Experimental Equalization of Polarization Dispersion

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Abstract—**In this letter we describe a demonstration of the equalization of polarization dispersion in a direct-detection lightwave system. Polarization maintaining fiber was used to generate first-order polarization dispersion, and equalization was achieved by a manually-adjustable, analog tapped delay line that equalized the baseband electrical signal at the receiver. At a 1.1 Gbps data rate, a two-tap equalizer reduced the intersymbol interference due to polarization dispersion by more than 20 dB, eliminating a 3 dB eye closure penalty.**

I. Introduction

POLARIZATION dispersion is a significant factor limiting the maximum bit rate-distance in future high-speed, long-haul lightwave systems. It will cause substantial signal degradation at data rates of 8 Gbps and higher in optical amplifier systems for terrestrial and undersea lightwave.

Previous papers [1]-[4] have studied the effect of polarization dispersion in coherent- and direct-detection lightwave systems. The main effects on the transmitted signal are a first-order effect of different relative delays and amplitudes in the received signals in two orthogonal polarizations, and second-order effect of depolarization and effective chromatic dispersion. However, with external modulation of the transmit laser or with FSK modulation (i.e., with negligible laser chirp), experimental [3] results have shown that second-order effects are negligible.[1] Since the signals in orthogonal polarizations add in optical power at the receiver (i.e., in amplitude in the electrical domain), with external modulation polarization dispersion is a linear distortion in the electrical signal. Thus, as described in [4] an electrical analog tapped delay line can be used to equalize polarization as long as the received signal eye is not closed by dispersion, while a decision feedback equalizer (DFE) or nonlinear canceler (NLC) with a sufficient number of feedback taps can eliminate any amount of polarization dispersion.

In this letter, we describe a hardware demonstration of the equalization of polarization dispersion by an electrical analog tapped delay line. The lightwave system used a DBR laser with external modulation for a transmission at 1.1 Gbps with direct detection by an APD. Polarization maintaining fiber was used to generate first-order polarization dispersion. Results show that a two-tap, manually adjustable equalizer reduced the intersymbol interference due to polarization dispersion by more than 20 dB, eliminating a 3 dB eye closure penalty.

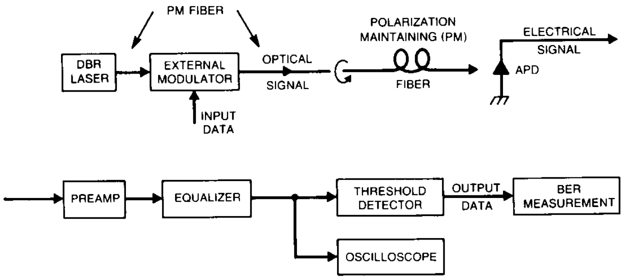

Fig. 1. Lightwave system experimental setup.

In Section II we describe the experimental setup. Results are described in Section III. A summary and conclusions are presented in Section IV.

II. System

The lightwave system used in the experiment is shown in Fig. 1. The output of a DBR laser is externally modulated to generate a 1.1 Gbps on–off keyed optical signal. This signal is transmitted through polarization maintaining fiber and converted to an electrical signal at the receiver by direct detection. The electrical signal is amplified and equalized, and the output bits are determined by a threshold detector.

Polarization maintaining (PM) fiber was used to generate the polarization dispersion for the following reasons. In a single-mode (SM) fiber (i.e., not polarization maintaining) the bit rate-distance at which polarization dispersion is noticeable with external modulation and direct detection is quite large—fiber lengths greater than 100 km and data rates greater than 10 Gbps are required [1]. Furthermore, in a SM fiber the polarization dispersion changes with time (on the order of seconds or minutes), which makes measurement of the improvement with equalization more difficult and requires an adaptive equalizer. To overcome these problems, we used a polarization maintaining fiber[2] which had a 500 ps/km propagation delay difference between polarizations. Thus, large delay differences could be obtained with a short length of fiber, e.g., a 300 ps delay difference with just 600 m of fiber. The PM fiber pigtail (which has only one mode excited) out of the external modulator was butt-coupled to another (much longer) PM fiber. This fiber was rotated to change the coupling ratio of the linearly polarized signal out of the external modulator

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[1] With chirp, the second-order effects can dominate first-order effects.

[2] Polarization maintaining fiber maintains the polarization because it has a large refractive index or propagation velocity difference between the two orthogonal polarization modes, and hence there is less coupling between the modes.

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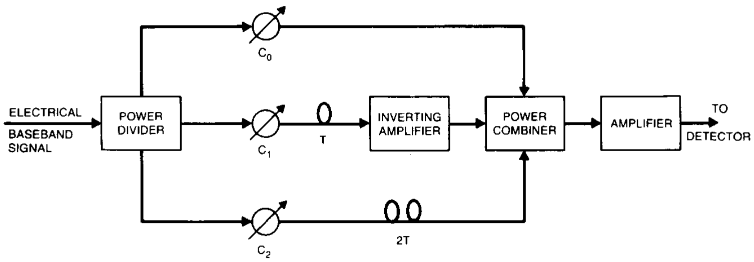

Fig. 2. Analog tapped delay line equalizer.

pigtail into the two orthogonal polarization modes of the PM fiber. At a particular rotation angle θ, the signal was coupled into only one mode, while at $\theta + 90°$ it was coupled only into the other mode, with the output signal having a greater delay, e.g., 300 ps at 600 m. Thus, by rotating the fiber we could control the relative power of the signals in the two polarization modes, with the worst case dispersion occurring at $\theta + 45°$ where the two modes have equal power. Thus, by changing the length and rotating the PM fiber we can overcome the problems of generating polarization dispersion in a SM fiber, because we can generate any level of first-order polarization dispersion, with the level fixed and easy to calculate, using a short length of fiber at low data rates ($\approx$Gbps). For the results given in Section III, 600 m (300 ps delay) of PM fiber and a data rate of 1.1 Gbps were used (a data rate of 1.4 Gbps was also used). This data rate was limited mainly by the response of the receiver.

The analog tapped delay line equalizer is shown in Fig. 2. The electrical baseband signal is divided three ways, attenuated, delayed, and recombined. The signal is then amplified to overcome losses due to the power divider and combiner. The tap weights c_0, c_1, and c_2 were manually adjustable attenuators with 1 dB resolution. The delays of one and two bit durations (T) were obtained by increased cable length (18 cm per T at 1.1 Gbps). As shown in Section III, with polarization dispersion, the tap weight c_1 has the opposite sign of the other weights, and therefore an inverting amplifier was used in the center tap.

III. RESULTS

Let us first consider the tap weights with polarization dispersion for the case of equal power in the two polarization modes (worst case), and delay τ less than T ($0 \leq \tau < T$). The optimum values for these weights depend on the sampling time of the threshold detector.[3] If the signal is sampled at the peak of the first output pulse, then, assuming the transmit pulse $p(t)$ is symmetrical ($p(t) = p(-t)$) and time limited ($p(t) = 0,\ |t| > T$), the kth signal sample is

$$s_k = b_k[p(0) + p(\tau)] + b_{k-1}p(T - \tau) \tag{1}$$

where b_k is the kth bit (0 or 1). Then the channel transfer function (in the z domain) is

$$H_c(z) = [p(0) + p(\tau)][1 + \alpha z^{-1}] \tag{2}$$

where

$$\alpha = \frac{p(T - \tau)}{p(0) + p(\tau)}. \tag{3}$$

The optimum (in terms of minimum intersymbol interference) transfer function for the analog tapped delay line equalizer is

$$H_{\mathrm{EQ}}(z) = \begin{cases} 1 - \alpha z^{-1} & 2-\mathrm{tap} \\ 1 - \alpha z^{-1} + \alpha^2 z^{-2} & 3-\mathrm{tap} \end{cases} \tag{4}$$

and the equalized transfer function is

$$H_c H_{\mathrm{EQ}} = \begin{cases} [p(0) + p(\tau)](1 - \alpha^2 z^{-2}) & 2-\mathrm{tap} \\ [p(0) + p(\tau)](1 + \alpha^3 z^{-3}) & 3-\mathrm{tap} \end{cases}. \tag{5}$$

Thus, the output signal-to-interference power ratio is reduced from α^{-2} to α^{-4} and α^{-6} for the two-tap and three-tap equalizers, respectively.[4]

With rounded transmit pulses, the optical power penalty for a 300 ps delay at 1.1 Gbps is approximately 0.4 dB [4], corresponding to $\alpha = 0.09$, or

$$H_c(z) = [p(0) + p(\tau)](1 + 0.09z^{-1}) \tag{6}$$

and a signal-to-interference power ratio S/I of 21 dB. Thus, for the equalizer of Fig. 2, $c_0 = 0$ dB and $c_1 = 11$ dB, or

$$H_{\mathrm{EQ}}(z) = 1 - 0.09z^{-1} \tag{7}$$

and

$$H_c H_{\mathrm{EQ}} = [p(0) + p(\tau)][1 - 0.0081z^{-2}]. \tag{8}$$

Thus, the output signal-to-interference power ratio is 42 dB. This is about the same as the maximum residual S/I caused by the 1 dB quantization of the tap weights and is too low to be noticeable either in terms BER degradation or eye closure on the oscilloscope.

Fig. 3 shows the eye with polarization dispersion before and after equalization. For the tap weight c_1, the optimum value was 11 dB as predicted. However, the decrease in eye opening with polarization dispersion (i.e., the increase with

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[3] The detector actually examines the signal over a short period of time rather than just at a single instant, which could slightly change the optimum tap weights from the values determined in this section. (However, an adaptive algorithm would find the correct values.)

[4] Note that the intersymbol interference is due to one previous bit. Thus, the dispersion compensation can also be done by a one-bit decision feedback equalizer or nonlinear canceler [4] that can be implemented on a single chip with the threshold detector.

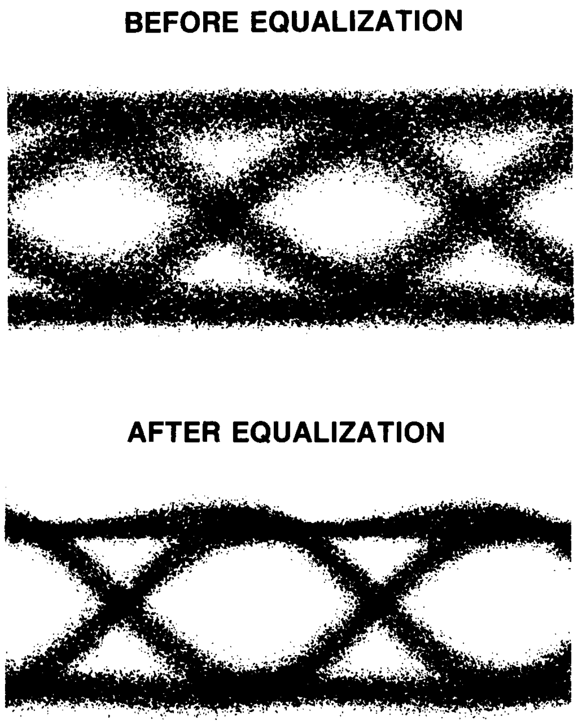

Fig. 3. The received signal eye with polarization dispersion before and after equalization.

equalization) is greater than predicted from (6) and (8). This is because pattern dependent noise was present in the transmitted signal (since the transmitter was ac coupled). That is, the transmit signal level for 1's and 0's varied up and down at a low frequency (up to 20 kHz). This noise increased the optical power penalty due to polarization dispersion from 0.4 dB to 3 dB (a $2^{23} - 1$ length pseudorandom sequence was used for the transmitted bits). Although the equalizer cannot remove the noise,[5] it can still equalize the polarization dispersion to the same extent as if this noise was not present. Thus, the equalizer removed the 3 dB optical power penalty, reducing the BER from (for one particular received power level) 10^{-6} to below 10^{-9}.

To demonstrate that a two-tap equalizer can increase the fiber length for a given penalty, we first increased the data rate to 1.4 Gbps in order to measure a 1 dB penalty with 600 m of fiber and a 2-tap equalizer ($c_1 = 8$ dB). We then removed the equalizer and shortened the fiber to 300 m to obtain the same 1 dB penalty, demonstrating that the two-tap equalizer doubled the length of the PM fiber for a 1 dB penalty. Note that since in SM fiber the delay varies with the square root of the length rather than linearly with the length (in PM fiber), this result indicates that a two-tap equalizer would quadruple the length of SM fiber for a 1 dB penalty.

Finally, we note that to be effective against polarization dispersion in single-mode fibers (where the dispersion varies slowly with time), the equalizer must be adaptive. Also, to compensate for dispersion that is much larger than that considered in this letter, a one bit decision feedback equalizer or nonlinear canceler may be required. Implementation of both these techniques is considered in [4].

IV. Conclusions

In this letter we have described the demonstration of the equalization of polarization dispersion in a direct-detection lightwave system at 1.1 Gbps. First-order polarization dispersion was equalized in the electrical signal at the receiver by a manually-adjustable, two-tap analog tapped delay line. This equalizer reduced the intersymbol interference due to polarization dispersion by more than 20 dB and decreased the error rate from 10^{-6} to below 10^{-9}.

Acknowledgment

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References

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[5] The effect of the noise can be eliminated by an adaptive threshold in the detector.