A novel scheme for achieving quasi-uniform rate polarization scrambling at 752 krad/s

Leon Yao,[1,*] Hao Huang,[1] James Chen,[2] Ernie Tan,[2] and Alan Willner[1]

[1]*Department of Electrical Engineering, University of Southern California, Los Angeles, California 90089, USA*
[2]*General Photonics Corporation, Chino CA 91710, USA*
[*]*leonxyao@gmail.com*

Abstract: We propose and demonstrate a novel scheme for obtaining quasi-uniform rate polarization scrambling at up to 752 krad/s in fiber optic systems by using cascaded multiple fiber squeezers with each one placed in a certain orientation. Additionally, this polarization scrambler is compatible with both single-polarization and polarization-multiplexing systems. We also show that scrambled SOP with this scheme uniformly covers the whole Poincare Sphere and that the scrambling rates are mostly concentrated towards the high end of the rate distribution histogram. Such a scrambling scheme is advantageous for the deterministic characterization of performances for modern fiber optic transceivers, especially those deploying coherent detection techniques, against rapid polarization variations.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.2340) Fiber optics components; (060.1660) Coherent communications.

References and links

1. M. G. Taylor, "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments," IEEE Photon. Technol. Lett. **16**(2), 674–676 (2004).
2. F. Derr, "Coherent optical QPSK intradyne system: concept and digital receiver realization," J. Lightwave Technol. **10**(9), 1290–1296 (1992).
3. E. Ip, A. P. Lau, D. J. Barros, and J. M. Kahn, "Coherent detection in optical fiber systems," Opt. Express **16**(2), 753–791 (2008).
4. J. Zyskind, R. Barry, G. Pendock, M. Cahill, and J. Ranka, "High-capacity, ultra-long haul networks," Ch. 5, in *Optical Fiber Telecommunication IVB, Systems and Impairments*, eds. I. Kaminow and T. Li (Academic Press, San Diego, 2002).
5. H. Kogelnik, R. Jopson, and L. Nelson, "Polarization mode-dispersion," in *Optical Fiber Telecommunication IVB, Systems and Impairments*, eds. I. Kaminow and T. Li, (Academic Press, San Diego, 2002) chap. 15.
6. P. M. Krummrich and K. Kotten, "Extremely fast (microsecond scale) polarization changes in high speed long hail WDM transmission systems," in Proc. OFC 2004, paper FI3.
7. D. L. Peterson, P. J. Leo, and K. B. Rochford, "Field measurements of state of polarization and PMD from a tier-1 carrier," Proc. OFC 2004, paper FI1.
8. M. Boroditsky, M. Brodsky, N. J. Frigo, P. Magill, and H. Rosenfeldt, "Polarization dynamics in installed fiber optic systems," Proc. LEOS 2005, paper TuCC1.
9. P. J. Leo, G. R. Gray, G. J. Simer, and K. B. Rochford, "State of polarization changes: classification and measurement," J. Lightwave Technol. **21**(10), 2189–2193 (2003).
10. P. M. Krummrich, E.-D. Schmidt, W. Weiershausen, and A. Mattheus, "Field trial on statistics of fast polarization changes in long haul WDM transmission systems," in Proc. OFC 2005, paper OThT6.
11. L. Yan, Q. Yu, and A. E. Willner, "Uniformly distributed states of polarization on the Poincare Sphere using an improved polarization scrambling scheme," Opt. Commun. **249**(1-3), 43–50 (2005).
12. Y. K. Lize, R. Gomma, R. Kashyap, L. Palmer, and A. E. Willner, "Fast all-fiber polarization scrambling using re-entrant Lefevre controller," Opt. Commun. **279**(1), 50–52 (2007).
13. B. Koch, R. Noé, V. Mirvoda, and D. Sandel, "100-krad/s endless polarisation tracking with miniaturised module card," Electron. Lett. **47**(14), 813–814 (2011).
14. http://www.novoptel.de/Scrambling/EPS1000_flyer.pdf
15. A. Hidayat, B. Koch, H. Zhang, V. Mirvoda, M. Lichtinger, D. Sandel, and R. Noé, "High-speed endless optical polarization stabilization using calibrated waveplates and field-programmable gate array-based digital controller," Opt. Express **16**(23), 18984–18991 (2008).
16. S. Yao, "Polarization in fiber systems: squeezing out more bandwidth," in *The Photonics Handbook* (Laurin Publishing, Pittsfield, MA 2004).

Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

17. R. Noe, H. Heidrich, and D. Hoffmann, "Endless polarization control systems for coherent optics," J. Lightwave Technol. **6**(7), 1199–1208 (1988).
18. W. H. J. Aarts and G. Khoe, "New endless polarization control method using three fiber squeezers," J. Lightwave Technol. **7**(7), 1033–1043 (1989).
19. E. Collett, *Polarized Light in Fiber Optics* (PolaWave Group, Lincroft, New Jersey, 2003).
20. A. M. Smith, "Single-mode fibre pressure sensitivity," Electron. Lett. **16**(20), 773–774 (1980).
21. M. Martinelli, P. Martelli, and S. M. Pietralunga, "Polarization stabilization in optical communications Systems," J. Lightwave Technol. **24**(11), 4172–4183 (2006).
22. http://www.generalphotonics.com/pdf/FAQPolariteII.pdf

1. Introduction

As the appetite for bandwidth continues to sky rocket, polarization multiplex and coherent detection [1–3] are being used for increasing the transmission speed to reach 100 Gbit/s and beyond. As a result, polarization issues, i.e., time-varying polarization mode dispersion (PMD), polarization dependent loss (PDL), and state of polarization (SOP) become increasingly critical for an optical fiber communication system [4, 5]. Therefore, performance tests of a system against these polarization-related parameters are extremely important for assuring the healthy operation of high speed fiber optic communication systems. As such, a polarization scrambling device for changing SOP at an adjustable rate to reach all possible SOP is required to test the performance of the systems against rapid SOP variations. It has been reported that SOP changing rate in a real fiber optic system can be as high as 280 krad/s [6]. Therefore for testing the performance of coherent detection systems, a polarization scrambling scheme must be able to generate SOP changes faster than this rate. On the other hand, for the deterministic test of the polarization response of coherent receivers, a uniform rate polarization scrambling is desired, because non-uniform rate polarization scrambling introduces large test uncertainty and less test repeatability.

Present adjustable-rate polarization scramblers are generally made with different types of polarization controllers and are programmed so that SOP traces uniformly cover the whole Poincare Sphere. Some polarization scramblers are made with a SOP changing rate following Rayleigh Distribution [7], mainly for emulating SOP variations in a real fiber optic transmission system for statistical system testing [8–10]. Other scramblers are made to change SOP as fast and randomly as possible for mitigating polarization related transmission impairments, with unspecified scrambling rate distributions [11, 12]. Some literatures suggested that polarization scramblers using $LiNbO_3$ based rotating wave plate approach can simultaneously satisfy both the uniform rate and high scrambling speed requirements, up to 10 Mrad/s [13, 14], however no detailed discussion on rate distribution was reported. In addition, it is preferable to find an alternative technology to $LiNbO_3$ waveguide [15] for fast scrambling applications to avoid the disadvantages of high cost, high insertion loss, high PDL associated with $LiNbO_3$ approach.

In this paper, we propose and demonstrate a novel scheme to uniformly scramble polarization at a quasi-uniform rate using multiple variable phase retarders, such as fiber squeezers [16–19], with low cost, low insertion loss, and low PDL. To overcome the speed limitation of the fiber squeezers, we additionally propose and demonstrate an approach to effectively multiply the scrambling rate by cascading multiple fiber squeezers in series. Finally, by combining the quasi-uniform rate scheme with the rate multiplication method, we achieve polarization scrambling at an adjustable quasi-uniform rate of up to 752 krad/s. The method is polarization insensitive, wavelength insensitive, and scalable to even higher scrambling rates by adding more squeezers. Such a polarization scrambling scheme is attractive for testing the performance of coherent detection systems and coherent receivers against rapid polarization variations.

2. Concept and principle of operation

2.1 Device construction

Polarization scrambling is generally realized by programming a polarization controller with a certain control algorithm such that the output SOP changes with time and distributed uniformly over the whole Poincare Sphere. Although high-cost $LiNbO_3$ waveguide based polarization controller [15] has the advantage of high speed, in this paper, we concentrate on using low-cost fiber squeezers [16–19] to realize polarization scrambling with adequate speed and uniform rate for testing the performance of coherent receivers.

The propose polarization scrambler and the experimental demonstration setup is shown in Fig. 1, where multiple fiber squeezers are cascaded in series. Each squeezer is driven by an amplified electrical control signal. The first three fiber squeezers are oriented 45 degrees from one another, and the last three fiber squeezers have the same orientation as the third squeezer for overcoming the speed limitation of the fiber squeezers, as will be explained below.

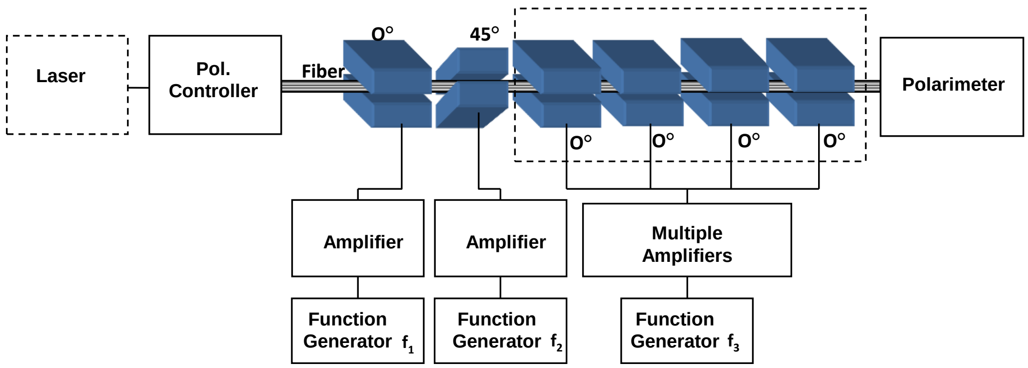

Fig. 1. Fiber squeezer arrangement and experiment setup for demonstrating different scrambling approaches. The first three fiber squeezers are oriented 45 degrees from one another and the last three are oriented the same as the third squeezer. The polarization controller in front of the fiber squeezers is for adjusting the input SOP into the fiber squeezers, and the polarimeter is for observing SOP changes on a Poincare Sphere.

2.2 Simulation program

In order to quickly verify the feasibility of new polarization scrambling ideas and learn how different parameters affect scrambling, it is necessary to simulate how SOP varies when a specific scrambling scheme is applied to the fiber squeezers in Fig. 1. We developed a Labview based simulation program to calculate SOP variations caused by N fiber squeezers of different orientations when they are driven by N electrical signals of different waveform, frequencies, and amplitude, and display SOP traces on Poincare Sphere. In addition, the program can calculate the SOP variation rate and plot the rate distribution histogram. Moreover, the time or point averaged DOP can also be obtained with the program to reflect SOP coverage uniformity of a particular scrambling scheme [11].

In the simulation program, the i^{th} fiber squeezer wave plate is represented by a Mueller Matrix [19]:

$$\tilde{M}_i = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\theta_i \sin^2\phi_i/2 + \cos^2\phi_i/2 & \sin 4\theta_i \sin^2\phi_i/2 & 0 \\ 0 & \sin 4\theta_i \sin^2\phi_i/2 & -\cos 4\theta_i \sin^2\phi_i/2 + \cos^2\phi_i/2 & -\cos 2\theta_i \sin\phi_i \\ 0 & 0 & \cos 2\theta_i \sin\phi_i & \cos\phi_i \end{pmatrix} \quad (1)$$

where θ_i is the orientation angle and ϕ_i is the retardation of the fiber squeezer. The Stokes vector $\vec{S}_i$ of the output SOP from the i^{th} fiber squeezer is obtained by multiplying its Muller matrix $\tilde{M}_i$ with the previous Stokes vector $\vec{S}_{i-1}$:

$$\vec{S}_i = \tilde{M}_i\,\vec{S}_{i-1} \quad (2)$$

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

The SOP variation rate is obtained by first calculating the angle between two consecutive points $\vec{S}_m$ and $\vec{S}_n$ on the SOP trace using:

$$\cos\theta_{mn} = \vec{S}_m \bullet \vec{S}_n \big/ |S_m||S_n|, \tag{3}$$

where $\vec{S}_m \bullet \vec{S}_n$ is the dot product of the two SOP vectors; and dividing the angle by the time interval between the two points. The rate distribution can be obtained by calculating all the rates between two adjacent SOP points and displaying them on a histogram.

Finally, the averaged DOP of the scrambled polarization can be calculated using

$$<DOP> = \sqrt{<S_1>^2 + <S_2>^2 + <S_3>^2} \big/ S_o \tag{4}$$

where < > denotes for either time or point average. With this simulation program, we can easily analyze scrambling schemes with different combinations of driving frequencies and determine which scheme has the required SOP coverage uniformity and scrambling rate distribution.

2.3 SOP changes induced by fiber squeezers

The retardation of each fiber squeezer is varied linearly by applying a driving voltage to the piezo-electric actuator on the fiber squeezer [20]. As the retardation is varied from 0 to 2π, the output SOP from the fiber squeezer traces out a complete circle on the Poincare Sphere [17–19]. The radius of the circle depends on the angle between the input SOP with respect to birefringence axis of the variable phase plate, i.e., 45 degree angle results in the largest circle on the Sphere while a small or large angle produces small SOP changes and hence small radius, as shown in Fig. 2. In addition, for a given retardation variation of the fiber squeezer, the SOP variation rate is proportional to the radius of curvature of the SOP trace. The largest radius of curvature produces the largest rate of SOP variation for a given retardation variation.

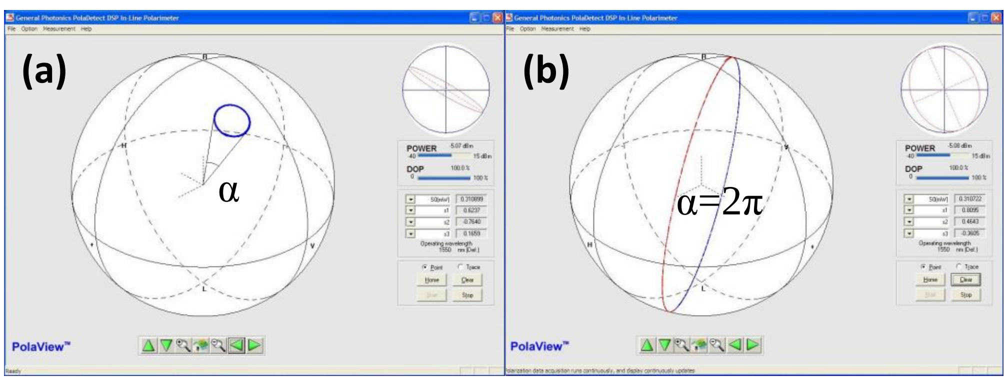

Fig. 2. (a) When SOP traces out a small circle on Poincare Sphere, the SOP variation angle α is small (a small fraction of 2π) and so is the SOP changing rate; (b) when SOP trace out a great circle on Poincare Sphere, corresponding to the case that input SOP to the wave plate is 45 degree from its birefringence axis, the angular change per circle reaches its largest value of 2π. The corresponding SOP changing rate is also maximized. In general, for a given retardation variation, the smaller the radius of curvature of the SOP trace, the smaller the rate of SOP variation.

Two circular traces generated by two adjacent fiber squeezers with a relative orientation of 45 degrees are orthogonal from each other. It can be shown that at least three fiber squeezers are required to generate SOPs to cover the whole Poincare Sphere from any input SOP [17–19]. To program the fiber squeezers for effective polarization scrambling, four parameters on the driving signals can be selected: waveform, frequency, amplitude, and phase. The most

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

important considerations of a polarization scrambling scheme include: 1) SOP coverage uniformity, 2) maximum scrambling rate, and 3) scrambling rate distribution.

3. Experimental results

SOP coverage uniformity describes how uniform SOPs are distributed on Poincare Sphere after a certain time, and is generally characterized by observing SOP distribution on Poincare Sphere and average DOP over time or over SOP points [6]. The point-averaged degree of polarization (DOP) is a good indicator for uniform SOP coverage, i.e., the smaller the averaged DOP, the better the SOP uniformity is. In particular, if the scrambled SOP can reach the entire sphere with equal probability, the averaged DOP will be zero.

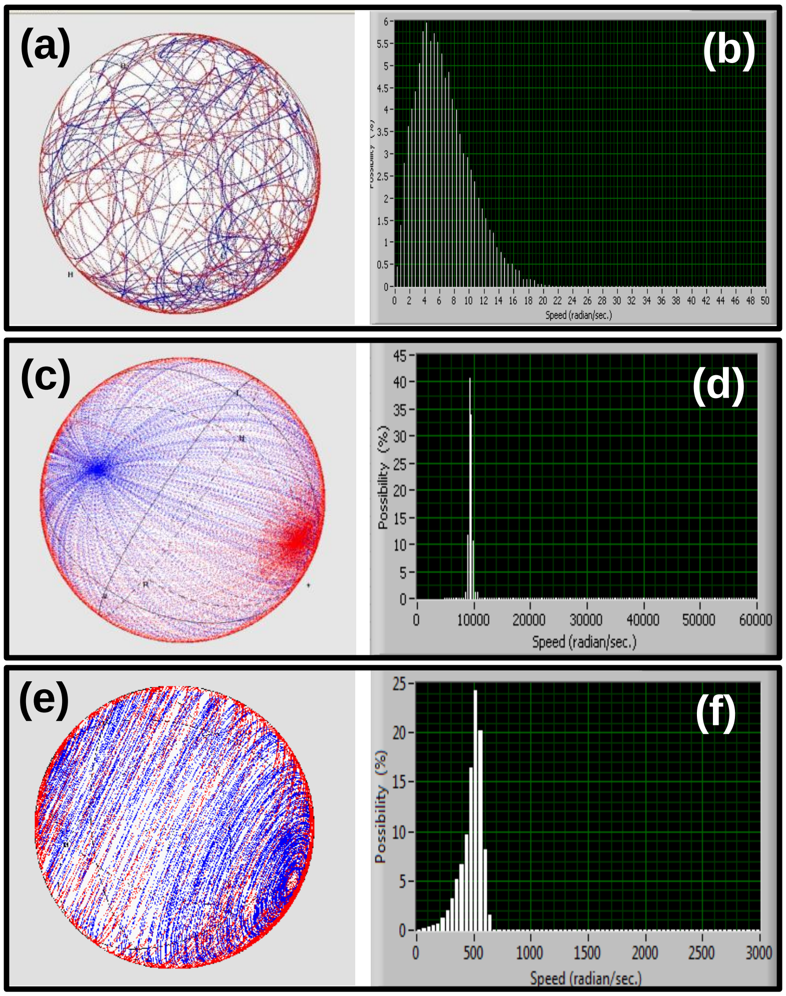

Fig. 3. (a) Illustration of random SOP variation of a conventional scrambling scheme; (b) The corresponding SOP variation rate histogram following Rayleigh distribution; (c) Measured SOP trace of the uniform rate scrambling approach, where the trace evolves like a circle spinning around a diametric axis; (d) Polarization scrambling rate histogram showing a single scrambling rate; (e) Measured SOP trace of the quasi-uniform rate scrambling approach. SOP rotates around Poincare Sphere at a high speed to form a circle, which moves back and forth along the rotation axis of the circles to cover the whole sphere. (f) Polarization scrambling rate histogram showing a quasi-uniform scrambling rate.

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

3.1 Conventional polarization scrambling

Conventional polarization scramblers make the SOP trace move randomly on Poincare Sphere with time and covers the whole sphere uniformly, as shown in Fig. 3(a). However, because of the randomly varying trace, the corresponding radius of curvature of the SOP trace also changes randomly, resulting in a wide spread of SOP variation rates, as shown in Fig. 3(b). As mentioned previously, such a wide rate distribution is not desirable for testing the polarization response of a system due to the lack of repeatability.

3.2 Uniform rate scrambling

One simple method to achieve uniform rate polarization scrambling is only using the first two fiber squeezers in Fig. 1. The input SOP has to be aligned to 45 degrees from the first fiber squeezer. Both the first and the second squeezers are modulated by a triangle wave with an amplitude of $2V_\pi$ (2π phase retardation). However, the frequency of the driving signal on the first squeezer (f_1) is much higher than that on the second (f_2). In this way, the first squeezer causes the SOP go around the Poincare Sphere in a great circle at a high speed, while the second squeezer rotates the great circle in one of its diametric axis, as shown in Fig. 3(c), to cover the whole sphere completely and uniformly (a video showing the SOP evolution during the scrambling can be seen at http://www.youtube.com/watch?v=SIdA2en4-lc). In the experiment, the two driving frequencies are f_1 = 180 Hz and f_2 = 1.1459 Hz. The scrambling rate using this approach is uniform, as shown in Fig. 3(d), because SOP always moves around the great circles of equal radius. The small rate spread is cause by limited sampling point in the polarimeter. The measured 10000- point averaged DOP is about 6.8%, indicating a uniform SOP coverage over entire Poincare Sphere is achieved. The non-zero DOP is obtained here due to the high sensitivity to the input polarization as it is difficult to align the input SOP at perfect 45 degrees from the first fiber squeezer. Even low DOP is expected to be achieved with a better alignment of the input SOP. The experimental results in Fig. 3(c) and Fig. 3(d) also agree with the simulation results by using our Labview program under the same driving conditions.

Although the uniform rate polarization scrambling can be achieved, this method requires that the SOP of the input optical signal has to maintain 45 degree with the first fiber squeezer. However, the SOP in a real fiber system is not stationary and varies with time. Therefore, in order to keep the SOP input to the first fiber squeezer at 45 degrees, a polarization stabilizer must be used. As we know that a polarization stabilizer generally uses a polarizer or polarization beam splitter to derive a feedback signal for polarization stabilization [15, 17, 18, 21]) and therefore only one polarization state is supported. This not only adds cost, but also causes problems with polarization multiplexed signals in most coherent systems.

3.3 Quasi-uniform rate scrambling

In order to overcome the problems described above, we propose a new method of polarization scrambling with a nearly uniform rate. The new scheme requires at least three variable phase retarders oriented 45 degrees from one another, as shown in Fig. 1. The first two squeezers are driven by two triangle waves of different frequencies but with the same amplitude of $2V\pi$. The 3rd squeezer, oriented 45 degrees from the 2nd one, is driven by a triangle wave of the same amplitude, but a much higher frequency than these of first two squeezers. The frequency relationships of the driving signals on the three squeezers are: $f_3 >> f_2 >> f_1$ (or $f_3 >> f_1 >> f_2$).

One may visualize that the first two squeezers cause SOP to vary along certain paths on Poincare Sphere in the absence of the 3rd squeezer. With the 3rd squeezer driving at much higher rate, each SOP point generated by the first two squeezers becomes the starting point for a complete SOP circle. All the circles have the same rotation axis, but different diameters. The circle moves back and forth along circle's axis as the SOP changes by the action of the first two squeezers, and eventually covers the whole Poincare Sphere.

Figure 3(e) shows the experimental result of SOP coverage using the quasi-uniform rate scrambling (a video showing the SOP evolution during the scrambling can be seen at

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

http://www.youtube.com/watch?v=aiO0wVgyKzY). The evolution of the SOP trace with time agrees with our reasoning and simulation described above. The three driving signals are all triangle waves with 60 volts amplitude for inducing 2π phase retardation, with frequencies of f_1 = 0.1 Hz, f_2 = 1.414 Hz, and f_3 = 34.6 Hz respectively. We purposely choose low driving frequencies here is for the easy observation of SOP evolution on Poincare Sphere. The measured DOP (10000 point average) is only about 3.2%, indicating uniform SOP coverage over the entire sphere. Finally, as shown in Fig. 3(f), the scrambling rate concentrates heavily at the highest end of the rate distribution histogram with a narrow spread. It is important to note that for this proposed scheme, the SOP coverage and scrambling rate distribution of this scheme are not sensitive to the input polarization variations, and therefore no stabilizer is required for implementing the scheme in real systems. Most importantly, the scheme works equally well for signals of both single polarization and polarization-multiplexed signals. Although the scrambling rate in this scheme is not ideally uniform as the scheme in Fig. 3(d), we anticipate it is sufficient for the high speed polarization-related testing of coherent systems with high repeatability.

3.4 Rate multiplication method for overcoming fiber squeezer speed limitations

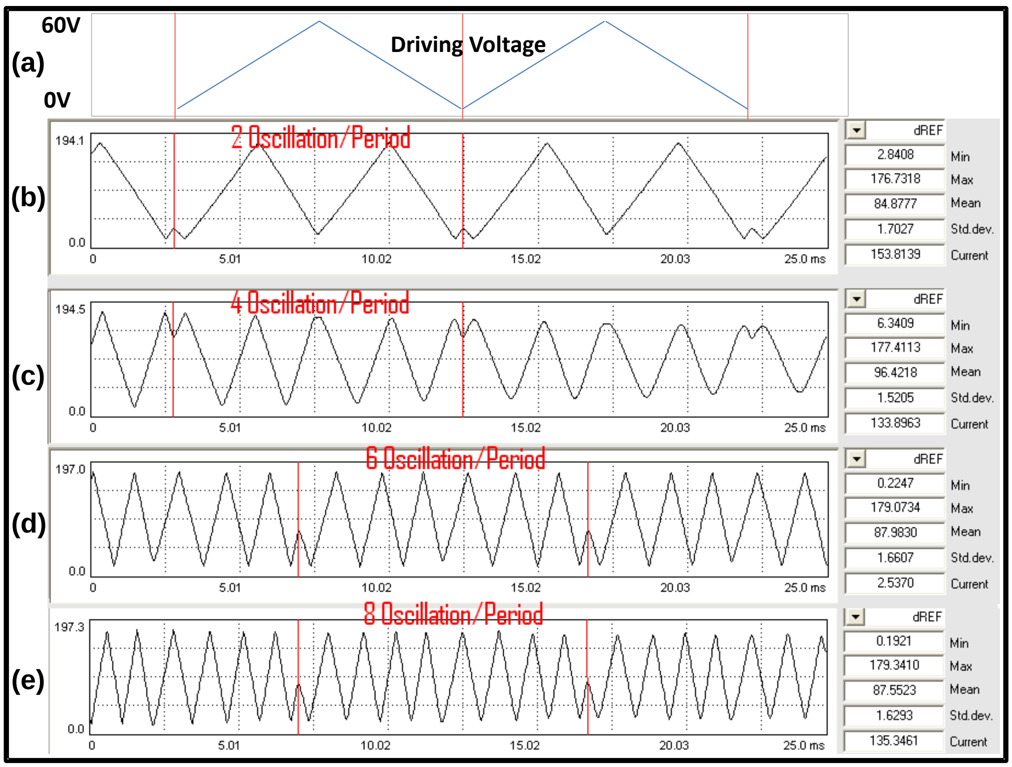

Fig. 4. Experimental results showing that SOP variation rate adds up with multiple fiber squeezers oriented in the same directions. In the experiment, the triangle wave with a frequency of 101.9 Hz and an amplitude of 60 volts drives the SOP to rotate a full circle on Poincare Sphere (phase retardation of 2π). (a) Driving signal with a triangle waveform. (b), (c), (d) and (e) correspond to the SOP variation as a function of time for simultaneously using 1, 2, 3, and 4 fiber squeezers respectively.

Fiber squeezers generally have a speed limit around 30π krad/s. Such a speed is not sufficient to achieve 100π krad/s scrambling required for testing the performance of coherent receivers. Therefore it is important to find a way to extend the speed limit of the fiber squeezers.

It can be shown mathematically that when N squeezers are placed in succession with the same relative angle, the phase retardations add up. If all the fiber squeezers are driven by a

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

same triangle signal with the same frequency, the phase variation rate will be increased by a factor of N. Consequently, if this composite fiber squeezer is used as the 3rd squeezer in the quasi-uniform rate scrambling scheme in Fig. 1, the total scrambling rate will also be increased by a factor of N. Note that this method can be applied to any scrambling device using multiple wave plates.

Figure 4 shows the experimental results demonstrating the rate additive effect. In the experiment, the last four fiber squeezers in Fig. 1 are used and the amplitude of the triangle wave is adjusted to induce a full circle on the Poincare Sphere with each squeezer. The manual polarization controller is adjusted so that SOP traces out a great circle on Poincare Sphere. A polarimeter (POD-101D) is used to record SOP variation in the oscilloscope mode when 1, 2, 3, and 4 squeezers are driven with the same signal and the results are shown in Fig. 4. Note that the vertical axis is dREF, representing the relative angle between a moving SOP point and a reference SOP point on the SOP circle calcultated using Eq. (3), with a maximum angle of 180 degrees (π). Therefore, when SOP rotates a complete circle of 2π, dREF moves from 0 to a maximum value of π, and comes back to 0. As shown in Fig. 4(a), in a period of triangle wave for inducing a maximum retardation of 2π, we see two periods of dREF variation, with a single squeezer. One corresponds to voltage ramping up, and the other voltage ramping down. It is evident from Fig. 4 that when N squeezers are used, 2N dREF oscillations per triangle wave period are present. The additive effect is immediately evident because with increased number of fiber squeezers in each succeeding curves, the number of dREF period increase per 9.8 ms triangle wave period, indicating that the increase of SOP changing rate is proportional to the number of fiber squeezers N. We also observe the rate additive effect on Poincare Sphere: N fiber squeezers induce N circles per period of the driving signal. Note that we chose a low frequency in this experiment in order to demonstrate the concept more clearly because of the limited response time of the polarimeter.

3.5 Achieving 752 krads/s quasi-uniform rate polarization scrambling

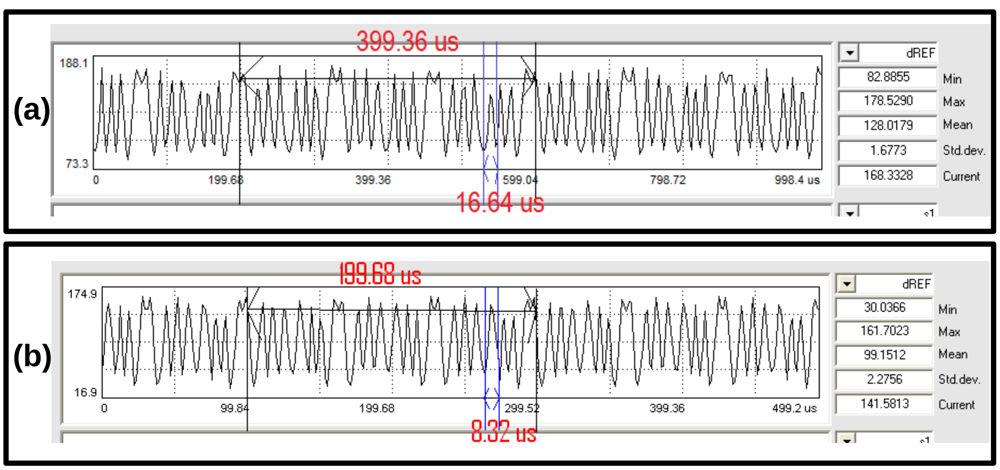

Fig. 5. Experiment data (a) for demonstrating quasi-uniform rate scrambling at 120π krad/s (376 krad/s). With an SOP angle change of 2π in 16.64 us, corresponding to a SOP variation rate of 120π krads/s (2π/16.64 us). (b) Experimental data demonstrating scrambling rate at 240π krad/s (752 krad/s).

As mentioned previously, fiber coherent optic communication systems require polarization scrambling with a uniform rate of at least 280 krad/s for testing performances with a good repeatability. Because of the incompatibility with the polarization multiplexing system, the uniform rate scheme using a polarization stabilizer cannot be used. Here, we describe combining the quasi-uniform rate scrambling scheme with the rate-additive multiple squeezer

#157398 - $15.00 USD Received 2 Nov 2011; revised 7 Dec 2011; accepted 10 Dec 2011; published 11 Jan 2012

approach to satisfy the requirements for nearly uniform rate and high-speed scrambling up to 752 krad/s.

In the experiment, six fiber squeezers are arranged as in Fig. 1. The last four squeezers are oriented in the same direction and are driven by the same triangle wave with the amplitude of 60 volts. Because of the rate additive effect, the total phase changing rate is quadrupled and readily to achieve a total rate of 120π krads/s, assuming each squeezer can operate at 30π krad/s. Figure 5(a) shows the measured SOP variation curve using a polarimeter (General Photonics POD-101D), when the frequency and amplitude of the driving triangle signal are set at 7.5 kHz and 60 volts, respectively. As in Fig. 4, dREF is recorded as a function of time. Clearly, a SOP variation rate of 120π krads/s, i.e., 376 krad/s, is achieved. It is noted that the data curve is not as clean as those in Fig. 4, caused by the limited bandwidth of polarimeter's electronics circuit. When taking the data, the first two fiber squeezers are disabled in order not to affect the rate measurement in Fig. 5. When the first two fiber squeezers are enabled, the SOP points immediately fill out the whole Poincare Sphere, and it is difficult to see the SOP evolution as shown in Fig. 3(e). In experiments, we also tried using 15 kHz triangle wave to drive the squeezers and achieved a SOP variation rate of 240π krad/s (752 krad/s), as shown in Fig. 5(b). Although the recorded curves are even more distorted due to the limitations of polarimeter's speed and the electrical amplifier for driving the squeezers, it shows the potential of achieving even higher scrambling speed for the proposed scheme.

Note that that a scrambling rate of 376 krad/s is sufficient to meet the requirements of system tests in general, since the maximum polarization variation rate in a real system is about 280 krad/s [6]. Considering that each PZT actuator in our fiber squeezers has a capacitance of 0.18 uF, the minimum total power consumption is about 20 watts for the scrambler operating at 376 krad/s, and ~40 Watts at 752 krad/s. In practice, 50% more power may be required to account for power consumption overhead by electronic circuit itself. For longtime reliability, we recommend to add more fiber squeezers for scrambling rate higher than 376 krad/s. This will help to lower the driving current or voltage on each PZT actuator and ensure longtime reliability. In addition, one may operate the fiber squeezers at resonant frequencies [22], which can significantly lower the power consumption, while increasing the scrambling rate, although this may compromise the scrambling rate adjustability by the users. Finally, it should be pointed out that fiber squeezer technology for polarization control and scrambling has proven to be commercially reliable with more than 10 years production history. We anticipate similar reliability for scrambling operation at 376 krad/s, especially when we double the number of parallel fiber squeezers in Fig. 1 and thus halve the driving voltage on each fiber squeezer, which allows us to operate each fiber squeezer at a modest driving condition of 30 volts at 7.5 kHz.

4. Conclusion

We propose and demonstrate a new scheme for quasi-uniform rate polarization scrambling for deterministic system performance tests that accommodate both single polarization and polarization multiplexed systems. A scheme to overcome the speed limitations of fiber squeezers is also demonstrated by using rate additive effect of multiple fiber squeezers. By combining both the quasi-uniform rate scrambling scheme and the cascaded multiple fiber squeezer approach, we achieve a 240π krad/s (752 krad/s) quasi-uniform rate polarization scrambler. The proposed scheme is scalable to even higher scrambling rates by adding more fiber squeezers. Furthermore, the schemes described in this paper still work if the fiber squeezers used are replaced with different types of variable phase retarders.

Acknowledgments

We thank General Photonics Corp. for providing special fiber squeezers arranged according to our specifications and Steve Yao for enlightening technical discussions, suggestions, and proof-reading of this paper.