Recommendations for Receiver PMD and Polarization-Demux Test Specifications

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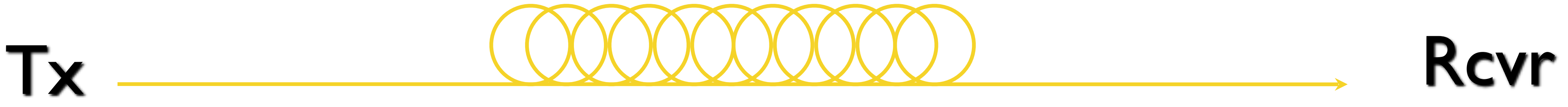
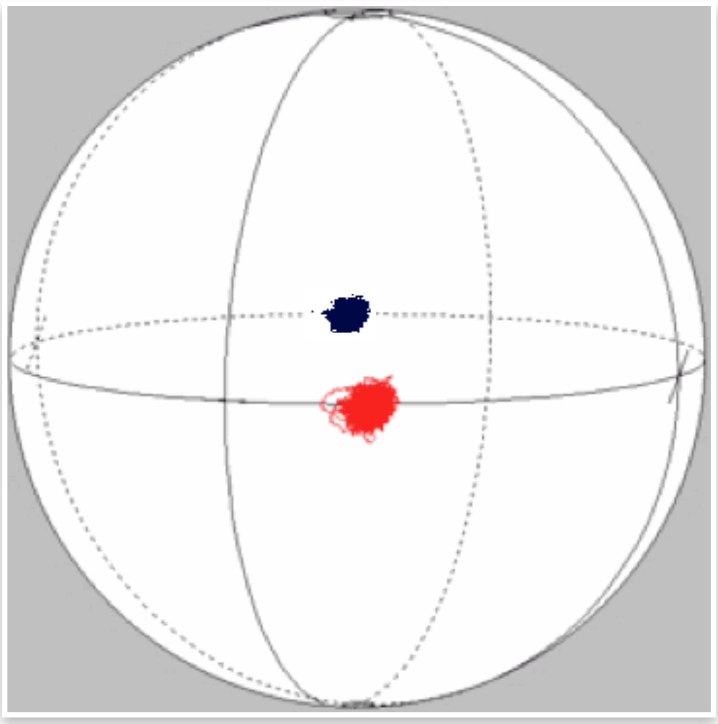
Simple and Sufficient PMD and SOP Tests Yet Quantitative, Repeatable, Comparable and Complete

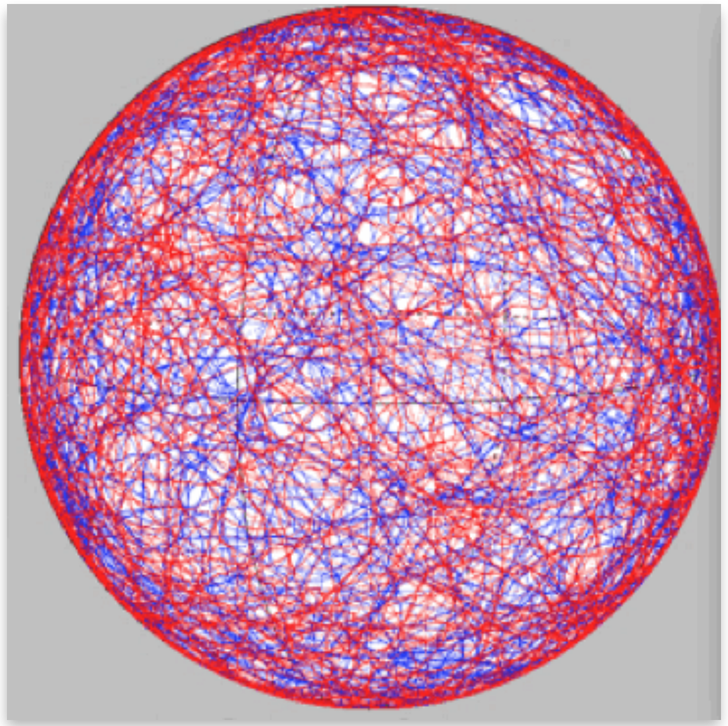
Test	1st Pol Controller	PMD state	2nd Pol Controller	Comment
Determine DSP pol demux limit	0	0	1/2-waveplate Rotating at 0 - 100 krad/s	orientation of waveplate varied to cover all SOPs, but ΔSOP/Δt remains constant
〈PMD〉=10 ps pass/fail	Scrambler with 〈ΔSOP/Δt〉 = 30 rad/s	≥33 ps DGD	Scrambler with 〈ΔSOP/Δt〉 = 30 rad/s	Only test needed for FIR DSP algorithm PMD tolerance
Lightning survival/recovery	0	0	ΔSOP jump in 20 µs	Simulate lighting in the lab ΔSOP/Δt from 100k to 2M rad/s

Part 1: Testing SOP Tracking Of The DSP: The DSP Must Track & Demultiplex The Polarizations

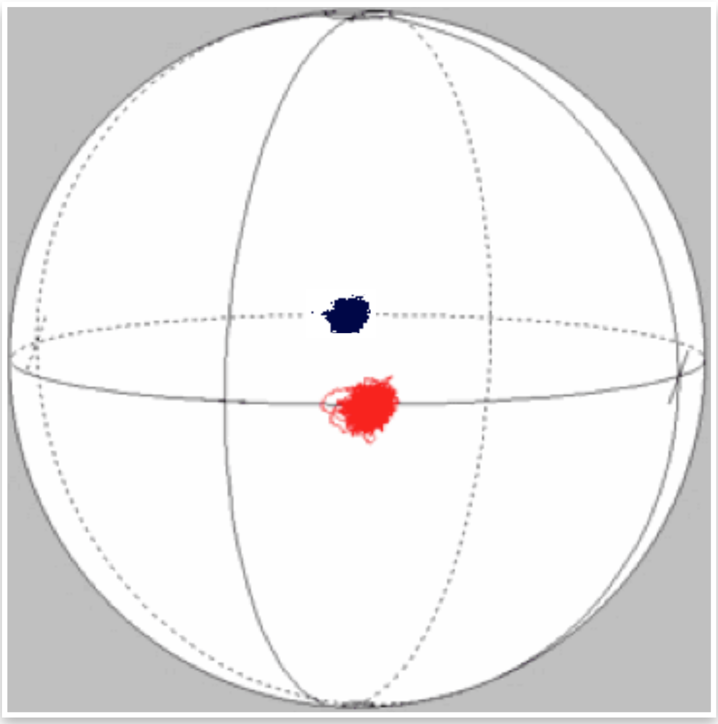




The two PM signals are launched perpendicular, along S_1 and $-S_1$, at the transmitter



As the signals pass through the fiber the PM signals change their SOP



The DSP must demultiplex the two signals at the receiver, realigning to S_1 and $-S_1$

Coherent DSP Transponders Need to Address Three ΔSOP Speed Ranges

1. '**Normal Operation**' for aerial fiber ~60 rad/sec demux rate is required, while ~20 rad/sec is needed for buried fiber.
   - *Peterson, Leo, Rochford, "Field Measurements of state of Polarization and PMD from a tier-1 Carrier", in Proc. OFC 2004, paper FI1.*
2. **'Fast events'** at ~300 rad/sec; impulsive changes in SOP were observed with a probability of ~2 x E-8 (i.e. ms/day)
   - *Boroditsky, Brodsky, Frigo, Magill, Rosenfeldt, "Polarization Dynamics in Installed Fiberoptic Systems," in Proc LEOS, 2005, paper TuCC1, p 414-415.*
   - *Krummrich, Schmidt, Weishausen, Mattheus, "Field Trial on statistics of fast polarization changes in long haul WDM transmission systems," in Proc. OFC 2005, paper OThT6.*
3. **'Ultrafast'** SOP change events, >250,000 rad/sec; banging on a spool of DCF or a lighting strike near a cable.
   - *Krummrich, Kotten, "Extremely fast (microsecond scale) polarization changes in high speed long haul WDM transmission systems", in Proc. OFC 2004, paper FI3.*
   - *Henry Yaffe, "Are Ultrafast SOP Events Affecting Your Coherent Receivers?" blog on NRT website February 16, 2016.*

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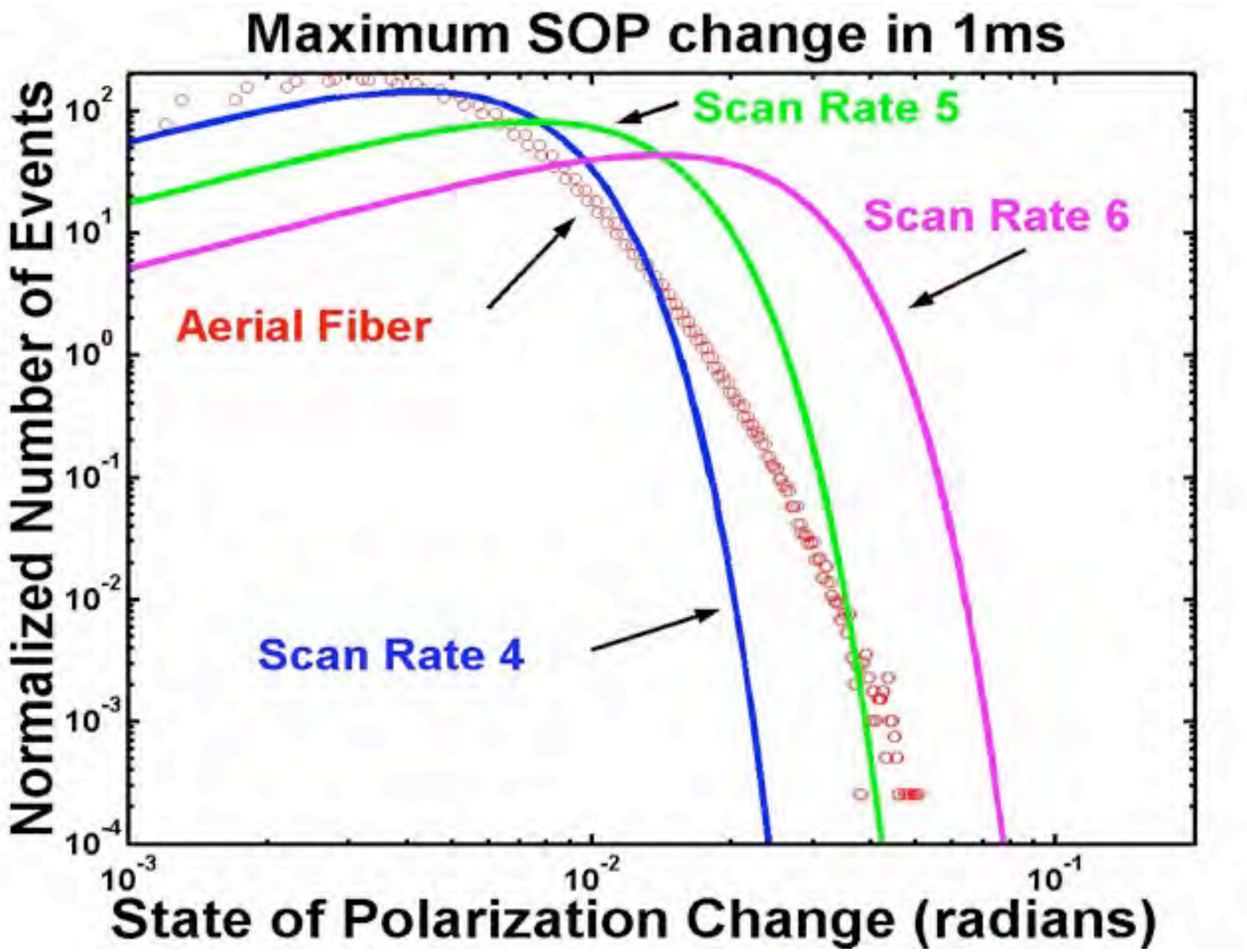
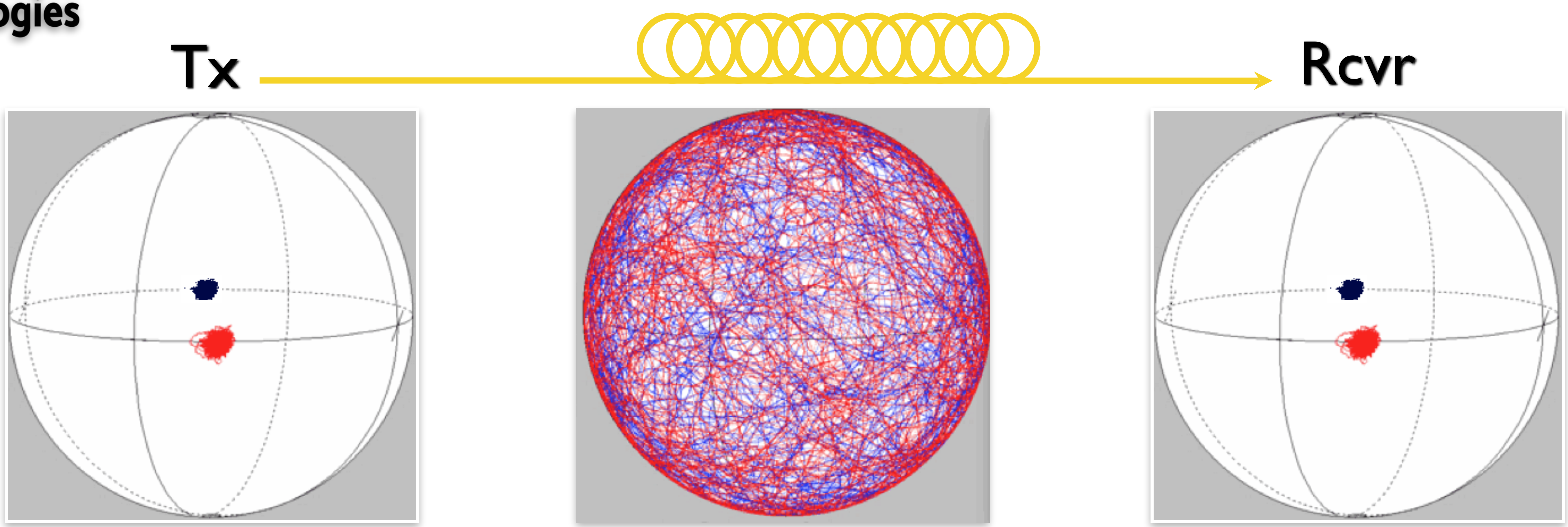
ΔSOP/Δt for ‘**Normal Operation**’ is less than 60 radians/sec Speed Ranges



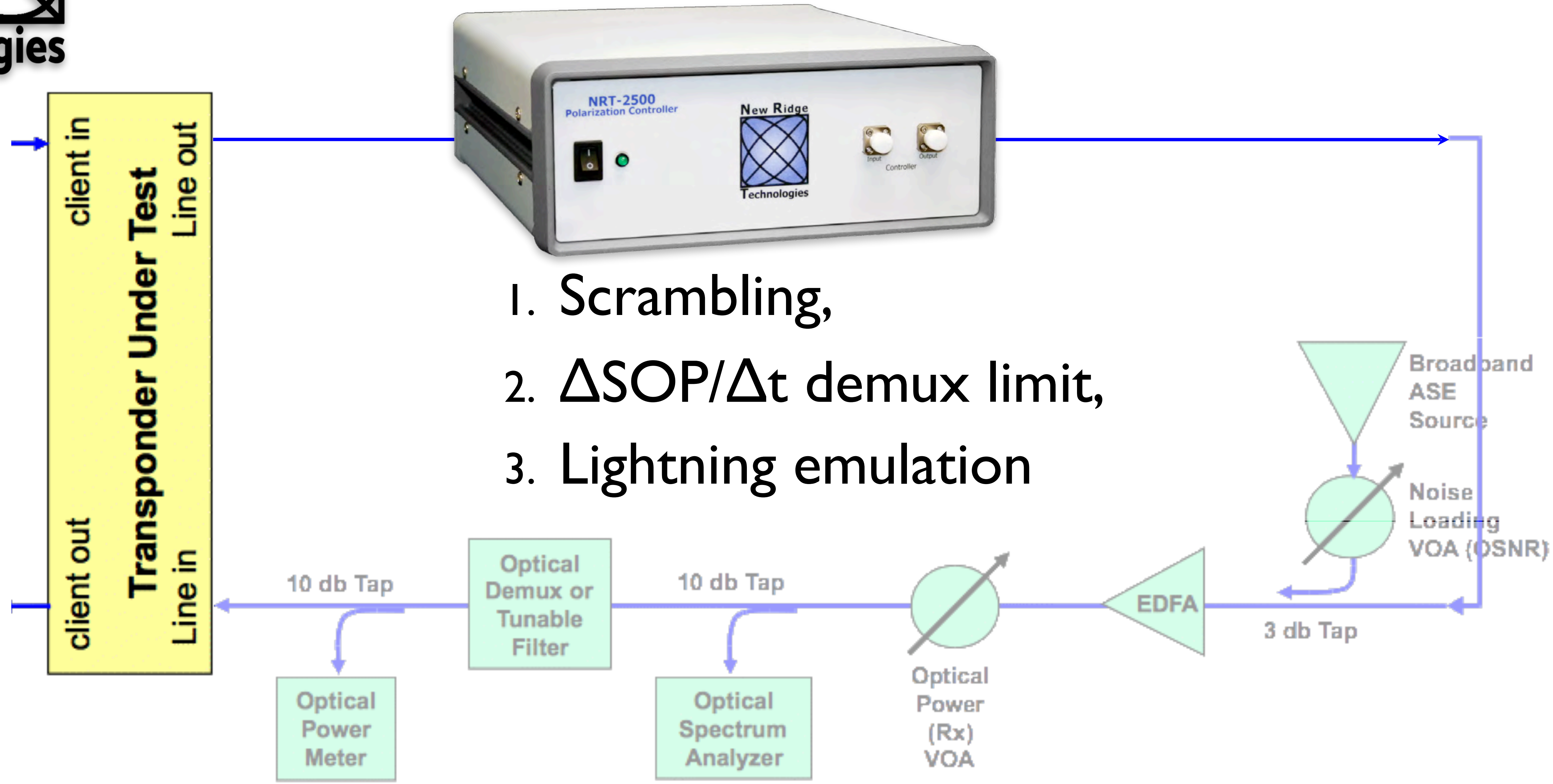
How Can We Replicate The SOP Scrambling to Test the Polarization Demux Capabilities?



We must generate this type of behavior in the lab at the required speed rates

Zero bit-errors will confirm good polarization demultiplexing

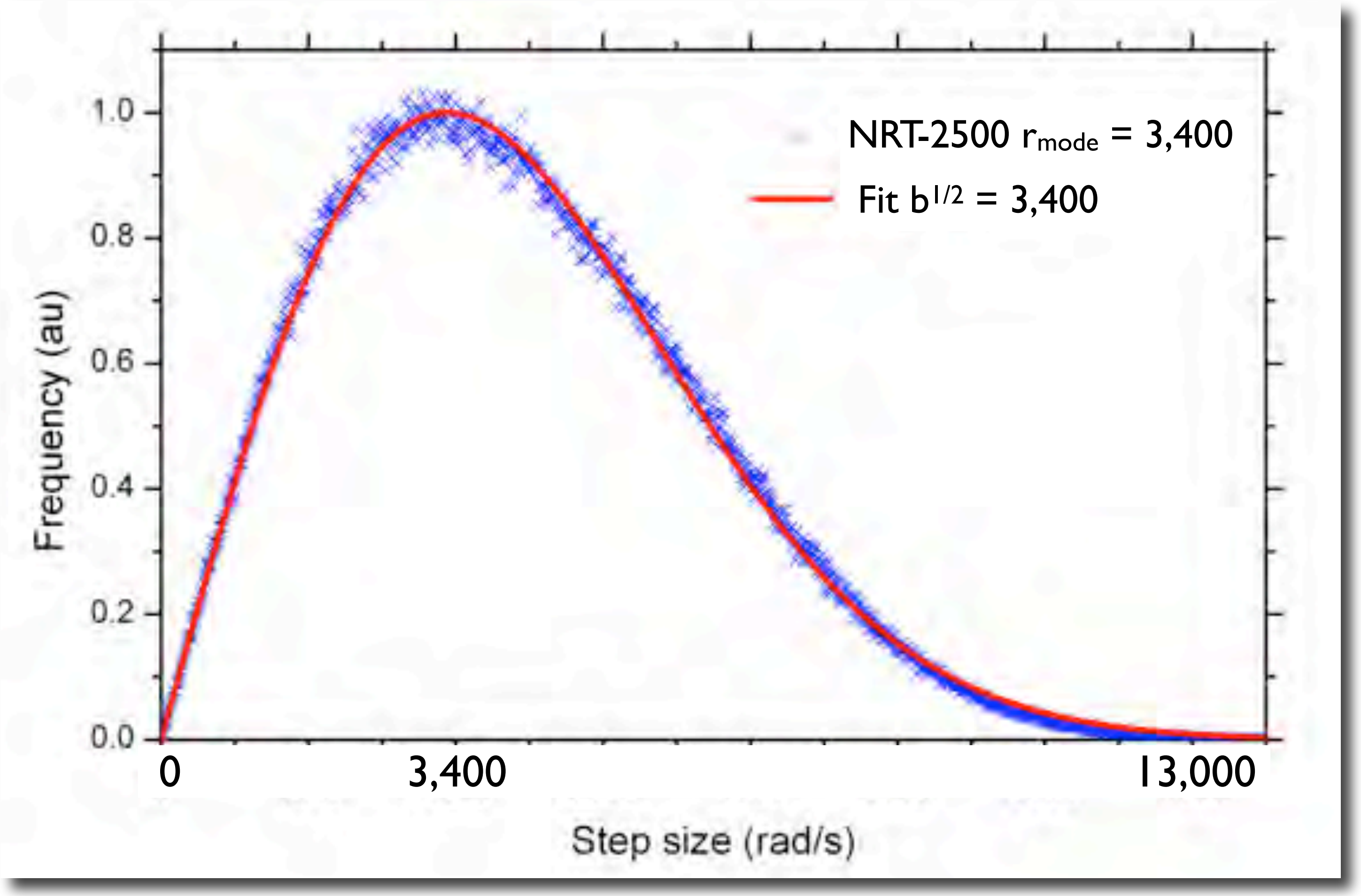
An Endless Polarization Controller Is Best to Determine Pol-Demux Capability of the DSP in 3 Modes



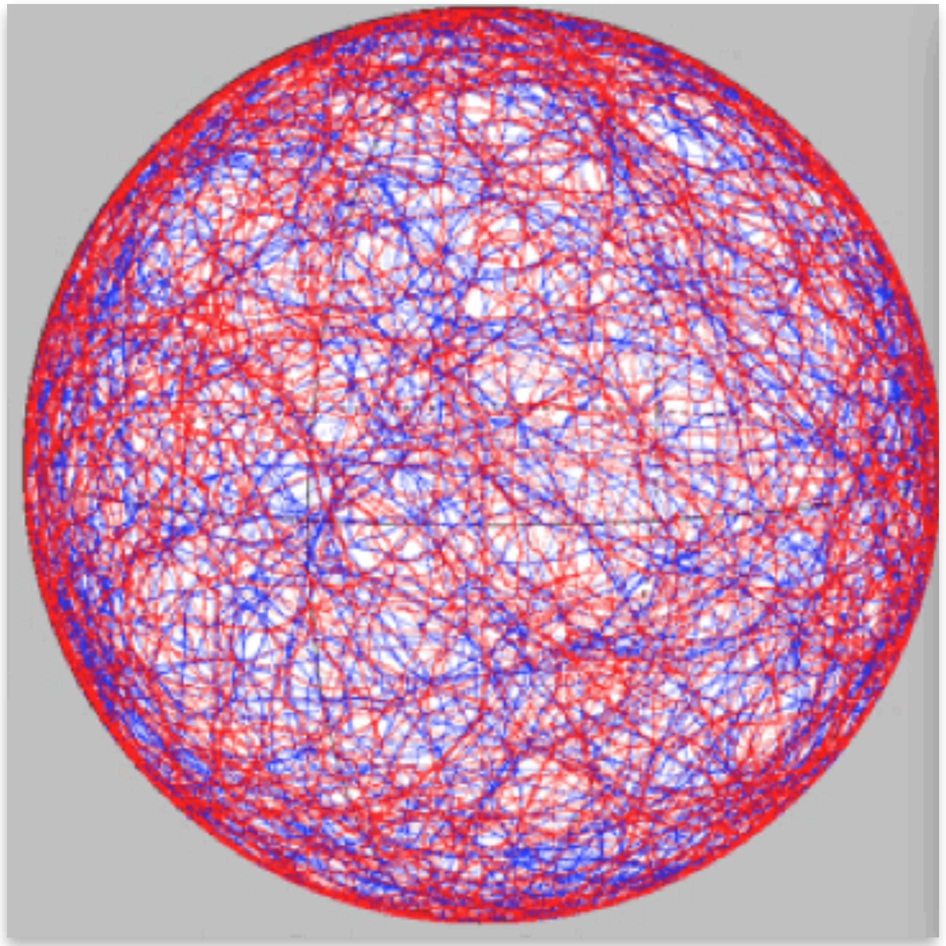
1. Scrambling,
2. ΔSOP/Δt demux limit,
3. Lightning emulation

Mode 1: 'Normal Operation' Requires Scrambled Output: (1) Stochastic and (2) Completely Random

Set the desired stochastic Rayleigh distribution of ΔSOP on the GUI



Uniform & Even Coverage of the Poincaré Sphere



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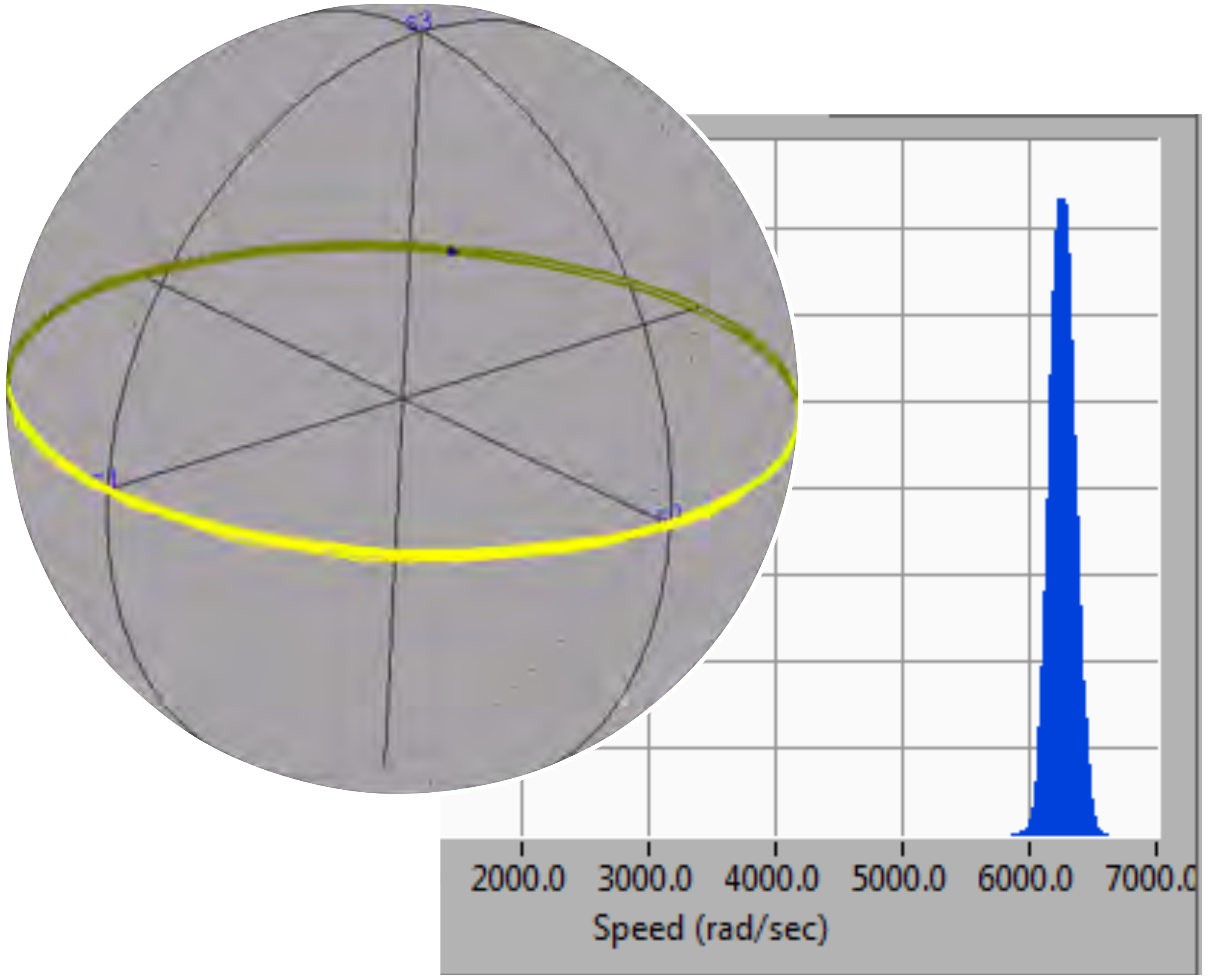
Mode 2: Determining The Polarization Demux Limit With ‘Spinning’ 1/2 Waveplate

1. Digitally synthesized rotating electrooptic ½-waveplate creates **continuous, controlled and repeatable** SOP changes at superfast speeds.
2. Rotation speed adjustable up to 1 Mrad/sec
3. Rotation rate is uniform producing a narrow well-defined dS/dt histogram
4. Rotation can be oriented in any direction to cover all SOPs at the same speed
5. This test requires an electro-optic and endless polarization control technology

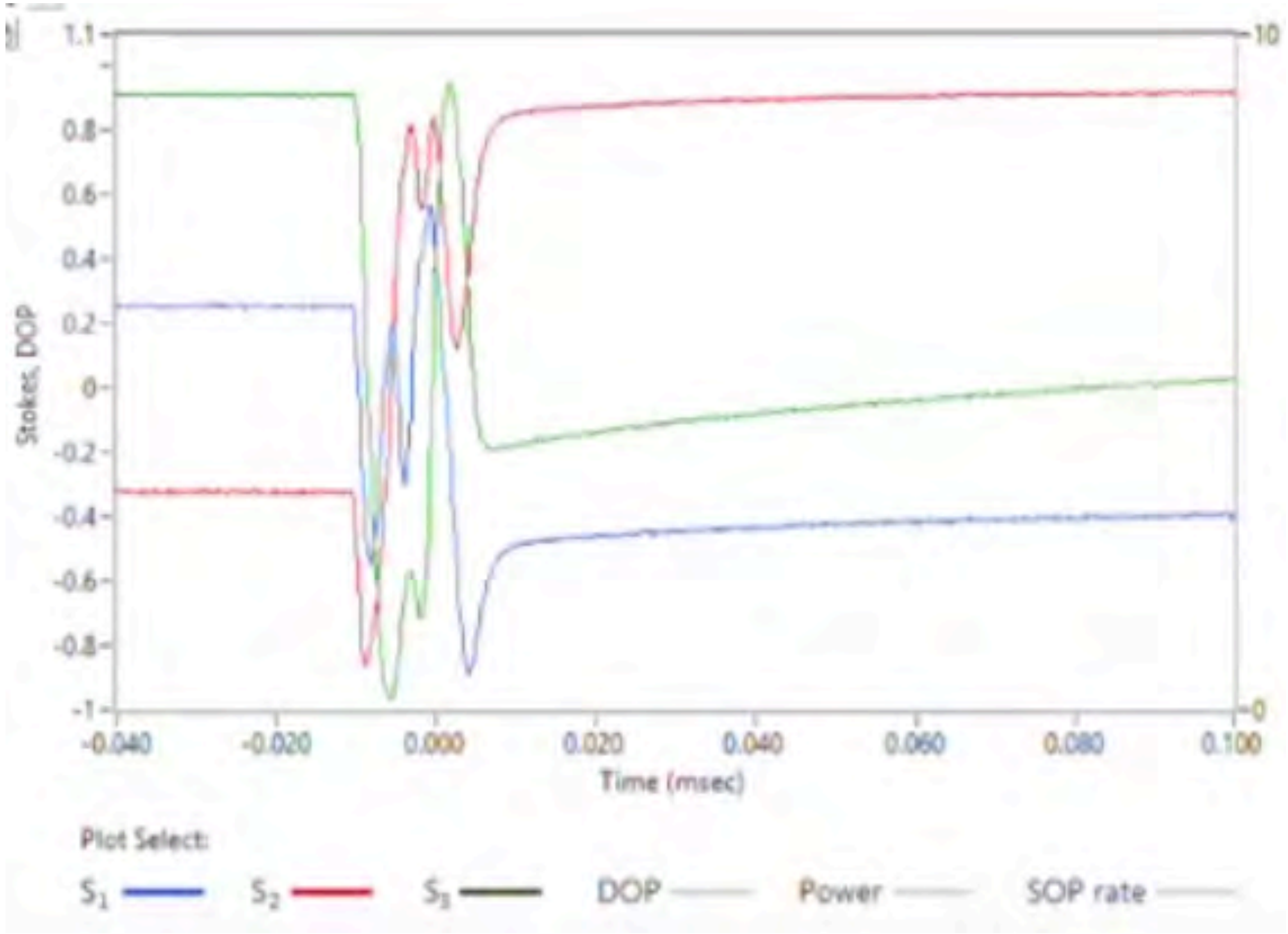


See video of orientation Spinner https://www.youtube.com/watch?v=UyutgflycEo

Mode 3: SOP Jump or **Randomizer** To Simulate Ultrafast ΔSOP Impulses As Induced By Lightning

1. A random voltage jump induces a random SOP change
2. The ΔSOP time slot is ~20 µs providing SOP slew rates up to >1,000,000 rad/sec, followed by a ~3 ms relaxation
3. Externally trigger the SOP jump,
4. Or set the repetition rate (i.e. dwell time) of the random SOP jump can be set.

https://youtu.be/6LiQAbpLy8E



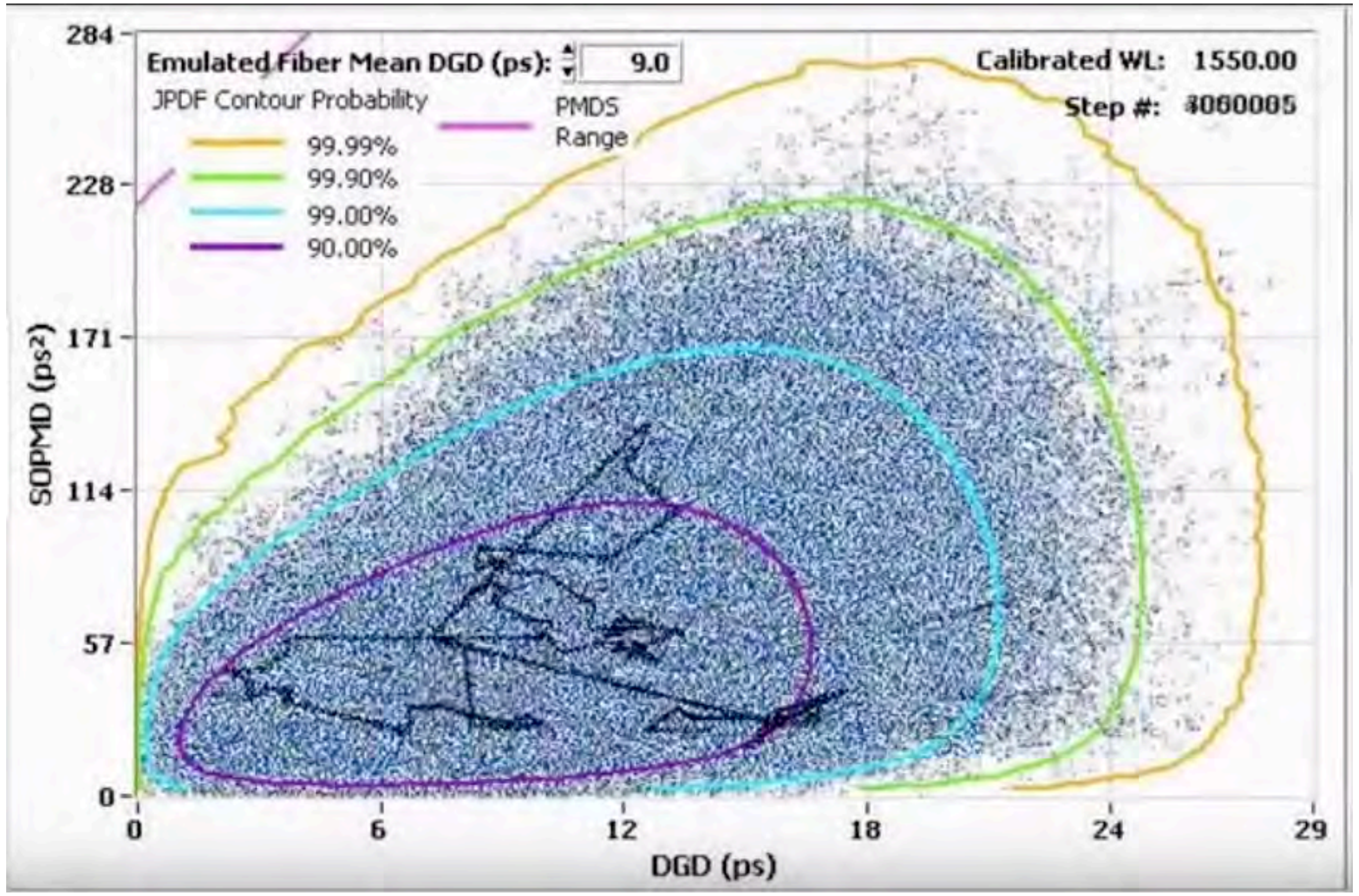
Part 2: Deterministic and Repeatable Dynamic PMD Tolerance Testing DOES NOT Emulate Fiber PMD

PMD Emulation creates PMD dynamics and its statistical distribution of PMD states.

But it is not useful for quantitative PMD Tolerance Testing.

1. **Time Waster:** >99.9% of the time at benign PMD states with no bit errors.
2. **Not Deterministic:** The PMD State is unknown when errors occur.
3. **Not Repeatable:** Each run differs from the previous test.
4. **No Comparable:** Your measurement is different from your customers', clients', competitors'.

Another Quantitative and Repeatable PMD test method is needed.

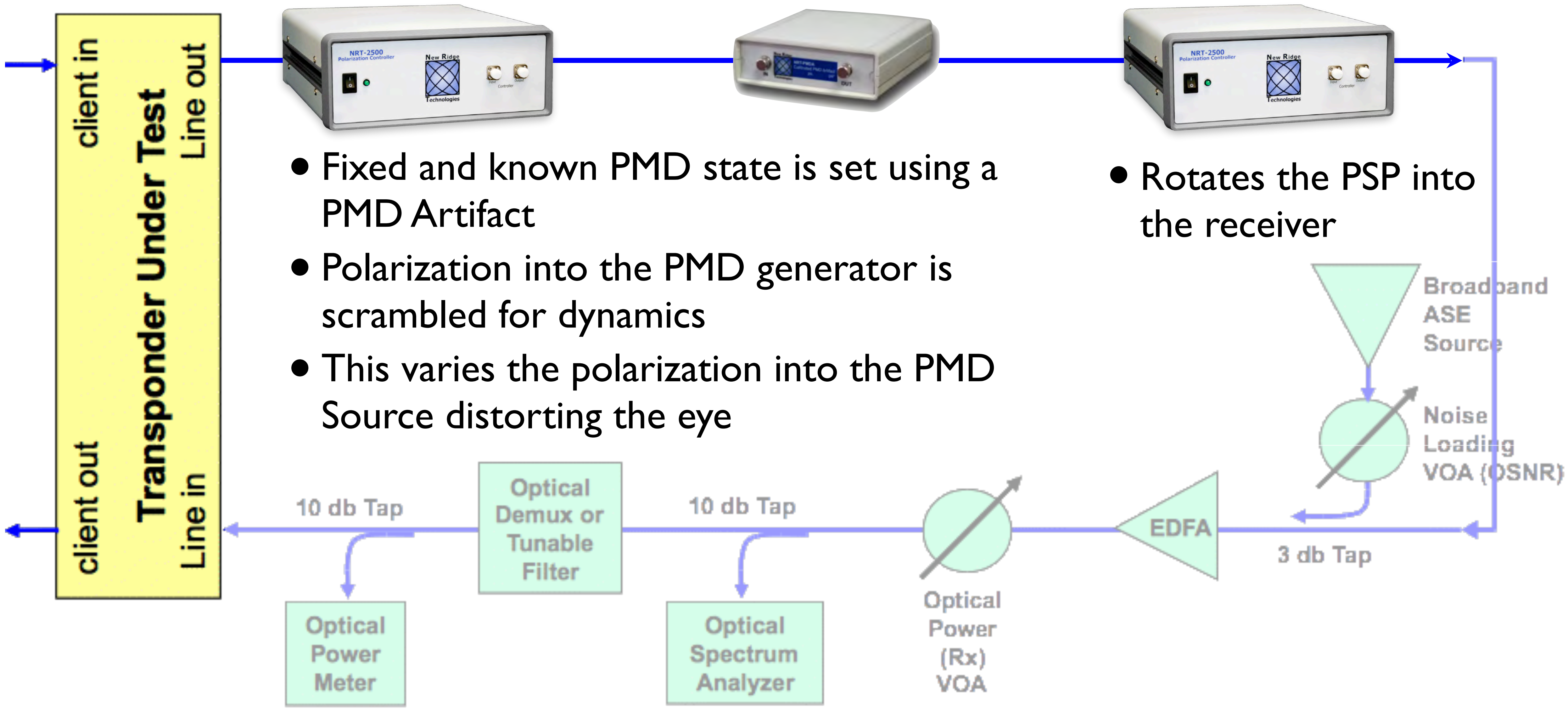


PMD emulator random-walk animation in (DGD, SOPMD)
https://www.youtube.com/watch?v=rnspc5R2n7M

PMD Tolerance Is Best Measured With Fixed and Known PMD States

Dynamic & Settable PMD Generation

Pol-Demux

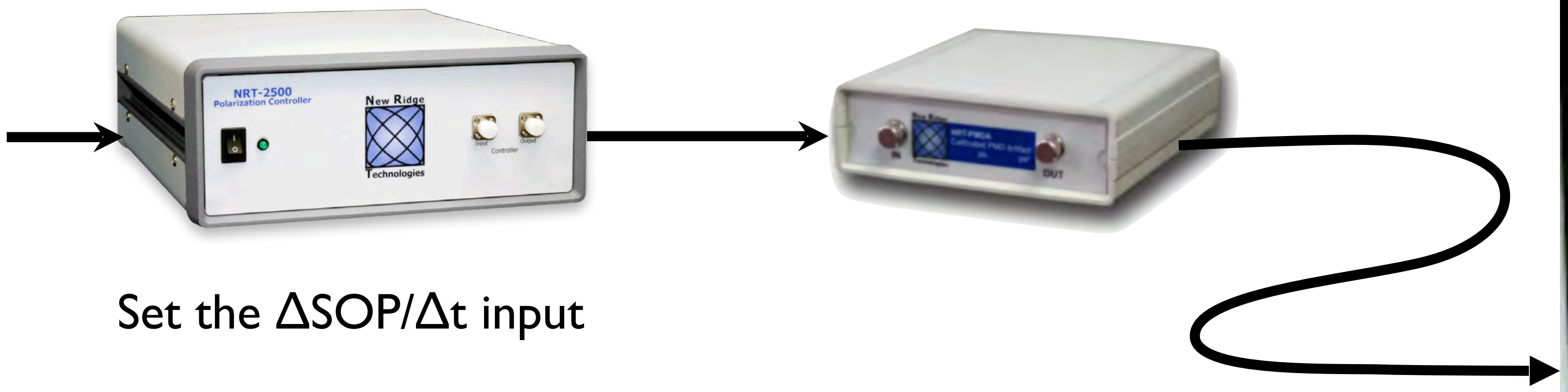


- Fixed and known PMD state is set using a PMD Artifact
- Polarization into the PMD generator is scrambled for dynamics
- This varies the polarization into the PMD Source distorting the eye

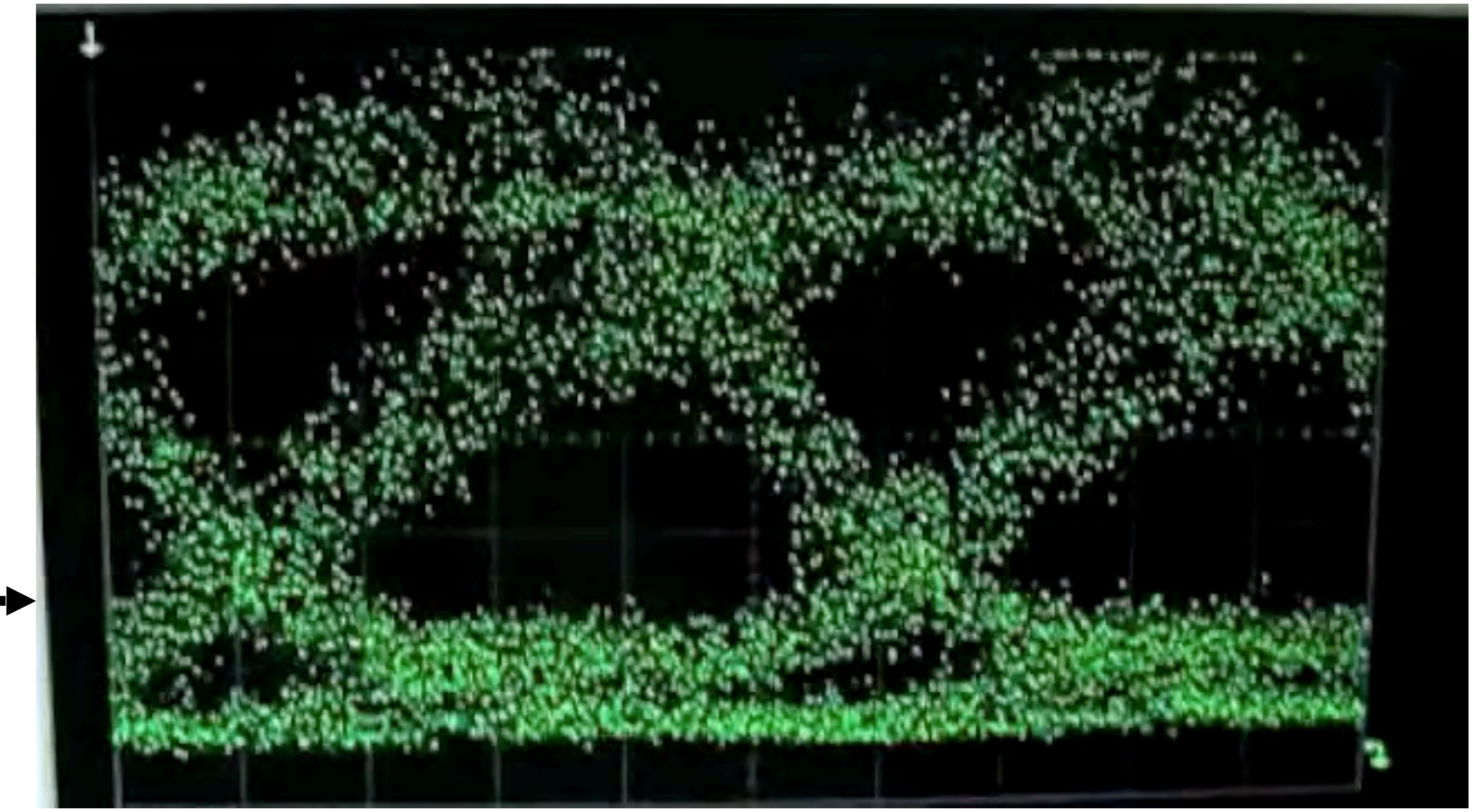
- Rotates the PSP into the receiver

Scrambling The Input Polarization Into A Fixed PMD State Creates Dynamic PMD

Dynamic Polarization Input + Static PMD State =



Set the ΔSOP/Δt input



(old) Example: PMD = 23 ps DGD, 100 ps^2 SOPMD into a demodulated 40G NRZ-DPSK. Displayed on DCA with a very slow SOP scramble.

https://www.youtube.com/watch?v=RmiO2pEPTKw

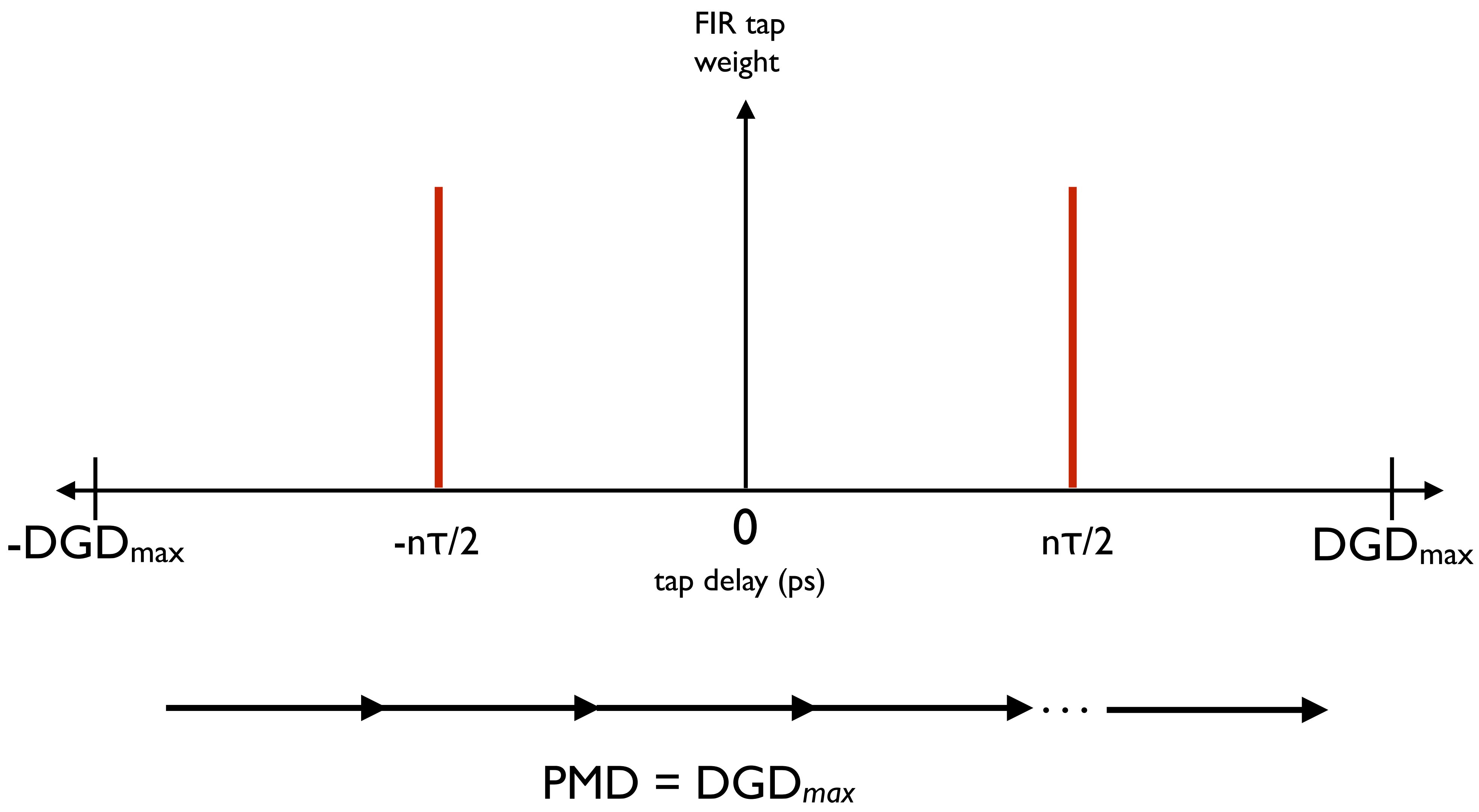
This is a best way to test the dynamic PMD mitigation of receivers

The Hardest PMD State For a Coherent DSP Receiver To Correct is PMD = DGD_{max} - *Huh?*

- With DSP correction you can fix ANY linear impairment limited only by the depth of the FIR filter. The DSP cannot and does not correct for amplitude.
- PMD has a linear, "all-pass", spectral response, requiring only a phase and SOP correction. PMD only redistributes the energy in time and polarization. No information is lost.
- Therefore the DSP can fix all PMD orders. The DSP doesn't even know about DGD or SOPMD, …
- In fact, the correction FIR filter creates the time-reversal of the PMD impulse response.
- Therefore the hardest PMD state to correct for a DSP FIR is the PMD with the LONGEST impulse response delay in time. i.e ***DGD_{max} should be the sole PMD test spec artifact.***

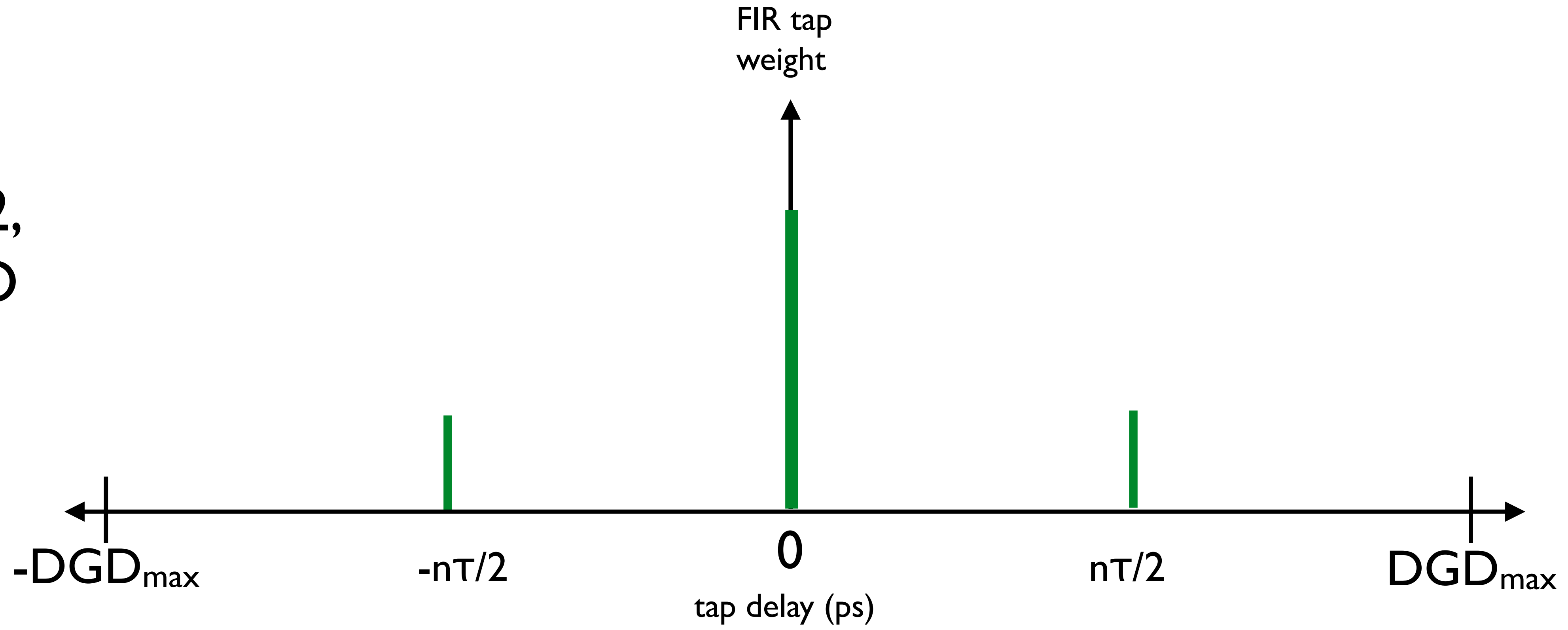
The Hardest PMD State To Test For a Coherent DSP Receiver is PMD = DGD_{max}

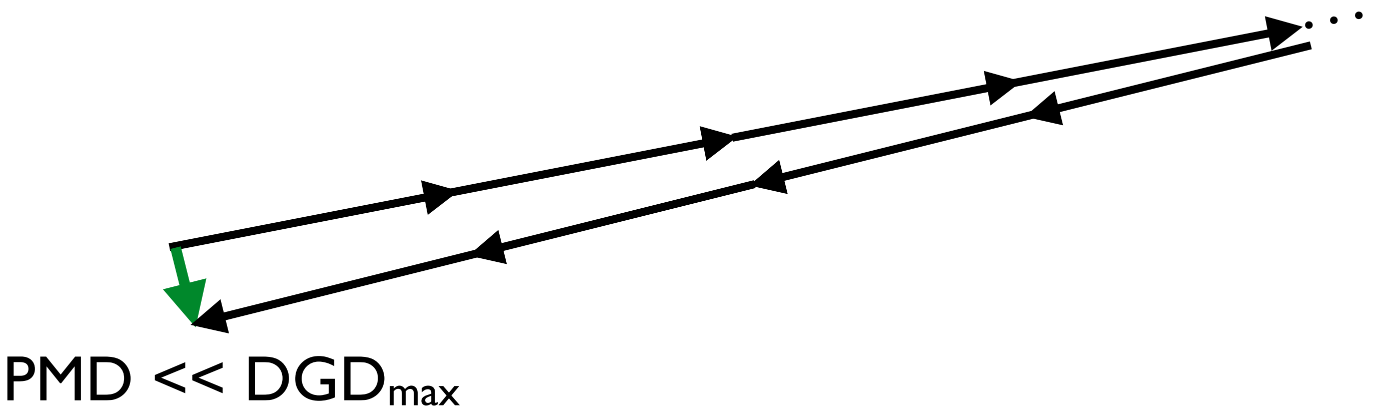
- DGD_{max} requires the most tap delay to realign all the power in the bit
- The state DGD_{max} is created when all the birefringence elements that exists in the fiber are aligned into one long delay.
- And no other birefringence exists in the fiber to cause any more impairment.



Consider Another PMD State

- An artifact made of two equal pieces of birefringence, each with delay n*τ/2, at an obtuse angle creating small DGD and small SOPMD
- The green bars are the impulse response of this artifact.
- The magnitude of the sidebands change with varying input SOP
- All elements require less DSP correction than the most stressful, DGD_{max}





Example of PMD Artifact With DGD and Depolarization SOPMD

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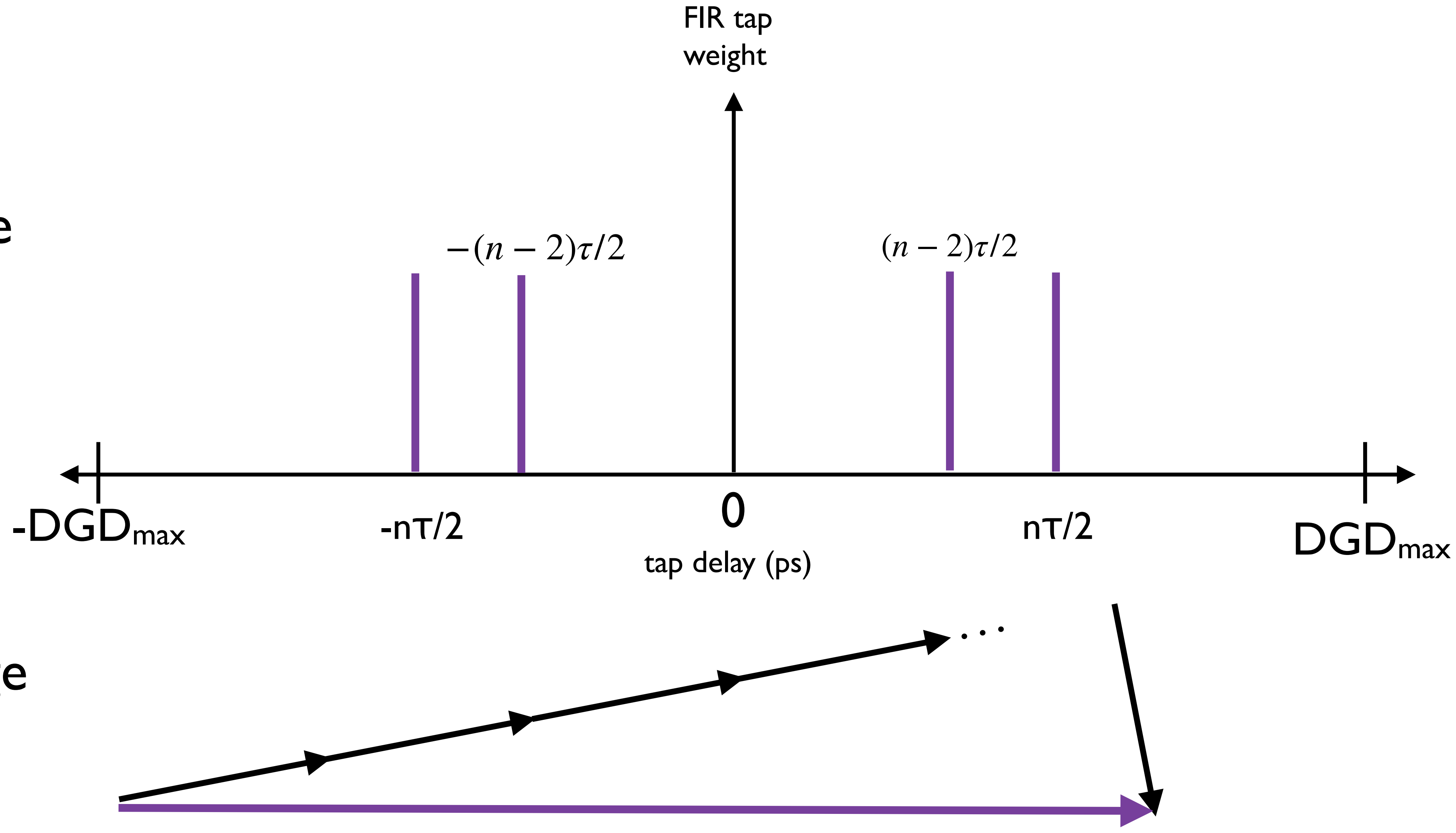
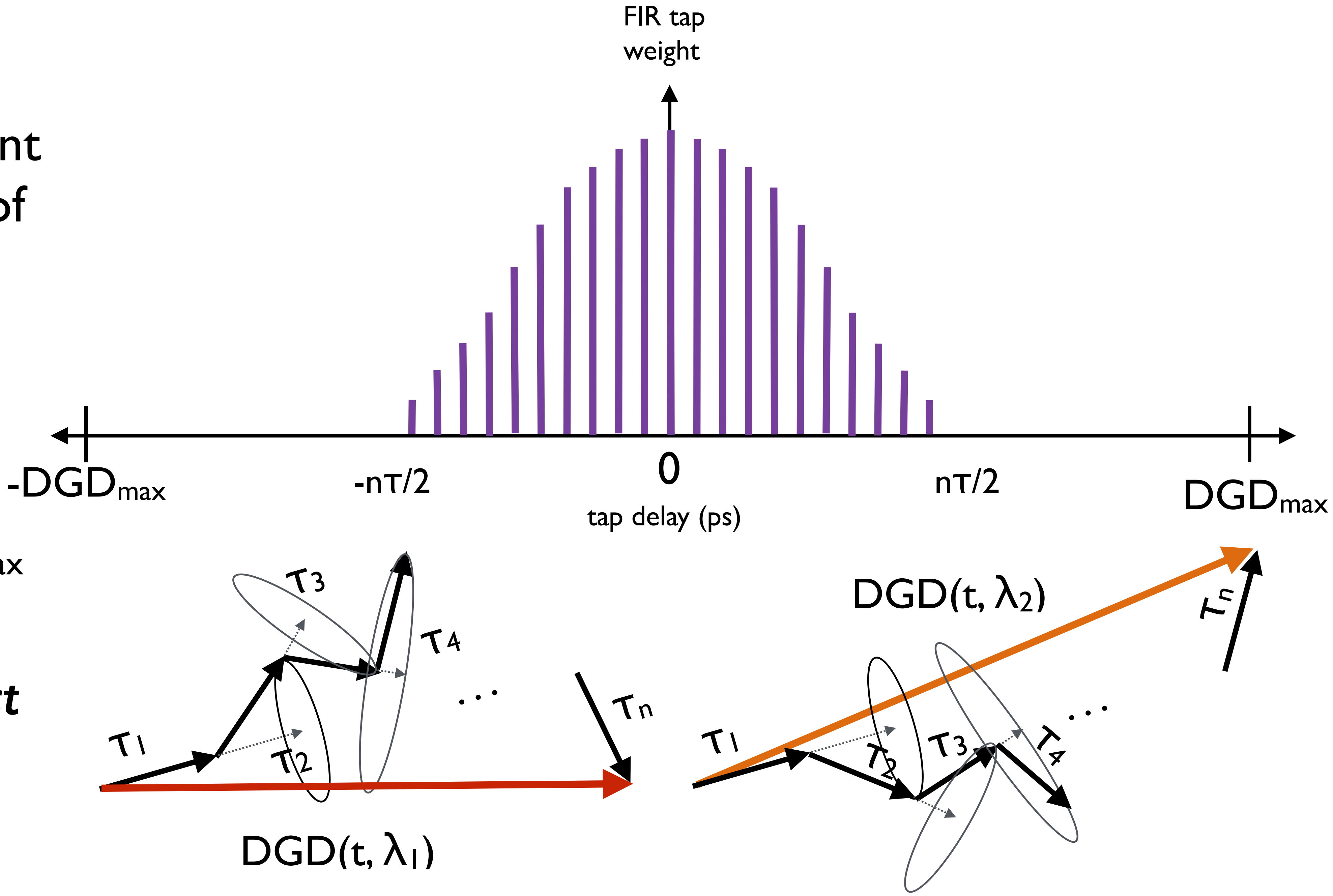
- An artifact made of two pieces of birefringence, (n-1)*τ/2 and τ, with the fast slow axes at 45° to each other, creating a fairly large DGD with depolarization SOPMD
- The purple bars are the impulse response of this artifact.
- The magnitude of the sidebands change with varying input SOP
- All these elements require less DSP delay and correction than DGDmax



$$DGD = \sqrt{[(n-1)\tau]^2 + \tau^2}$$

A General PMD State Has More Impulse Response Taps But All Less than DGD_{max}

- Each birefringent element is a a different angle creating a state of Many orders of PMD that changes with wavelength.
- The purple bars are the impulse responses of this state.
- Again all these elements require less DSP delay and correction than DGD_{max}
- *So more complicated PMD states are NOT harder for the DSP FIR to correct than the most basic & simple PMD = DGD_{max}*



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Conclusions and Summary

- Coherent and Pol-mux Transceivers must be tested for their ability to continuously operate when the polarization changes
- There are three types ΔSOP/Δt changes that need to be tested, scrambling, spinning and jumping the SOP.
- More controlled and repeatable dynamic PMD tolerance of a coherent DSP receiver testing is done by scrambling the ΔSOP into a PMD artifact with DGD_{max}.
- Two high speed endless polarization controllers are required for testing Coherent and Pol-muxed receivers: (1) pol-demux and (2) dynamic PMD

Simple and Sufficient PMD and SOP Tests Yet Quantitative, Repeatable, Comparable and Complete

Test	1st Pol Controller	PMD state	2nd Pol Controller	Comment
Determine DSP pol demux limit	0	0	1/2-waveplate Rotating at 0 - 100 krad/s	orientation of waveplate varied to cover all SOPs, but ΔSOP/Δt remains constant
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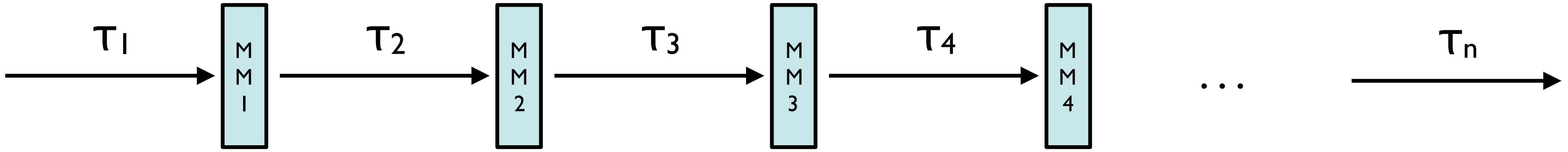
Modeling and Emulating PMD



- The standard (numerical) model for fiber PMD (and PMD Emulators) has n ≳ 8 birefringence elements, τ_i , separated by n-1 mode-mixers, MM_i.
- The PMD generated by emulator is the vector sum of the elements, τ_i , $PMD(t, \lambda) = \sum_{1}^{n} \vec{\tau_i}$
- The model assumes random-walk of all mode-mixing angles such that the DGD make a random walk between $DGD_{min} = 0$ to $DGD_{max} = \sum_{1}^{n} |\vec{\tau_i}|$
- The histogram of the random walk of DGD states is given by a Maxwellian distribution where $DGD_{max} \equiv 3.3 \langle PMD \rangle$