TABLE I
EXPERIMENTAL TRANSMISSION RESULTS

Bit rate (Gb/s)	Configuration (postamplifier in all cases)	Distance (km)	Budget (dB)
0.622	Preamplifier	365	68.5
0.622	Remote + preamplifier	401	73
2.488	Preamplifier	341	62.5
2.488	Remote + preamplifier	357	68

Telecom Norway, and J. Artur, S. Morin, L. Sniadower from Alcatel CIT for their contribution to these experiments.

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Direct Modulation 565 Mb/s DPSK Experiment with 62.3 dB Loss Span and Endless Polarization Control

R. Noé, E. Meissner, B. Borchert, and H. Rodler

***Abstract*—Optical DPSK at 565 Mb/s is performed by direct modulation of a narrow-linewidth 1.5 μm SL-QW-DFB transmitter laser. The bipolar RZ drive signal has no dc component which allows penalty-free transmission of $2^{23} - 1$ bit patterns. The heterodyne receiver contains an endless polarization controller with > 6.3 or > 12 rad/s tracking speed, depending on the tolerable intensity loss. A loss span of 62.3 dB is achieved, without degradation due to stimulated Brillouin scattering.**

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INTRODUCTION

MUCH effort has been devoted to FSK heterodyne systems; however, as narrow-linewidth semiconductor lasers are becoming available, direct modulation DPSK [1]–[7] is an attractive option because it yields lower chromatic dispersion penalties [1], [5] than FSK. If bipolar

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[2]–[4], [6], [7] rather than unipolar [1], [3], [5] modulation is used the problem of nonuniform FM response at low frequencies is eliminated.

We present a DPSK system with bipolar *RZ* current modulation of the transmitter laser. The heterodyne receiver uses endless polarization control.

EXPERIMENTAL SETUP

Strained layer quantum-wall (SL-QW) DFB lasers similar to [8] with up to 38 mW output power are used as transmitter and local oscillator lasers in the 1.5 μm wavelength region. The transmitter phase is directly modulated by applying short current pulses to the laser. These *RZ* pulses have alternately positive and negative polarity. This bipolar drive eliminates the dc component of the modulation signal. As a consequence, the nonuniform FM response of the transmitter laser at low frequencies—caused by distortion and counteraction of the carrier-density-change-induced FM by the thermally induced FM—can not produce harmful effects. A directional coupler that is inserted after the transmitter taps off 6% of forward traveling and backscattered optical powers for measurement purposes. The remaining 94% of the signal is transmitted through 94 km of non-dispersion shifted optical fiber and subsequent attenuators. An engineered 565 Mb/s DPSK receiver [9] is slightly modified and is provided with an endless polarization controller that consists of four fiber squeezers. The IF level in the receiver is detected, fed to the polarization controller, and maximized by the control algorithm.

ENDLESS POLARIZATION CONTROL

Some of the published endless polarization control algorithms ([10]–[16] and references given therein) do not require knowledge of absolute but only of relative retardation values, i.e., differential retardation change versus drive signal change [12]–[15]. However, algorithms that "know" the retardations in absolute terms [10], [11], [15] can choose the optimum control strategy. Resets can be performed faster because unwanted polarization changes that are caused by resets are much smaller and can therefore be corrected by fewer additional intensity maximization steps. Depending on hard- and software, this speed advantage may be offset by slower, more complex control steps.

While three linear retarders, e.g., fiber squeezers, are sufficient for endless polarization control, it is better to use four because this additional degree of freedom can compensate both nonideal retarder behavior and polarization changes during resets. The theoretical algorithm from [15] was implemented for the experiment with a few modifications.

The limits of polarization control speed were assessed with a variable polarization analyzer. For higher measurement accuracy and photocurrent intensity was minimized rather than maximized. Endless polarization changes on 42 different great circles of the Poincaré sphere were generated by manual polarizer rotation. The speeds were 6.3…10.4 rad/s on the Poincaré sphere. Experimental results are given in Fig. 1. The normalized intensity I of the signal is drawn on the abscissa, 0 being the best achievable value. The ordinate gives the cumulative density $F(I)$ of the intensity, i.e., the time-averaged probability that the intensity becomes worse than the value given on the abscissa. In spite of fast polarization changes the intensity loss was $< 2.4\%$ in all cases. If the signal were maximized, this would correspond to $-10 \log (1-(<0.024)) = < 0.11$ dB loss. For tracking speeds of 12…18 rad/s the intensity loss stayed $< 5\%$ (< 0.22 dB assuming maximized signal). The tracking speed for polarization changes of limited amount is considerably higher than for endless changes.

One control step needs 2.8 ms on an 80286 processor, dominated by the transducer response time. Table I summarizes results on fast endless polarization control using linear limited-range retarders, with tracking speeds of up to 15π rad/s = 47 rad/s. It is evident that knowledge of the absolute retardation values allows more efficient tracking in terms of rad/iteration. Very recently, high-speed control (at 88 kHz) of endlessly rotatable electrooptic waveplates on $LiNbO_3$ has enabled a record tracking speed of 4900 rad/s [16]. Their control is based on the generation of sine and cosine functions. On the other hand, linear limited-range retarders require relatively complicated reset operations. Our algorithm would be particularly suited for liquid crystal polarization controllers which feature low losses and stable retardation, but also slow speed.

SYSTEM PERFORMANCE

For data transmission the endless polarization control system is incorporated in the local oscillator path of the heterodyne receiver. The transmitter laser is modulated at 565 Mb/s with a bipolar $2^{23}-1$ pseudorandom pattern (Fig. 2). For good performance positive and negative pulses must have equal integrals and should not have postcursors. In our case this is achieved by strict class-A operation of a wide-bandwidth driver amplifier. Table II summarizes the results achieved with endless polarization control in operation for different transmitter powers and IF linewidths. The best usable loss span is 62.3 dB. A linewidth increase to 3.5 MHz reduces the receiver sensitivity by 0.8 dB.

In Fig. 3 calculated sensitivity penalties are shown for zero IF linewidth as a function of deviation $|M-1|$ of the normalized modulation amplitude M from its optimum value 1. Both PSK and CPFSK modulations yield baseband signals $\pm\sin(\pi M/2)$. However, the asynchronous demodulation of CPFSK signals reduces the tolerance to modulation deviations with respect to synchronous PSK. Asynchronous DPSK, with baseband signals 1 and $\cos(\pi M)$, yields a narrower eye opening and places the highest stability requirements on the modulation although we assume the decision threshold is optimized for each M. With fixed/threshold (which is suboptimum for $M \neq 1$), 1.6 MHz IF linewidth and nonideal drive pulses (Fig. 2)

TABLE I
ENDLESS POLARIZATION TRACKING USING LINEAR LIMITED-RANGE RETARDERS

	this work		BT [13], [12]	NEC [14]
iteration/s	360		2000	10000
intensity loss [dB]	0.11	0.22		0.2
tracking speed [rad/s]	6.3...10.4	12...18	25	47
tracking speed [rad/iter.]	0.018...0.029	0.033...0.05	0.0125	0.005
unwinding speed [rad/s]	140		25	47
unwinding speed [rad/iter.]	0.39		0.0125	0.0047
sum of range widths [rad]	25		151	110
knowledge of absolute retardation values needed	yes		no	no

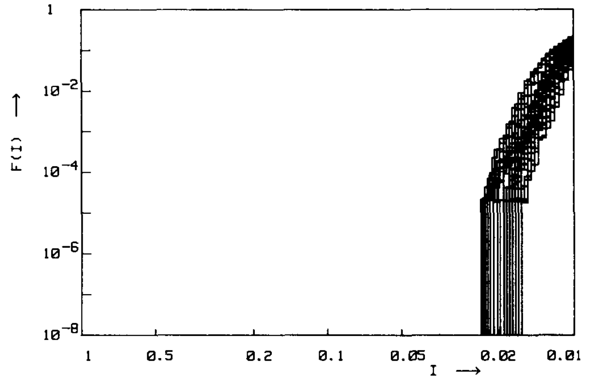

Fig. 1. Intensity distribution function while tracking endless polarization changes on 42 different great circles of the Poincaré sphere. Speed is 6.3... 10.4 rad/s.

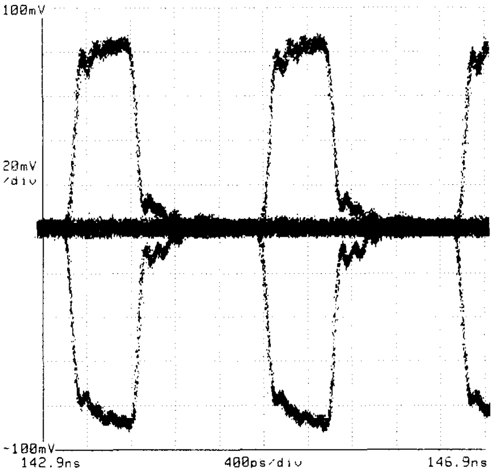

Fig. 2. Eye pattern of bipolar transmitter drive signal.

TABLE II
TRANSMISSION RESULTS (565 MB/S, $2^{23}-1$ PRBS, BER = 10^{-9})

Launched TX power [dBm]	7	9.7	10.3
IF linewidth [MHz]	0.9	1.6	3.5
RX sensitivity ηP [dBm]	−54.5	−54.5	−53.7
RX sensitivity P [dBm]	−52.6	−52.6	−51.8
usable loss span [dB]	59.6	62.3	62.1

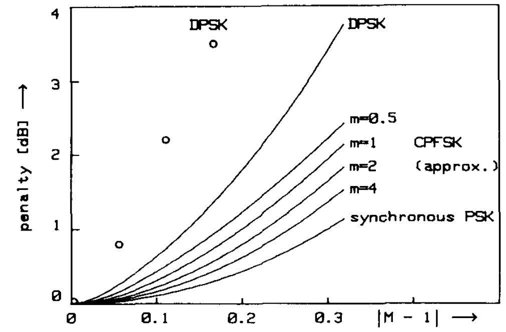

Fig. 3. Calculated penalty versus deviation of the normalized modulation amplitude M form its optimum 1 (solid lines; an approximation is used for CPFSK) and experimental values (*o*).

acting as sources of degradation with respect to theory, and experimental sensitivity degradation of 1 dB is obtained already for a change of about ±7% of the DPSK modulation amplitude.

Finally, the powers launched into and backscattered from the 94 km long transmission fiber are determined by measuring the powers at the unused ports of the 6% directional fiber-coupler. Fig. 4 reveals that there is strong stimulated Brillouin scattering (SBS) if high powers are launched without modulation (+). With DPSK modulation (*o*), the width of the modulated optical spectrum is much larger than the Brillouin gain bandwidth [17] which reduces scattering to the Rayleigh level (up to 11 mW which is more than the < 10.7 mW used for transmission experiments) or slightly more (at 12.2 nW). Accordingly, transmission over 94 km of fiber is not degraded by SBS. Identical results were obtained for 2^9-1 to $2^{23}-1$ bit patterns (*o*). At 12.2 mW forward power, 2^7-1 and 1010 patterns caused 0.1 and 2.6 dB more scattering than the long patterns, respectively. The system loss span was identical for the different data patterns within a few tenths of a dB.

CONCLUSION

We report on a 565 Mb/s DPSK heterodyne system with a loss span of 62.3 dB. A 1.5 μm SL-QW-DFB transmitter laser is directly modulated by a bipolar *RZ* drive signal. The receiver features endless polarization control with a tracking speed of up to > 12 rad/s. The

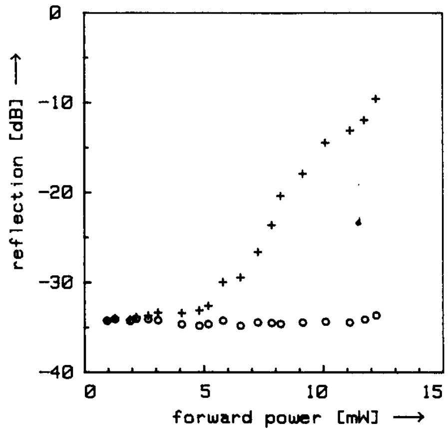

Fig. 4. Reflections from transmission fiber with (*o*) and without (+) DPSK modulation as a function of forward traveling power [milliwatts].

tolerance of PSK, DPSK, and CPFSK transmission to deviations of the modulation amplitude from its optimum is also discussed.

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Equalization and Mode Partition Noise in All-Plastic Optical Fiber Data Links

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Abstract—**High-speed, short distance data transmission over all-plastic step-index fiber (POF) is normally considered to be limited by intermodal dispersion. Theoretical calculations in this letter show that the baseband frequency response can be significantly improved, using simple linear equalization. However, as the fiber length is increased, the sharp absorption attenuation peaks of PMMA fiber can potentially introduce mode partition noise. The bounds on practical laser characteristics and fiber lengths are explored; these results indicate that 530 Mb/s transmission over 100 m of 1 mm diameter POF is feasible, thus potentially satisfying a significant segment of future computer interconnect applications.**

I. INTRODUCTION

FOR *very short* distance interconnects, the various types of copper cables are most economical, while for

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