Study of System Performance in a 107-km Dispersion-Managed Recirculating Loop Due to Polarization Effects

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***Abstract*—We investigate the polarization evolution for both signal and noise in two 107-km recirculating loops with polarization-dependent loss per round-trip of 0.35 dB and less than 0.1 dB, respectively. When the system is optimized, in the first case, both signal and noise are polarized, while in the second case, the signal tends to depolarize due to the noise. We experimentally measured and theoretically simulated the Q factor distribution, which is far from what is expected for straight-line systems, after 5000 km in the second case. We also suggest a simple method for obtaining the same Q distribution in recirculating loop experiments as expected in straight-line experiments.**

***Index Terms*—Dispersion management, fiber transmission systems, optical polarization, polarization dependent gain, polarization dependent loss.**

I. Introduction

POLARIZATION effects can have a significant impact on long-haul high-bit-rate optical communication systems. Polarization-dependent loss (PDL) and gain (PDG) were considered in [1], [2] and were shown to have a strong influence on optical long-haul transmission systems. Recirculating loops have proven to be an effective and inexpensive experimental model of long-haul transmission systems. There have been relatively few published studies on the polarization effects in such loops and the differences between these loops and straight-line systems. In this letter, we investigate the polarization evolution in two recirculating loops, one with a measured $\mathrm{PDL} = 0.35$ dB per round-trip and another one with a PDL less than 0.1 dB per round-trip, respectively. We also present a theoretical and experimental study of the Q distribution in the second recirculating fiber loop. The Q distribution of the recirculating loop is far from that expected for a randomized straight-line system due to the quasi-static nature of the loop. PDL and PDG parameters for our loop were determined. Our work suggests an experimental procedure for making the Q distribution in these types of loops approximate a more realistic distribution expected in straight-line systems.

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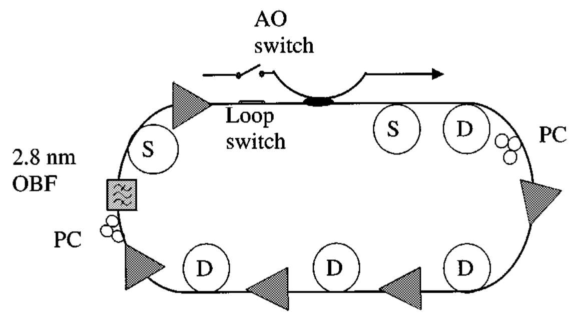

Fig. 1. The configuration of the 107-km recirculating loop. S indicates 3.5-km single-mode fiber and D indicates 25-km dispersion-shifted fiber.

II. Study of the Polarization Evolution

Fig. 1 shows a schematic of the recirculating loops used in these experiments. The loops are configured with a dispersion map with 100 km of fiber, $D = -1$ ps/nm·km, followed by ≈7 km of fiber, which has $D = 17$ ps/nm·km. This configuration has been used to study the communication performance of dispersion-managed solitons at 10 and 20 Gb/s over distances of 20 000 km [3], [4]. Four erbium-doped fiber amplifiers (EDFAs) are equally spaced to compensate for fiber loss and a fifth EDFA is used to overcome the loss of the loop switch and coupler. The isolators in these EDFAs are the primary source of the PDL in our loop.

For the first set of experiments reported here, we used mechanical polarization controllers in the loop to vary the state of the polarization. To estimate the PDL in the loop, we bypassed the loop switch and coupler, producing a 107-km straight line. Our measurements gave a net PDL for the entire loop ≈0.35 dB. Using [5], we estimated the PDG per amplifier to be ≈0.05 dB. In the recirculating configuration, we propagated 10 Gb/s return-to-zero (RZ) pulses modulated by a $2^{15} - 1$ PRBS pattern over 20 000 km error free by adjusting the polarization controllers inside the loop. In this configuration, the pulses propagated as dispersion-managed solitons in a single channel at a wavelength of 1551 nm with a launch power of 0 dBm. We used a commercial polarization analyzer to measure the degree of polarization (DOP) of the entire channel as a function of propagation distance. Fig. 2(a) shows the results for the data

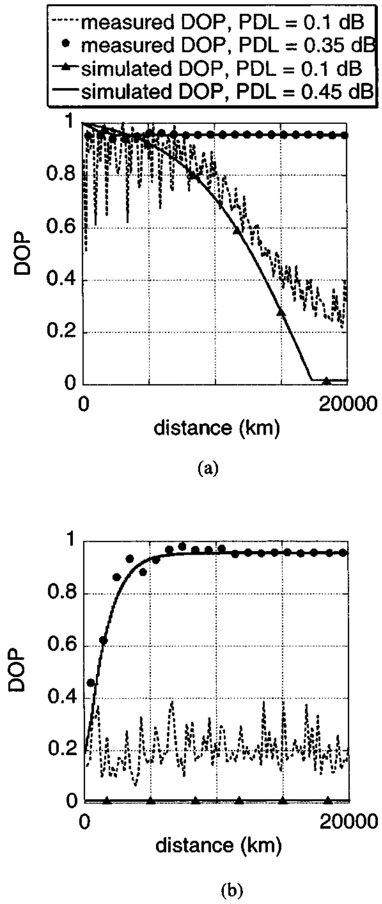

Fig. 2. Theoretical and experimental comparison of the DOP evolution as a function of propagation distance. (a) Measured and simulated DOP evolutions of signal plus noise under the circumstance that the highest SNR is obtained. (b) The DOP evolution of noise under the same circumstance as (a).

stream, which consists of both the signal plus the noise when the bit-error rate (BER) is less than 10^{-9} at 20 000 km. In Fig. 2(b), we show the DOP of noise without signal propagating in the loop with the same experimental condition as in Fig. 2(a). Due to PDL inside the system, the signal and noise become highly polarized as a function of propagation distance.

Then, we reduced the PDL in the system by using isolators in the EDFAs with $\mathrm{PDL} < 0.1$ dB and repeated the experiment described before. The net PDL in this system was less than 0.1 dB and we achieved error free transmission at 17 000 km. The DOP evolution as a function of propagation distance is shown in Fig. 2. Due to the low PDL, the signal plus noise, Fig. 2(a), are depolarized as a function of propagation distance, while noise, Fig. 2(b), remains unpolarized in contrast to the system that we described before. The residual DOP in Fig. 2(b) is due to the polarization dependence of the acoustic-optic switches in the system.

We used the approach described in [6] to model the polarization evolution in our system. The loop polarization configuration remains stable for the duration of the DOP measurements. Because the loop is static, we lumped all of the PDL in this loop into a single element in our model. The 107-km loop is subdivided into 1-km sections with a random rotation between each section. We kept the same set of rotations for each subsequent round-trip in our simulated loop. A different set of rotations leads to a different polarization evolution. The signal-to-noise ratio (SNR) was calculated after 5000 km for every set of rotations. Noise is added at each amplifier and results in the SNR decrease with propagation distance since the amplifiers are saturated. The DOP evolution as a function of propagation distance was determined for the highest SNR. As shown in Fig. 2(a), when we chose the lumped $\mathrm{PDL} = 0.45$ and 0.1 dB, respectively, the theoretical and experimental results are in good agreement taking into account that in the straight-line measurements on the 107-km length, the loop switch and coupler were bypassed. Note that the low PDL case becomes depolarized more quickly in Fig. 2(a), because the polarization component of the noise orthogonal to the signal also accumulates in addition to the parallel component while in the high PDL case only the polarization component of the noise parallel to the signal accumulates.

The experimental and theoretical results show that PDL plays a major role in the loop performance. In recirculating loop systems, by optimizing the polarization evolutions, large values of PDL will help to improve the performance by suppressing the noise orthogonal to the signal.

III. Study of the Q Distribution

In subsequent experiments, we measured the Q, defined as $Q = (\langle I_1\rangle - \langle I_0\rangle)/(\sigma_1 + \sigma_0)$, where $\langle I_1\rangle$ and $\langle I_0\rangle$ correspond to the mean values of the mark and space powers, and σ_1 and σ_0 correspond to the standard deviations, at a propagation distance of 5000 km, when the net PDL in the system was less than 0.1 dB. We gated the trigger of a sampling oscilloscope to measure the Q at this specific propagation distance. We then mechanically varied one polarization controller in the loop (shown in Fig. 1). We measured the Q value at each adjustment of the polarization controller. This process was repeated until the adjustment of the polarization controller gave an even coverage on the Poncairé sphere. Except for the polarization controller, the rest of the loop remained in a quasi-static orientation. The measured result is shown in Fig. 3. Instead of a Gaussian-like distribution expected in a straight-line system, the Q distribution of the loop has two peaks.

We then used our model to calculate the theoretical Q again using the lumped PDL and PDG values obtained from the DOP measurements. We kept the same set of rotations for each circulation of the light in the loop since our loop is quasi-static. We calculated the Q at 5000 km. We then added one random rotation just before the lumped PDL element and then recalculated the Q at a distance of 5000 km. This extra random rotation simulates our mechanical adjustment of the polarization controller. After changing the extra random rotation 10 000 times, we obtained a theoretical Q distribution. Fig. 3 shows the experimental and theoretical Q distributions. What is striking about these distributions is that they are double-peaked due to the PDL. This fact is a dramatic indication that optimizing the polarization in the loop to give a large Q value does not give a complete picture of what would happen in a truly random straight-line experiment over long distances where the Q distribution would be Gaussian.

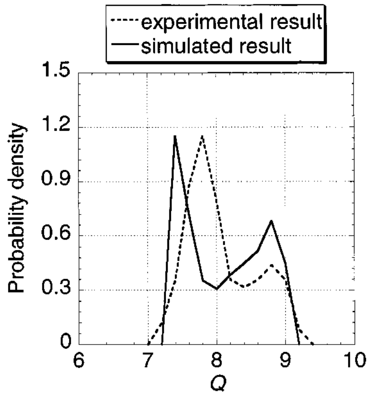

Fig. 3. Comparison of the measured Q distribution of a 107-km loop after the signals propagate 5000 km and the simulated Q distribution for a 100-km loop.

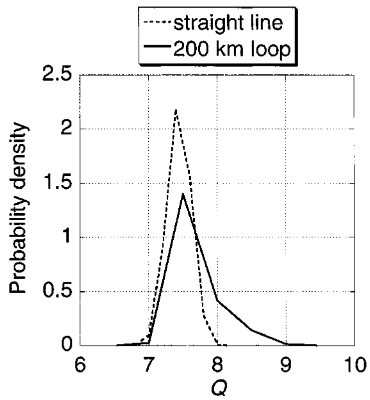

Fig. 4. Comparison of simulated Q distributions for a 200-km loop after signals propagate 5000 km and a 5000-km straight-line system.

In Fig. 4, we show a simulated straight-line experiment. The straight line consisted of EDFAs spaced every 25 km with the same noise output and PDG as in our experimental EDFAs. Every 100 km in the loop, we placed a lumped PDL element with the value of the $\mathrm{PDL} = 0.1$ dB. The total length of the straight line was 5000 km. We still kept 1 km per step and applied a different random rotation in every step. Fig. 4 simulated the Q distribution is a Gaussian distribution.

Lengthening the loop does not necessarily make the Q distribution more like a Gaussian. In fact, if one lengthens the loop and neglects the PDG, one will obtain the same shape of the Q distribution as shown in Fig. 3 as long as the fibers in the loop remain fixed. We theoretically illustrate a solution to this problem by doubling the loop to 200 km with two lumped PDL elements separated by 100 km each with $\mathrm{PDL} = 0.1$ dB. This simulated loop consisted of eight equally spaced EDFAs each with $\mathrm{PDG} = 0.05$ dB. We added an extra random rotation at one point in the loop between the PDL elements. A new random rotation was chosen for each circulation. Fig. 4 shows the theoretical Q distribution for 5000 km for such a loop. While it is not Gaussian, it is a lot closer than the distribution shown in Fig. 3. Thus, even a relatively short loop can approximate a straight-line random Q distribution. Clearly the "memory" of each round-trip illustrated in Fig. 3 is largely removed in Fig. 4. Since the propagation time through one circulation in a 200-km loop is approximately 1 ms, to achieve the Q distribution in Fig. 4 one can realize a random rotation per round-trip using a mechanical polarization scrambler with a frequency response ≥ 1 kHz (several such devices are commercially available) at one point in the loop.

IV. Conclusion

Our experimental and theoretical results show clearly in this letter that due to the static nature of recirculating loop, polarization effects, especially PDL and PDG, will cause different polarization evolution and different Q distribution from straight-line systems. Optimizing the polarization in the loop to give a good system performance does not give a complete picture of what would happen in a truly random straight-line experiment over long distances. In our study, we also suggest an experimental procedure to achieve more realistic system performance in recirculating loop systems.

References

[1] E. Lichtmann, "Limitations imposed by polarization-dependent gain and loss on all-optical ultralong communication systems," *J. Lightwave Technol.*, vol. 13, pp. 906–913, May 1995.

[2] ——, "Performance degradation due to polarization dependent gain and loss in lightwave systems with optical amplifiers," *Electron. Lett.*, vol. 29, pp. 1969–1971, Oct. 1993.

[3] J. M. Jacob and G. M. Carter, "Error-free transmission of dispersion-managed solitons at 10 Gbit/s over 24 500 km without frequency sliding," *Electron. Lett.*, vol. 33, pp. 1128–1129, Dec. 1997.

[4] G. M. Carter, R. M. Mu, V. S. Grigoryan, C. R. Menyuk, P. Sinha, T. F. Carruthers, M. L. Dennis, and I. N. Duling, III, "Transmission of dispersion-managed solitons at 20 Gbit/s over 20 000 km," *Electron. Lett.*, vol. 35, pp. 233–234, Feb. 1999.

[5] V. J. Mazurczyk and J. L. Zyskind, "Polarization dependent gain in erbium doped fiber amplifiers," *IEEE Photon. Technol. Lett.*, vol. 6, pp. 616–618, May 1994.

[6] D. Wang and C. R. Menyuk, "Reduced model of the evolution of the polarization states in wavelength-division-multiplexed channels," *Opt. Lett.*, vol. 23, pp. 1677–1679, Nov. 1998.