$\pi/2$ Alternate-Phase On–Off Keyed 42.7 Gb/s Long-Haul Transmission Over 1980 km of Standard Single-Mode Fiber

Douglas M. Gill, Alan H. Gnauck, Xiang Liu, Xing Wei, and Yikai Su

***Abstract*—The authors present 42.7-Gb/s return-to-zero on–off keying pulse-overlapped 1980-km transmission experiments on standard single-mode fiber, which compare the performances of the 33% duty-cycle $\pi/2$ alternate-phase format to the 33% duty-cycle return-to-zero and the 67% duty-cycle carrier-suppressed return-to-zero on–off keying formats. The results show that an effective reduction in nonlinear transmission penalty from intrachannel four-wave mixing can be achieved in systems where strong pulse overlap occurs. Experiments show an increased optimum launch power of 2 dB can be realized with the $\pi/2$ alternate-phase format resulting in a >3 dB improvement in Q as compared to the return-to-zero and carrier-suppressed return-to-zero formats due to a reduction in intrachannel four-wave mixing.**

***Index Terms*—Modulation coding, modulators, nonlinear distortion, optical fiber communication.**

I. INTRODUCTION

AMPLIFIER spontaneous emission noise and nonlinear transmission penalty are generally responsible for fundamentally limiting the reach of dense wavelength-division multiplexed (DWDM) optical transmission links. The major nonlinear penalties in 40-Gb/s pseudo-linear transmission result from intrachannel interactions such as intrachannel four-wave mixing (IFWM) [1]–[3] and intrachannel cross-phase modulation (IXPM). IXPM can be effectively suppressed by proper design of the transmission link dispersion map [4]; however, IFWM is still a source of limiting nonlinear impairment in highly pulse-overlapped long-haul high-bit-rate transmission, e.g., 40-Gb/s transmission over standard single mode fiber (SSMF) links with dispersion compensation spacing >80 km. This issue is of interest since the dominant worldwide installed fiber base is SSMF.

The dynamics of ghost pulse generation during pseudo-linear on–off keying (OOK) transmission through a dispersion-managed fiber link depend on many factors such as signal power, transmission distance, and dispersion map [3]. Previous work has found that the ghost pulse amplitude generally grows sublinearly within each span, although it grows almost linearly with the number of spans [3]. In addition, it has been shown that the relative initial phases of the interacting optical pulses within the transmission link have a significant impact on the growth dynamics of IFWM products [5].

Distortions in OOK transmission signals that result from IFWM include amplitude fluctuation in “1” bits and the generation of ghost pulses through energy transfer from “1s” to “0s”. Techniques to suppress IFWM have included the use of unequally spaced data pulses, which sacrifices some spectral efficiency [6], and the use of the duobinary and alternate mark inversion transmission formats [7], [8]. However, the duobinary and alternate mark inversion formats generally require additional electronic or optical hardware in the system transmitter.

The $\pi/2$ alternate-phase return-to-zero (AP RZ) OOK transmission format has also been proposed as a means to reduce IFWM in strongly pulse overlapped high-bit-rate fiber optic transmissions [9], [10]. To date, most of the published work proposing the use of $\pi/2$ AP RZ OOK has been theoretical and has implied that additional hardware such as a phase modulator or an optical time-domain multiplexer would be required in the transmitter to implement this format. To the best of our knowledge there have been two experimental reports of noncarrier-suppressed return-to-zero (CSRZ) AP RZ OOK formats [11], [12]. However, from the power spectra shown in these publications the $\pi/2$ AP RZ format does not seem to have been investigated and neither of these papers discussed IFWM. We have recently proposed a simple and cost effective way to implement a $\pi/2$ AP RZ format by reconfiguring the commonly used Mach–Zehnder modulator (MZM) pulse generator (PG) to provide both intensity and phase modulation in the resulting pulse train [13]; however, transmission experiments were not performed.

In the following, we present experimental results from $24\times \sim 80$ km transmission experiments on SSMF that demonstrate the impact the $\pi/2$ AP RZ OOK format can have on IFWM. This letter not only extends the work in [13] by presenting $\pi/2$ AP RZ OOK long-haul transmission but also shows that a significant increase in optimum system launch power and an improved required OSNR at the receiver can be realized as compared to the conventional return-to-zero (RZ) and CSRZ OOK transmission formats. Furthermore, we demonstrate a practical and effective method of implementing $\pi/2$ AP RZ OOK through a simple reconfiguration of a standard PG, although this technique does create a small amount of chirp on the signal. We also note that this technique can be

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D. M. Gill and X. Wei are with the Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974-0636 USA (e-mail: dmgill@lucent.com; xingwei@lucent.com).

A. H. Gnauck, X. Liu, and Y. Su are with Bell Laboratories, Lucent Technologies, Holmdel, NJ 07733-0400 USA (e-mail: gnauck@lucent.com; xliu20@lucent.com; yikaisu@lucent.com).

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used to create any desired phase shift between adjacent pulses in 33% or 67% duty cycle PGs [14].

II. EXPERIMENTAL SETUP

Transmission experiments at a bit rate of 42.7 Gb/s were performed on an SSMF recirculating loop that consisted of nominal 4×80-km fiber spans with 175-ps/nm residual dispersion per loop, which was evenly distributed amongst the four spans. The total loop distance was measured to be 330 km. A schematic diagram of the loop setup is shown in Fig. 1. The data was created by electronically multiplexing four copies of a 10.7-Gb/s pseudo-random bit sequence (PRBS) of length $2^{31}-1$, which were combined with a relative delay of 1/4 of the bit pattern so that the PRBS nature of the 42.7-Gb/s pattern was preserved. Experiments consisting of six loops were performed for a total transmission distance of 6×330 km with a carrier wavelength of 1551.72 nm. Span loss ranged from 16 to 18 dB (including the Raman wavelength division multiplexer) and was compensated with a combination of an erbium-doped fiber amplifier (EDFA) and a backward-pumped Raman amplifier with a 9.5 to 11 dB gain. A gain equalizing filter (GEF) was used to flatten the gain across the bandwidth of the channel and was also set to have a $\sim$3-nm pass-band to reduce amplified spontaneous emission noise build up. Dispersion precompensation of -500-ps/nm was used. Post-compensation after transmission was adjusted to minimize the bit-error rate (BER) at the output. The amount of dispersion precompensation was chosen to optimize the performance of RZ OOK transmission.

A polarization controller was used to minimize the polarization mode dispersion in the loop and EDFAs were used to maintain a good optical signal-to-noise ratio (OSNR) throughout the system. The polarization mode dispersion was carefully controlled to minimize its impact since we were specifically interested in IFWM effects in this letter. An arrayed waveguide grating with a 100-GHz channel spacing and 75-GHz band-pass (0.6-nm) was also used before the receiver. An optically preamplified receiver that had an EDFA with a noise figure of 4 dB was also used. In comparing transmission formats, the received optical power was maintained above -14 dBm; however, a variable optical attenuator was also used to allow us to load ASE noise onto the signal after transmission to investigate the received BER as a function of the OSNR. The signal was detected with a 35-GHz bandwidth photodiode used in conjunction with an electronic decision circuit. A 42.7-Gb/s clock recovery was used with an electronic demultiplexer to get a 10.7-Gb/s tributary that was used for measurements.

42.7-Gb/s RZ OOK transmission typically uses one modulator for pulse generation and a second for data encoding. A common transmitter configuration used to produce the 33% duty-cycle RZ and 67% duty-cycle CSRZ formats drives the PG MZM with a sinusoidal waveform at half the bit-rate frequency and twice its switching voltage (2^*V_π). The RZ or CSRZ format can be realized in this configuration by changing the dc bias on one arm of the PG MZM. The PG MZM can also be set up for $\pi/2$ AP RZ operation as has been described before [13]. The $\pi/2$ AP RZ MZM configuration results in a 33% duty-cycle intensity output from the MZM PG with a sinusoidal phase modulation at a frequency of half the pulse repetition rate such that a maximum relative phase shift of $\pi/2$ coincides with neighboring pulse intensity peaks within the pulse stream. For our experiments, we used a balanced dual drive MZM with a $\sim 120^\circ$ misalignment between the sinusoidal drive signals on each arm of the modulator, a drive frequency $f = 21.35$ GHz, and a drive voltage of 2.3^*V_π (a $\sim$15% drive voltage increase as compared to the RZ and CSRZ cases). The PG modulator V_π was $\sim$5 V at 1 GHz and had a bandwidth of $\sim$35 GHz. For comparison, we also created the $\pi/2$ AP RZ data stream by configuring the PG for an RZ output and using an additional phase modulator driven with a sinusoidal 21.35-GHz electrical drive to create the desired phase shifts in the transmitter. As

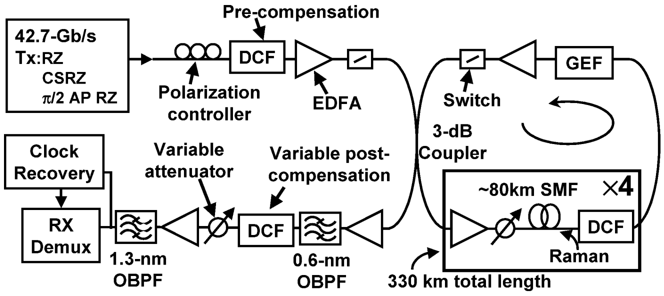

Fig. 1. Schematic diagram of the loop transmission system.

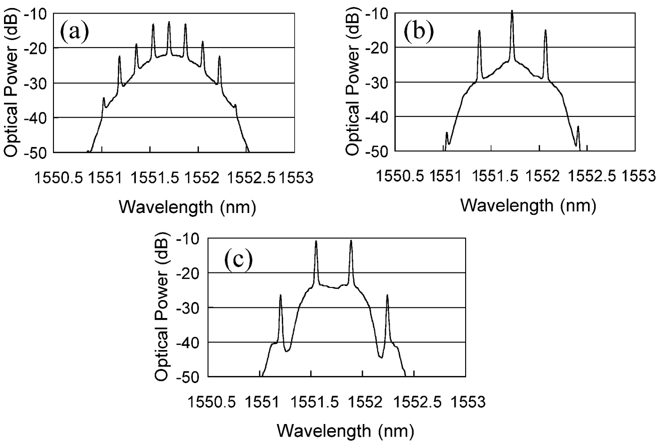

Fig. 2. Optical spectra of (a) 33% duty-cycle $\pi/2$ AP RZ, (b) 33% duty-cycle RZ, and (c) 67% duty-cycle CSRZ data streams.

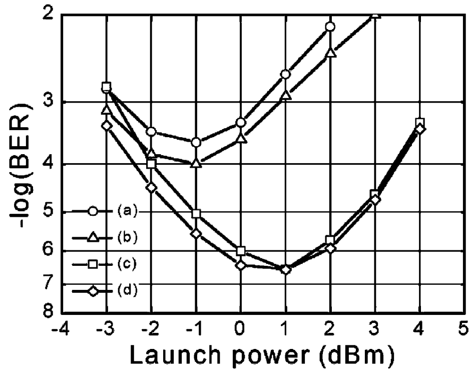

Fig. 3. BER as a function of launched power for (a) RZ, (b) CSRZ, (c) $\pi/2$ AP RZ (using an RZ PG followed by a phase modulator), and (d) $\pi/2$ AP RZ (using the $\pi/2$ AP RZ configured PG) OOK formats.

discussed in [13], the PGs were set up by monitoring their output optical spectra. Fig. 2 shows the optical spectra of the RZ, CSRZ, and $\pi/2$ AP RZ bit streams.

III. EXPERIMENTAL RESULTS

BERs after transmission as a function of launched optical power were measured for the three formats (Fig. 3). The optical launch power was adjusted by using variable optical attenuators before each span. Fig. 3 shows that the performance of the RZ and CSRZ formats are quite similar with an optimum launch power of ~ -1 dBm. However, the optimum launch power for the $\pi/2$ AP RZ format is $\sim$1 dBm, an increase of $\sim$2 dB in launch power. Furthermore, we note that in comparing the -1-dBm RZ and CSRZ BERs to the 1-dBm $\pi/2$ AP RZ BER we see an improvement in Q of >2 dB. This indicates that the $\pi/2$ AP RZ transmission incurs a slightly lower nonlinear penalty at 1 dBm than the RZ and CSRZ transmissions do at -1 dBm. These experimental results are in good agreement with simulations we have presented elsewhere [13]. Data from the two $\pi/2$ AP RZ transmitter designs tested are shown in Fig. 3, i.e., one design using the $\pi/2$ AP RZ configured PG and the other using a standard 33% duty-cycle RZ PG followed by a phase modulator. Both transmitter designs showed nearly identical behavior.

In addition, we measured the $\pi/2$ AP RZ BER as a function of received OSNR for a PRBS of $2^{31}-1$ and $2^{7}-1$ after transmission with a span launch power of 1 dBm (Fig. 4). The curves are nearly identical for the two pattern lengths, but do diverge very slightly below a BER of 1×10^{-5}. A BER dependence on pattern length is attributed to IFWM since increasing the pattern length introduces bit patterns that are more susceptible to ghost pulse formation. The lack of pattern length dependence seen with $\pi/2$ AP RZ OOK is a further indication that this format significantly reduces IFWM in this dispersion map.

IV. CONCLUSION

We have shown that the $\pi/2$ AP RZ transmission format can be effective in suppressing the detrimental effects of IFWM in highly overlapped pseudo-linear pulse transmission in SSMF. We find that the use of this format with our dispersion map in a 1980-km transmission gives an optimal span launch power that is 2 dB higher than that found for the RZ and CSRZ formats. In addition, the 2-dB higher launch power results in a >3-dB improvement in Q. Therefore, the $\pi/2$ AP RZ format not only allows a higher launch power to be used but also resulted in less signal distortion in our dispersion map than using lower launch powers with the RZ and CSRZ formats. This indicates that with the proper dispersion map the $\pi/2$ AP RZ format can increase transmission distance and/or system margin as compared to the RZ and CSRZ formats on SSMF.

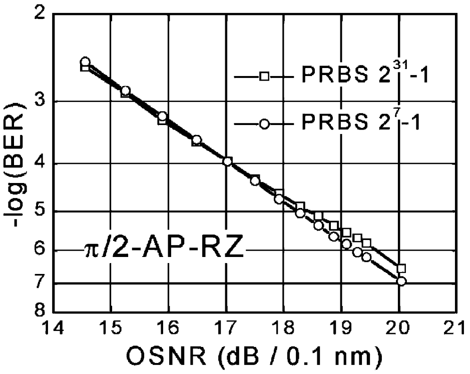

Fig. 4. BER versus OSNR after transmission for two different PRBS lengths.

REFERENCES

[1] P. V. Mamyshev and N. A. Mamysheva, "Pulse-overlapped dispersion-managed data transmission and intrachannel four-wave mixing," *Opt. Lett.*, vol. 24, pp. 1454–1456, 1999.
[2] R.-J. Essiambre, G. Raybon, and B. Mikkelsen, *Optical Fiber Telecommunications IV-B*. San Diego, CA: Academic, 2002, Pseudo-Linear Transmission of High-Speed Signals: 40 and 160 Gbit/s, ch. 6.
[3] A. Mecozzi, C. B. Clausen, and M. Shtaif, "Analysis of intrachanel nonnlinear effects in highly dispersed optical pulse transmission," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 392–394, 2000.
[4] R. I. Killey, H. J. Thiele, V. Mikhailov, and P. Bayvel, "Reduction of intrachannel nonlinear distortion in 40-Gbit/s-based WDM transmission over standard fiber," *IEEE Photon. Technol. Lett.*, vol. 12, pp. 1624–1626, 2000.
[5] X. Liu, X. Wei, A. Gnauck, C. Xu, and L. Wickham, "Suppression of intra-channel four-wave-mixing induced ghost pulses in high-speed transmissions by phase inversion between adjacent marker blocks," *Opt. Lett.*, vol. 27, pp. 1177–1179, 2002.
[6] S. Kumar, "Intrachannel four-wave mixing in dispersion managed RZ systems," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 800–802, 2001.
[7] K. S. Cheng and J. Conradi, "Reduction of pulse-to-pulse interaction using alternative RZ formats in 40-Gb/s systems," *IEEE Photon. Technol. Lett.*, vol. 14, pp. 98–100, 2002.
[8] Y. Miyamoto, A. Hiramno, K. Yonenaga, A. Sano, H.Hi Toba, K. Murata, and O. Mitomi, "320 Gbit/s WDM transmission over 367 km with 120 km repeater spacing using carrier-suppressed return-to-zero format," *Electron. Lett.*, vol. 35, pp. 2041–2042, 1999.
[9] P. Johannisson, D. Anderson, M. Marklund, A. Berntson, M. Forzati, and J. Martensson, "Suppression of nonlinear effects by phase alternation in strongly dispersion-managed optical transmission," *Opt. Lett.*, vol. 27, pp. 1073–1075, 2002.
[10] S.Sabastian Randel, B.Beate Konrad, A.Anes Hodzic, and K.Klaus Petermann, "Influence of bitwise phase changes on the performance of 160 Gbit/s transmission systems," in *Proc. ECOC2002*, 2002.
[11] R. Ohhira, D. Ogasahara, and T. Ono, "Novel RZ signal format with alternate-chirp for suppression of nonlinear degradation in 40 Gb/s based WDM," in *Proc. OFC2001*, 2001.
[12] I.Itsuro Morita and N.Noboru Edagawa, "Study in optimum OTDM signals for long-distance 40 Gbit/s transmission," in *Proc. OFC2002*, 2002, pp. 5–6.
[13] D. M. Gill, X. Liu, X. Wei, S. Banerjee, and Y. Su, "$\pi/2$ alternate-phase on-off keyed 40 Gb/s transmission on standard single mode fiber," *IEEE Photon. Technol. Lett.*, Dec. 2003.
[14] C. Dorrer, P. J. Winzer, R.-J. Essiambre, and I. Kang, "Validation of a simple, tunable-chirp 40-Gb/s RZ pulse carver using full optical field characterization," *Proc. OFC*, 2003.