is a low-pass filtered nonreturn-to-zero (NRZ) signal, representing the bit stream $b_{A,n}$. The amplitude modulator generates the amplitudes a (for bit "0") and b (for bit "1") as shown in Fig. 1.

Manuscript received June 13, 2002; revised August 29, 2002.

The authors are with the Institute of Telecommunications, University of Stuttgart, D-70569 Stuttgart, Germany (e-mail: ohm@inue.uni-stuttgart.de).

Digital Object Identifier 10.1109/LPT.2002.805776

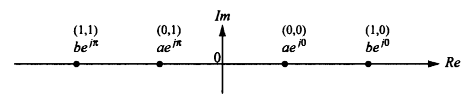


Fig. 1. Constellation diagram of ASK-DPSK modulation scheme and associated bits ($b_{A,n}$, $b'_{P,n}$).

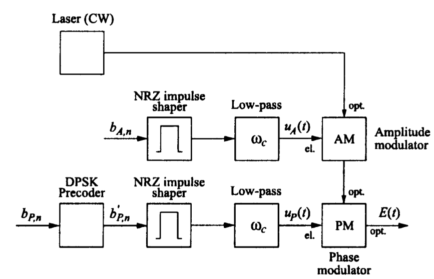


Fig. 2. ASK-DPSK modulator with amplitude and phase path. CW light is first modulated in its amplitude and then in its phase.

In the next stage, the phase of the optical signal is modulated by the electrical drive signal $u_P(t)$ in a phase modulator. The signal $u_P(t)$ representing the bit stream $b_{P,n}$ is also a low-pass filtered NRZ signal. In order to simplify the detection process we use DPSK instead of PSK. For this reason we insert a DPSK precoder as, e.g., in [4] such that $b'_{P,n} = \overline{b_{P,n}} \oplus b'_{P,n-1}$, with "$\oplus$" denoting logical XOR and "—" denoting logical NOT. The possible values of the phase angle are 0 (for bit "0") and π (for bit "1") as shown in Fig. 1.

Finally, we can write the electrical field strength of the optical signal at the output of the transmitter as

$$E(t) = \sqrt{P} A(t) \exp\{j[\omega_0 t + \phi(t)]\} \tag{1}$$

where $\omega_0/2\pi$ is the optical carrier frequency, P is the mean power of the CW laser, and $A(t)$ and $\phi(t)$ stand for the modulated amplitude and phase, respectively. At the time instants $t = nT$, $n = 0, \pm 1, \pm 2, \ldots$, we have $A(nT) = A_n \in \{a, b\}$ with $b > a > 0$ and $\phi(nT) = \phi_n \in \{0, \pi\}$ with the symbol duration T.

III. Demodulation of the ASK-DPSK Signal

Block diagrams of two DD receivers are given in Fig. 3. For the principle analysis we assume an ideal optical fiber, so that the input to the demodulators is $E(t)$ according to (1). The impact of real fibers is considered in Section IV.

A. Demodulator I

Demodulator I is shown in Fig. 3(a). The optical signal is split into an amplitude path $E_A^I(t)$ and a phase path $E_P^I(t)$ using a

Photonics Technology Letters, IEEE , Volume: 15 Issue: 1 , Jan. 2003 Page(s): 159 -161

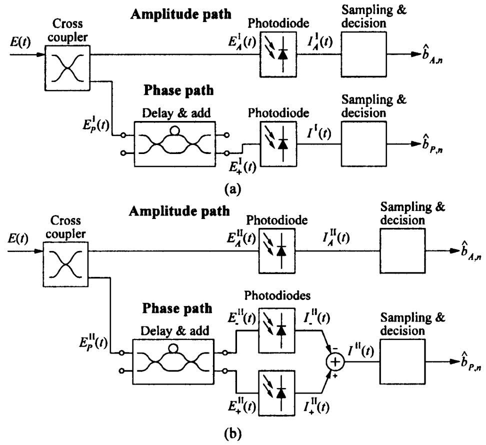


Fig. 3. ASK-DPSK/DD demodulator structures. (a) Demodulator I. (b) Demodulator II.

TABLE I
POSSIBLE VALUES OF I_n^I/kI_0

A_n	A_{n-1}	$\cos(\phi_n - \phi_{n-1})$	I_n^I/kI_0	$\hat{b}_{P,n}$	$\hat{b}_{A,n}$
a	a	+1	$a^2/2$	1	0
a	b	+1	$(a+b)^2/8$	1	0
b	a	+1	$(a+b)^2/8$	1	1
b	b	+1	$b^2/2$	1	1
a	a	-1	0	0	0
a	b	-1	$(a-b)^2/8$	0	0
b	a	-1	$(a-b)^2/8$	0	1
b	b	-1	0	0	1

cross coupler. (The superscript I denotes demodulator I.) From here on, the detection of the amplitude and the phase information is independent of each other.

The demodulation in the amplitude path is performed by a single photodiode. With the proportionality factor k, the responsivity R of the photodiode, and $I_0 = RP$, we get an electrical current

$$I_A^I(t) = kR\left|E_A^I(t)\right|^2 = \frac{1}{2}kI_0A^2(t) \tag{2}$$

which is fed into a sampling and decision device, which provides estimates $\hat{b}_{A,n}$ of the bit sequence (see Table I).

Demodulation of the phase information is achieved by a delay & add filter (DAF) using a Mach–Zehnder interferometer with an optical delay of one symbol period T in one arm and a photodiode, which is common practice for DPSK receivers [5].

The output field strength of the cross coupler is

$$E_P^I(t) = \sqrt{\frac{1}{2}}E(t) \tag{3}$$

and the signal $E_+^I(t)$ at the output of the DAF can be written as

$$\begin{aligned} E_+^I(t) =& \frac{j}{2}\left[E_p^I(t) + E_p^I(t-T)\right] = \frac{j}{2\sqrt{2}}[E(t)+E(t-T)] \\ =& \frac{j\sqrt{P}}{2\sqrt{2}}\bigg(A(t)\exp\{j[\omega_0 t+\phi(t)]\} \\ &+ A(t-T)\exp\{j[\omega_0 t+\phi(t-T)-\omega_0 T]\}\bigg). \end{aligned} \tag{4}$$

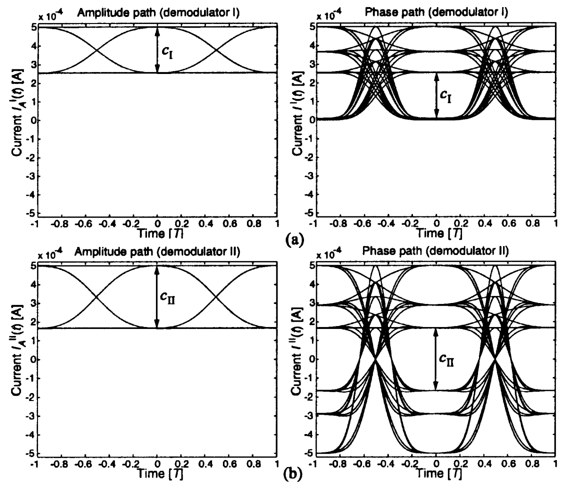


Fig. 4. Eye diagrams after amplitude and phase paths of (a) demodulator I, and (b) demodulator II. ($P = 1$ mW, ideal photodiodes with $R = 1$ A/W).

For the DAF we assume that by appropriate measures $\exp[-j\omega_0 T] = 1$. The electrical current after the photodiode is

$$I^I(t) = kR\cdot\left|E_+^I(t)\right|^2 \tag{5}$$

and at the sampling instants $t = nT$ we get with (4)

$$\begin{aligned} I^I(nT) =& I_n^I \\ =& \frac{1}{8}kI_0\left[A_n^2 + A_{n-1}^2 + 2A_nA_{n-1}\cos(\phi_n - \phi_{n-1})\right]. \end{aligned} \tag{6}$$

The noteworthy point here is, that although the amplitude of the optical signal changes independently of the phase, the phase information can be detected unambiguously. Estimation of the bit sequence $b_{P,n}$ requires the knowledge of whether the cosine term in (6) is $+1$ or -1. In spite of the amplitude-related terms in (6), it is possible to estimate the bit sequence, because the values of I_n^I are grouped for $\cos(\phi_n - \phi_{n-1}) = +1$ and for $\cos(\phi_n - \phi_{n-1}) = -1$. I_n^I takes on five different values as shown in Table I.

The difference between the highest level for "0" and the lowest level for "1" determines the eye opening c_I in the phase path. For the choice $a = 5b/7$ the eye openings $c_I = kI_0b^2\cdot 12/49$ of the electrical signals in the phase and in the amplitude paths are identical. This case is shown in Fig. 4(b).

The advantage of this receiver is that only two photodiodes for demodulation and binary decision devices in both the amplitude and the phase path are required. However, by using only one output of the DAF we throw away half the optical power. Thus, an alternative receiver is proposed in the following.

B. Demodulator II

Demodulator II in Fig. 3(b) is similar to demodulator I. In the amplitude path nothing is changed, whereas in the phase path, the second output of the DAF is also used. The signal at this output is similar to (4)

$$E_-^{II}(t) = \frac{1}{2\sqrt{2}}[E(t-T) - E(t)] \tag{7}$$

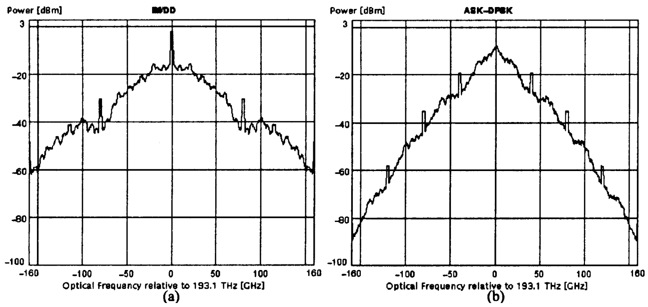
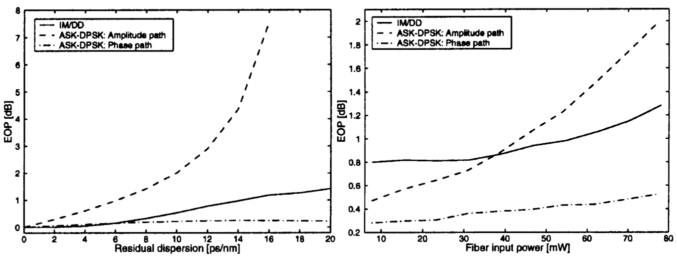


Fig. 5. Spectra of (a) 80-Gb/s IM/DD and (b) 80-Gb/s ASK-DPSK/DD.



(a) (b)

Fig. 6. Comparison of ASK-DPSK/DD and IM/DD. (a) EOP versus residual dispersion for 80-Gb/s IM/DD and 80-Gb/s ASK-DPSK/DD. (b) EOP versus fiber input power for Ch. 5 of an eight-DWDM system with 160-GHz channel spacing for 8 × 80-Gb/s IM/DD and 8 × 80-Gb/s ASK-PSK/DD after 60 km of SMF ($D = 16$ ps/(nm·km) at Ch. 5) and 10.67 km of DCF ($D = -90$ ps/(nm·km) at Ch. 5).

and at the other output $E_+^{II}(t) = E_+^I(t)$. Again we assume $\exp[-j\omega_0 T] = 1$. Both optical signals are fed into separate photodiodes and the output currents are subtracted. The resulting current $I^{II}(t)$ at the sampling instants $t = nT$ becomes

$$I^{II}(nT) = I_n^{II} = \frac{1}{2} k I_0 A_n A_{n-1} \cos(\phi_n - \phi_{n-1}). \tag{8}$$

Eye diagrams for demodulator II are shown in Fig. 4(b). For the estimates $\hat{b}_{P,n}$ it is just necessary to decide whether the electrical signal in (8) is positive or negative (binary decision). For obtaining equal eye openings c_{II} in the amplitude path and the phase path, we choose $a = b/\sqrt{3}$.

Demodulator II has the advantage, that it generates wider eye openings ($c_{II} = kI_0 b^2/3 > c_I$) in both the amplitude and the phase path than demodulator I, because both DAF outputs are used.

IV. Performance of ASK-DPSK/DD

Fig. 5 compares the spectra of conventional 80-Gb/s IM/DD and 80-Gb/s ASK-DPSK/DD. Clearly, ASK-DPSK/DD requires less bandwidth than IM/DD, allowing for a closer channel spacing in DWDM. The reason is that the ASK-DPSK/DD system operates at the symbol rate of 40 Gsymbols/s and each symbol carries two bits.

The dispersion tolerance of 80-Gb/s ASK-DPSK is investigated with simulations and compared to 80-Gb/s IM/DD in Fig. 6(a) (demodulator II for ASK-DPSK/DD). The eye opening in the phase path is only slightly affected even for rather high values of residual dispersion. For residual dispersion values up to 6 ps/(nm · km), the eye-opening penalty (EOP) of the phase path of ASK-DPSK/DD is comparable to the EOP of IM/DD. For higher dispersion values, the EOP of the phase path of ASK-DPSK/DD remains well below the EOP of IM/DD. The EOP of the amplitude path of ASK-DPSK/DD is greater than that of the phase path and increases stronger than the EOP of IM/DD with increasing dispersion. In conclusion, the DPSK signal part is much more robust against dispersion than the ASK signal part.

Simulation results for 8-DWDM transmission with both 80-Gb/s ASK-DPSK/DD and 80-Gb/s IM/DD are presented in Fig. 6(b). The channel spacing was 160 GHz and the signals were transmitted over 60 km of single-mode fiber (SMF, $D = 16$ ps/nm · km) and 10.67 km of dispersion compensating fiber (DCF), $D = -90$ ps/nm · km). For the investigated channel 5 dispersion was fully compensated. For low fiber input powers up to approximately 38 mW, the EOP for amplitude and phase paths of ASK-DPSK/DD are smaller than the EOP of IM/DD. In this region, linear crosstalk from adjacent channels is dominant and fiber nonlinearities play a minor role. ASK-DPSK/DD with its narrower spectrum is here advantageous over IM/DD. However, for higher fiber input powers, the EOP of the amplitude path of ASK-DPSK/DD exceeds the EOP of IM/DD. The DPSK is very robust against nonlinearities and the EOP of the phase path of ASK-DPSK/DD remains significantly below the EOP of IM/DD.

So ASK-DPSK/DD seems especially suited for medium-range fiber links or single carrier dispersion-compensated fiber links, for which the bit rate can be doubled at reasonable hardware overhead.

V. Conclusion

We have presented a quaternary optical modulation scheme, for which transmitters and receivers can be implemented rather easily. Two demodulator structures with different features are compared. The electrical and optical components operate at the symbol speed, which is half the bit rate. On the other hand, the proposed ASK-DPSK/DD scheme can double spectral efficiency by adding only moderate complexity.

References

[1] M. Rohde, C. Caspar, N. Heimes, M. Konitzer, E.-J. Bachus, and N. Hanik, "Robustness of DPSK direct detection transmission format in standard fiber WDM systems," *Electron. Lett.*, vol. 36, no. 17, pp. 1483–1484, Aug. 2000.

[2] S. Betti, G. De Marchis, and E. Iannone, *Coherent Optical Communications Systems*. New York: Wiley, 1995.

[3] S. Walklin and J. Conradi, "Multilevel signaling for increasing the reach of 10 Gbit/s lightwave systems," *J. Lightwave Technol.*, vol. 17, pp. 2235–2248, Nov. 1999.

[4] W. Kaiser, T. Wuth, M. Wichers, and W. Rosenkranz, "Reduced complexity optical duobinary 10-Gb/s transmitter setup resulting in an increased transmission distance," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 884–886, Aug. 2001.

[5] R. S. Vodhanel, "5 Gbit/s direct optical DPSK modulation of a 1530-nm DFB laser," *IEEE Photon. Technol. Lett.*, vol. 1, pp. 218–220, Aug. 1989.