Implementation of Ultrafast 1/2-Waveplate for Stressing Dual-Polarization Coherent Receivers

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In this white-paper we discuss the function of the NRT-2500 polarization controller platform's upgraded Spinner feature. We will describe the targeted functionality, the specifications and show some measurements of the Spinner operation and application.

Spinner Functionality

The NRT-2500's spinner implements an electro-optical rotating ½-waveplate. A ½-waveplate rotates the orientation of the input state of polarization (SOP). Specifically, the ½-waveplate delays one polarization axis from the second axis by half a wavelength. Thus when linear polarized light is incident on a ½-waveplate the output is rotated to another state of linear polarized light. The angle between the incident and resultant polarization depends on the rotation of the ½-waveplate with respect to the incident light. A common example is when the linear input is polarized 45° with respect to the fast (or slow) axis of the ½-waveplate, the output light is rotated 90° relative to the input.

A rotating ½-waveplate, therefore, will rotate the SOP of the output light. And an electro-optical rotating ½-waveplate will rotate the transmitted light with an angle proportional to the driving voltage signal. The advantage of the electro-optical rotating ½-waveplate is the ability to reach incredible SOP rotation speeds compared to motor driven or mechanical-optical rotating ½-waveplate technologies. The $LiNbO_3$ waveguide technology electro-optical rotating ½-waveplate used in the NRT-2500 is a superb choice for its ability to rotate the SOP endlessly, without the need to stop and rewind the waveplate mechanism, and for its extremely fast, nanosecond, electro-optic response.

The Spinner's functionality was developed from the need to verify the polarization sensitivities and polarization demultiplexing capabilities of the DSP PHY chips used in 40G and 100G dual-polarization coherent receivers. Specifically, the speed at which the DSP chips can separate the interleaved polarizations after detection must be specified. SOP scramblers produce distributions of both SOPs and SOP change rates (dSOP/dt). These variations make it impossible to clearly quantify the limits of the dynamic DSP demultiplexing. Customers are clamoring for a tunable yet well-specified and well-defined SOP and dSOP/dt generating instrument.

Spinner Specification

A rotating 1/2-waveplate perfectly addresses these requirements. In Figure 1 three representations for the performance of the same Spinner are shown. The top is the Poincaré sphere view. The input polarization before the rotating ½-waveplate, and the polarization after the ½-waveplate were adjusted such that the waveplate is rotating on the S_1-S_2 equator of the Poincaré sphere at the detecting polarimeter. The middle graph has SOP histograms for the S_1, S_2 and S_3 values observed on the Poincaré sphere. The red narrow distribution shows that S3=0 ± 0.03, while S_1 (green) and S_2 (blue) vary sinusoidally between 1 and -1. The bottom graph is a histogram of the speed, $dSOP_{Jones}/dt$. It clearly shows a very narrow, very well-defined, constant rotation rate of about 25,000 radians/second.

There is an ongoing debate over the unit used to define dSOP/dt. This is an important parameter as it is ultimately used to specify the demultiplexing capability of the various DSP chips. In terms of the dual polarization receivers, the power for the X and Y input signals will bounce back and forth between the two detection sides of the receiver at frequencies depending on the movements along the fiber path. Therefore, it is common to specify dSOP/dt in frequency (Hertz). Moreover, this definition is independent of SOP orientation at the receiver (or orientation with respect to the Spinner ½-waveplate).

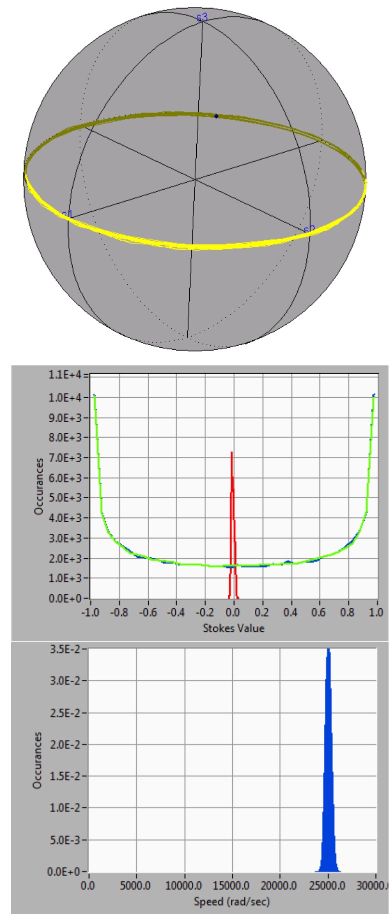


Fig 1: Poincaré Sphere trajectory (top), (middle) SOP histograms and $dSOP_{Jones}/dt$ ~ 25 kRad per sec (bottom) for a 4000 Hz Spinner aligned around the equator.

For example figures 1 and 2 both show a Spinner with frequency 4000Hz. However, when the Spinner SOP is aligned to the equator (or any great circle) the dSOP/dt is maximum, because the path around the Poincaré sphere is maximal. Conversely, if the input light happens to be circular (i.e. at $\pm S_3$) at the Spinner, the angular speed becomes nearly zero (fig 2). The receiver in this case does not need to dynamically transform the SOP to demultiplex the light, but must statically transform the received right and left circular polarized input signals into linear X and Y polarizations by recovering the input phases. Clearly, a 4000 Hz Spinner will present itself differently to the receiver depending on the SOP changes along the fiber path, varying from 0 to about 25,000 rad/sec.

Note that while the polarization rotates at 25,000 rad/sec, the change of the Stokes vector (on the Poincaré sphere) rotates at twice the real (Jones) space rate, at 50,000

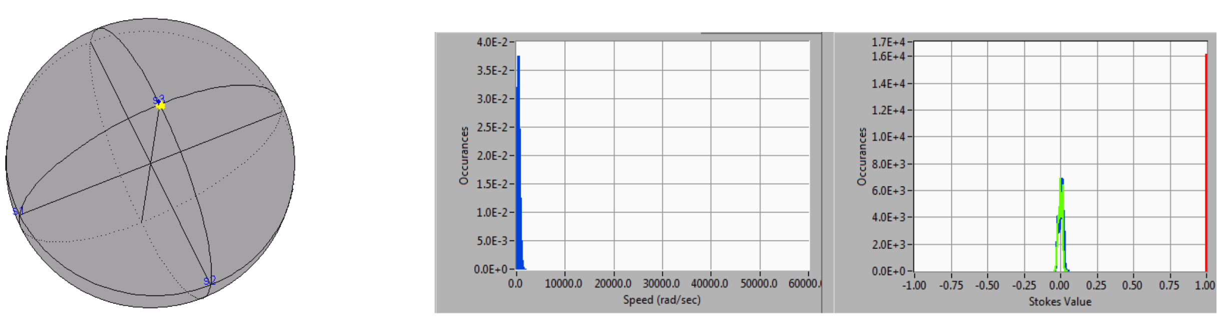


Fig 2: Poincaré Sphere trajectory is virtually a point (left), dSOP/dt ~ 0 radians/sec (middle) and SOP histograms (right) for a 4000 Hz Spinner aligned to S_3=1 ('north pole').

Stokes-radians/sec, i.e. $dSOP_{Stokes}/dt = 2 \times dSOP_{Jones}/dt$. We use the notation dSOP/dt when the statement applies to both Stokes and Jones spaces. Otherwise we will differentiate with the appropriate subscript.

We prefer to define the Spinner rotation speed unit in Hertz, because the NRT-2500 Spinner rotation is indifferent to the orientation of the rotating SOP incident to the experiment. Secondly, the sinusoidal voltage signal that drives the Spinner is that same frequency.

Some customers have specified their DSP speed requirements in Rad/sec (Hertz x 2π) while others use Stokes angular speed (Hertz x 4π). For example, the Spinner in figure 1 is rotated at 4000 Hz which is equivalent to SOP_{Jones}/dt = 25,132 rad/sec or $dSOP_{Stokes}/dt$=50,265 Stokes-radians/sec. Figure 3, at the right, shows two measurements for the 4000 Hz Spinner on orthogonal great circles. The fit Spinner rotation speeds were nearly identical at 25,035 rad/sec and 25,009 rad/sec respectively. Also impressive is the very narrow ½-waveplate Spinner width. The width is within ±3% of the set value measured at 10% of the peak.

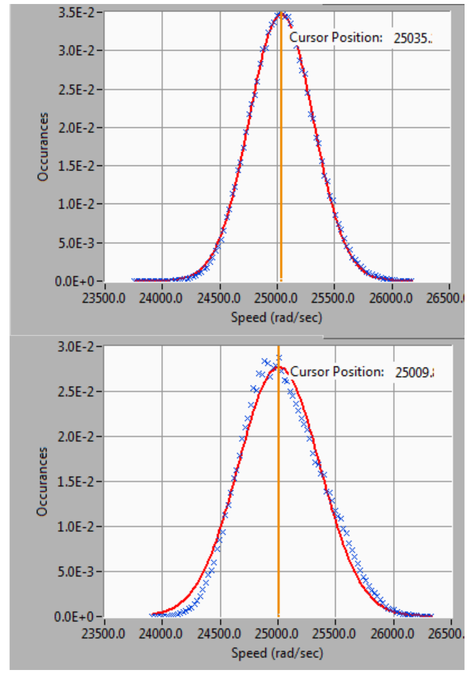
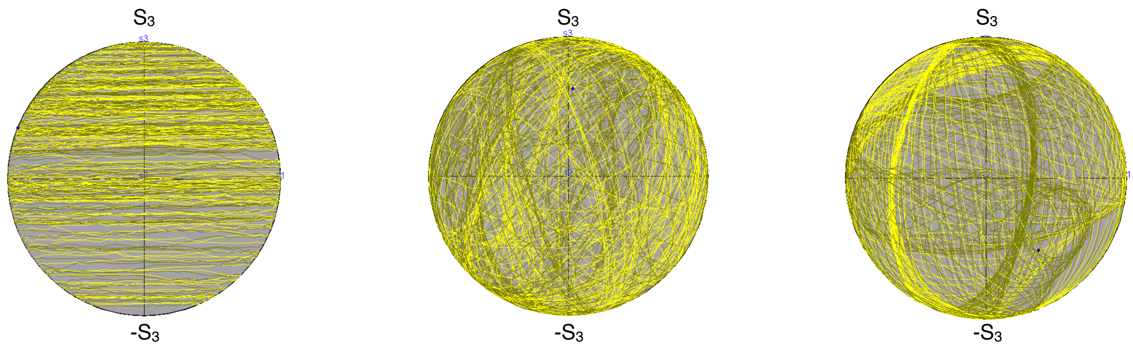


Fig 3: Enlarged histograms for 4000 Hz Spinner: Around the equator at S3=0 yielding a fit mean rotation rate of 25,035 rad/sec (top). The lower histogram is for the same Spinner, also on a great circle, in the S_2-S_3 plane (S_1=0) yielding virtually the same fit mean rotation rate of 25,009 rad/sec (bottom).

Spinner Measurements

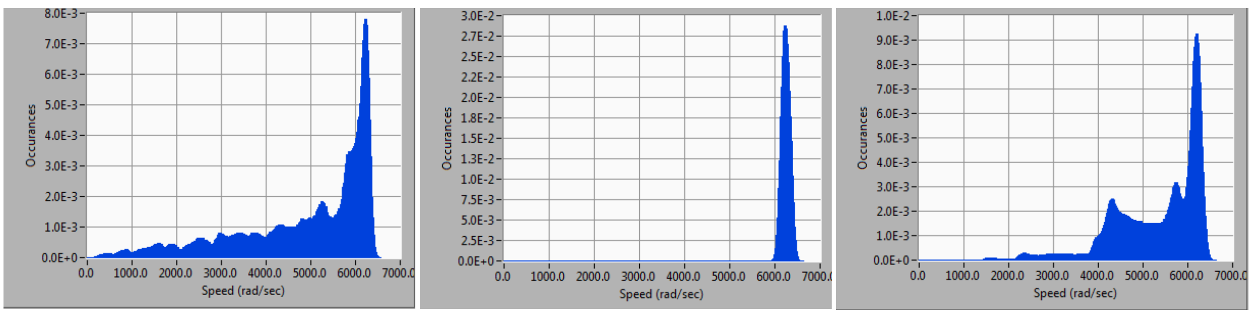
One of the issues many users encounter when testing their polarization speed response is that it is difficult to ascertain the SOP at the polarization beam splitter inside the DP-receiver. And therefore it is very hard to align the Spinner to that desired orientation (e.g. in the X-Y plane). One common solution is to vary the polarizations before and after the Spinner ½-waveplate. Figure 4 shows the difference between varying the input SOP 4(a), the output SOP 4(b) and varying both together 4(c). Varying the SOP input to the ½-waveplate causes the rotation to move up and down along the axis of rotation. This changes the SOP rotation speed from zero at S_3=±1 (e.g. fig. 2) to the maximum, 2π x frequency, at S_3=0 (e.g. fig. 1). This is shown in the left $dSOP_{Jones}/dt$ histogram of figure 5(a). Varying the SOP output from the ½-waveplate merely changes the orientation of the rotation at the detector. Therefore the measured speed of the rotation does not vary. This is shown in the center $dSOP_{Jones}/dt$ histogram of figure 5(b). Varying both the input SOP and output SOP changes both the speed and orientation of the Spinner. The corresponding speed $dSOP_{Jones}/dt$ histogram is shown in figure 5(c).

Only endless and non-reseting polarization control technologies are capable of producing the single frequency rotation histogram shown figure 5(b). The non-endless polarization control platforms requires the dSOP/dt rotation speed to go zero at every reset and reversal event. Hence non-endless polarization control device technologies will always have a rotation speed histogram with a low speed tail, such as figures 5(a) or 5(c), independent of the input SOP or output SOP, and can never achieve the single spin frequency histogram as shown in 5(b).



(a) *(b)* *(c)*

Fig 4: (a) When the SOP input to the Spinner is changed, the SOP rotation travels along the rotation axis from S_3 to the equator to $-S_3$. (b) When the SOP exiting the Spinner is changed, the direction of the axis of rotation changes as shown in the central sphere where the orientations of great circle rotations are changing. (c) When both the input and output SOPs to the Spinner are varied, both the size and the orientation of the Spinner vary.



(a) *(b)* *(c)*

Fig 5: (a) When the SOP input to the Spinner is changed, the $dSOP_{Jones}/dt$ speed histogram has a tail from the maximum speed down to zero. (b) When the SOP exiting the Spinner is changed, there is no effect on the $dSOP_{Jones}/dt$ speed histogram (center). (c) A combination of peaks and tail is observed in the $dSOP_{Jones}/dt$ when both the input and output SOPs to the Spinner are varied (right). In all three cases, the input and output rotation speeds are much slower than the Spinner ½-waveplate rotation speed.

DP- Receiver Testing

Figures 4 and 5 are very helpful in determining the appropriate SOP speed test for a DP-coherent receiver. The most commonly requested quantitative measurement is to determine the maximum SOP change that the DSP algorithm can demultiplex for all SOPs. Clearly all SOPs can be accessed by varying either the input polarization to the Spinner, or the output polarization, or both polarizations (figure 4). However, only when we vary the polarization exiting the Spinner ½-waveplate does the rotation speed remain at a constant speed (in radians/sec).

To achieve a constant maximum rotation speed for a set Spinner frequency, the Spinner's rotation should be set to a great circle. This is difficult with DP-transponders as the two polarization make polarization measurements impossible. Therefore, one of the polarization signals must be blocked using optical polarization demultiplexing. As shown in figure 6, polarization demultiplexing requires an additional polarization controller (i.e. polarization paddles) and a removable polarizer (or adjustable PDL device). At the receiver side of the set-up, some of the light is tapped into polarimeter, where the degree of polarization (DOP) can be measured. The first polarization controller (e.g. NRT-2500 in paddle mode) is used to align one of the DP-signals through the removable polarizer until the DOP is maximized to about 1. Then, by adjusting the input and output polarization controllers integrated with the Spinner GUI software, the SOP rotation can be placed on the equator of the Poincaré sphere representation of the polarimeter. Finally, the polarizer is removed. Both (orthogonal) dual polarizations are now rotating the same great circle. Any Spinner rotation speed can be used to align the great circle using this method.

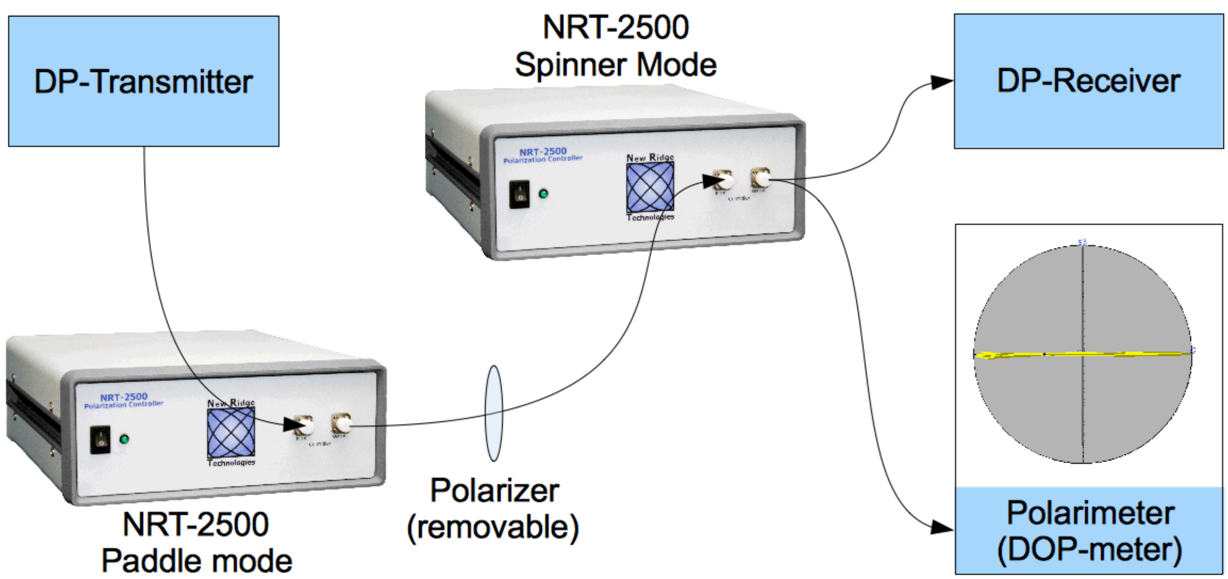


Fig 6: Set-up to align NRT-2500 (Spinner mode) to a great circle for Orientational Drift of ½-waveplate spinner. This requires a (pre-Spinner) polarization controller (paddles), removable polarizer and polarimeter to first demultiplex the two polarization signals. The paddles are adjusted until the DOP reaches about 1. Then the input and output SOP controls on the Spinner NRT-2500 are adjusted to align the rotation to the equator of the Poincaré sphere before the polarizer is removed. As log as the SOP from the transmitter to the NRT-2500 Spinner does not change, both DP signals will continue to rotate on a great circle at the input to the DP-receiver.

Once set, the great circle will be maintained as long as the polarization from the DP-transmitter to the Spinner NRT-2500 does not change. (See the YouTube demo, Improved Orientational Drift Spinner which demonstrates alignment of the Spinner to a great circle for this measurement.) Movement of the output fiber, between the NRT-2500 and the receiver under test, will only change the relative orientation of the rotation, and therefore will not affect the test.

Once the aligned great circle Spinner is input to the receiver, the Spinner's Orientational (Output) Drift mode can be started. If the DSP algorithm and chip are sufficiently fast, there will be no errors caused by the Orientation drifting Spinner. The Spinner test measurement should be continued until all SOPs are (i.e. the full Poincaré sphere is) covered. The Spinner speed can then be increased and the test repeated until the receiver begins to take errors. Bit errors or loss of frame are signs that the DSP algorithm/chip cannot keep-up and demultiplex at the set SOP Spinner rotation speed.

Often, it is not possible to demultiplex the dual polarizations for alignment to a great circle. But this is not a show stopper. In this case, the Spinner measurement requires that both the input (axial) and output (orientational) polarization controllers integrated with the Spinner be varied to insure complete SOP coverage for the test. Here the rotation speed histogram will develop a tail towards zero (figure 5c). Moreover, this measurement will take significantly longer (approximately the square of the orientational-only test time) to insure that all SOPs are covered with the maximal speed.

The enhanced Spinner mode of the NRT-2500 polarization control platform has been designed to provide quantitative SOP speed response testing. It is especially well suited to verify and specify the polarization performance of new dual-polarization coherent receivers for fiber optic communications.

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