Polarization: A Brief History and Overview

What is Polarization and Why Does It Matter?

In the 1990s, the internet was in its infancy and fiber optic communication was at the cusp of unlocking more bandwidth than anyone could possibly imagine. Back then, the perceived need for bandwidth was fueled by the promise of dot-com 1.0 companies, the emergence of cellular phones and early online software services led to enormous development, roll-out, and nearly ubiquitous adoption of high-bandwidth wavelength division multiplexing (WDM) fiber optic networks. At the time, the fiber-optic telecom community worried that the limitations of the fiber itself would impede development and deployment of higher bit rates and greater bandwidth fiber optic systems. Fiber impairments, such as polarization mode dispersion (PMD), which adversely affects system performance, were feared to be nearly insurmountable barriers that would impede the upgrades from 2.5 GB/s to 10 GB/s, especially for incumbent fiber networks.

Before the turn of the millennium, during the telecom boom years, three companies emerged with solutions to polarization challenges: Luna Innovations, General Photonics (GP) and YAFO Networks. Luna focused on fiber optic test and measurement, developing products such as the Optical Vector Analyzer (OVA), a device for all-parameter characterization of fiber components from couplers to specialty fiber, and everything in between (e.g. Fiber Bragg Gratings, arrayed waveguide gratings, free-space filters, tunable devices, amplifiers, etc.), with a single sweep of a tunable laser.

YAFO was the first to address the PMD fiber impairment with an optical compensator to enable 10 GB/s data rates over the legacy fiber plant. GP followed a similar path into PMD and polarization control, with its internally developed technology. When the dot-com bubble burst in 2000, and then the telecom bust of 2002, everything changed. The forecasted explosive growth of bandwidth demand evaporated, and with it the demand for many of these products nearly disappeared.

The deployment of low PMD fiber and WDM fiber optic networks had created a glut with much more bandwidth than was actually needed in the early 2000s. Companies like Luna, GP and YAFO each needed to regroup, refocus, redefine themselves and retarget on new markets, away from telecom. Luna migrated into sensing. And GP retrenched with its internal polarization control technology, shifting to medical applications and fiber optic test and measurement. YAFO liquidated, selling its intellectual property assets to New Ridge Technologies (NRT). NRT focused on fiber optic test and measurement, particularly PMD simulation and high speed polarization control.

All three companies survived, found their footing and developed new technologies and products, while re-establishing themselves as market leaders within their niches. They competed against, and worked with, each other over the years.

In time new issues related to polarization came to the fore, challenging the fiber-optic technology community. To address these challenges, expand its market, and in its pursuit of becoming the world leader in fiber-optic sensing, and optical test and measurement, Luna acquired GP in 2019, quickly followed in 2020 by its acquisition of NRT. This powerhouse trifecta created a much larger, world-class, fiber-optic test and measurement company, with a concentration in fiber optic polarization expertise unmatched anywhere else. With the combination of the three companies, Luna embodies the world's leadership in fiber optics polarization expertise, capable of meeting the full spectrum of industry's polarization needs from customers anywhere around the globe.

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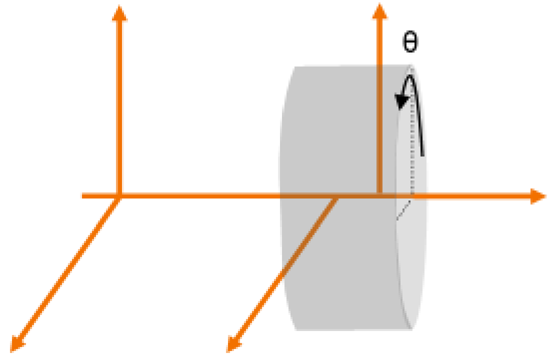
Fiber optic systems used to rely simply on transmitting and measuring the power of light. But in addition to power, the optical field has other characteristics such as its wavelength (or frequency), phase, and polarization. In particular, the polarization is the direction that the optical power is aligned (perpendicular to the propagation direction of the light). Polarization is often exploited to carry more information and power down the fiber. For instance, the emergence of internet 2.0 and ubiquitous video and audio mobile phone service (again) exploded

Figure 1. Representation of a waveplate, with fixed retardance, Δϕo-e, and ROTATABLE orientation, θ.



$$\Delta\phi_{o-e} = 2\pi\frac{[\Delta n_{o-e} \times L]}{\lambda}$$

bandwidth demands. The optical telecom industry responded, using polarization to help increase the bandwidth. With polarization-multiplexing, in which two perpendicularly polarized beams co-propagate without interfering with each other, the bandwidth of fiber optic channels was doubled. Polarization multiplexing is also used to double the intensity of high power industrial lasers and in military applications.

As polarization becomes increasingly used in fiber optic products, accurate control and analysis of polarization is essential in building and evaluating the performance of optical components, fiber and systems. Optical fiber and components may (intentionally or more often unintentionally) be anisotropic. Optical instruments that precisely control and characterize polarization are used to measure these effects of optical anisotropy such polarization dependent loss (PDL) and PMD. Luna's suite of polarization control, measurement, and emulation test and measurement products help improve processes by gathering more actionable data in the field, lab and assembly line.

In addition to test and measurement, Luna's polarization expertise is available in sub-systems incorporated into products such as Optical Coherence Tomography (OCT) devices using low-coherence light to capture micrometer-resolution two- and three-dimensional images for healthcare; distributed birefringence and transversal stress in Optical Frequency Domain Reflectometry (OFDR) to clearly identify the locations and magnitudes of the stresses inside a fiber; in Light Detection And Ranging systems (LIDARs), which is a remote sensing method for mapping used in aerospace and self-driving car applications; and coherent beam combination that uses polarization and phase control to add optical fields together into very powerful optical sources.

The Mechanics of Polarization Control

Fiber optic polarization control products are built upon a variety of technologies. To describe and compare their applications, one should begin with the waveplate, the original polarization control element, and how it is used to convert polarization. A waveplate is a cylindrical optical plate made from a birefringent crystal (e.g. calcite) for which two perpendicular axes in the plane of the plate have different indices of refraction (no and ne). Light traverses the waveplate at different speeds depending on the index of refraction aligned to the polarization of the light.

For instance, X polarized light may experience a phase shift of 2πnoL/λ. While the Y polarized light may experience a phase shift of 2πneL/λ. Making a birefringent phase difference between the two polarizations of light Δϕo-e (see Figure 1). Since this birefringent phase shift retards the exit timing of the polarization components compared to their entrance into the crystal, the net polarization of the light has been changed by the waveplate. Rotating the crystal varies the index of refraction seen by the different polarizations of light, modifying the output SOP.

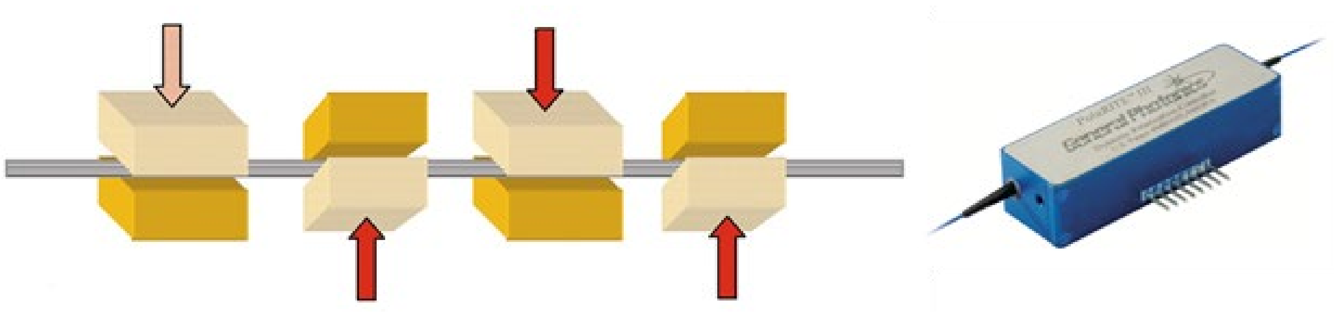


Figure 2. Multiple wave plates, with fixed orientation and variable retardance, make dynamic polcons that are low loss and wavelength insensitive. At the right is Luna's Polarite-III "squeezer" device.

Controllers based on waveplates of fixed retardation are wavelength sensitive. And physical rotation of crystals is generally slow. For better polarization control options, new technologies, with additional degrees of freedom, need to be introduced. One way is to cascade multiple waveplates. Many of us are familiar with the "Mickey Mouse ears," the fiber loop paddles to control polarization. This ingeniously simple device creates an equivalent of multiple birefringent crystals through the radial stress from circular loops of fiber. Fiber loop paddles have fixed retardance with rotational degrees of freedom limited to less than 2π. Although they are low cost and have low insertion loss, fiber loop paddles are limited to manual applications in the laboratory because of their slow response and inability to be automated.

Another way to add degrees of freedom is to dynamically change the birefringence of the waveplate. Changing the retardance requires modifying the optical properties of the waveplate. This is most commonly done by applying voltage to a waveplate made from an electro-optical material.

Moving from manual rotation of a fixed waveplate to electro-optically tuning a waveplate opens up huge practical advantages for polarization controllers (polcons). And each electro-optic waveplate technology has its own benefits and product limitations as speed, loss (IL and PDL), power handling, endless control and (of course) price. The key to Luna's polarization products is our experience and expertise with a wide variety of polarization control technologies. Over the years we have developed products with waveplates made from birefringent crystals, magneto-optics, liquid crystals, piezo-electric fiber squeezers and $LiNbO_3$. Each was picked to serve the specific purpose. In the remainder of this article we will cover the two complementary polarization control technologies that dominate the Luna product portfolio.

Fiber Squeezing

The fiber squeezer technology evolved out of General Photonics' labs in Chino, California. Simply put, a fiber squeezer does exactly what you may imagine: it pinches or squeezes the fiber, applying pressure to compress the glass, inducing optical birefringence to retard one polarization of light with respect to its orthogonal polarization. The localized birefringence in the fiber causes the polarization of the light passing through the squeezer to change the SOP. By changing the squeezer voltage, the birefringence is varied; from no voltage /no pressure/ no birefringence to maximum voltage / high pressure on the fiber / multiple radians of birefringence. The conceptual simplicity of the squeezer device is wrapped in a lot of sophisticated engineering. Three or four squeezer elements are

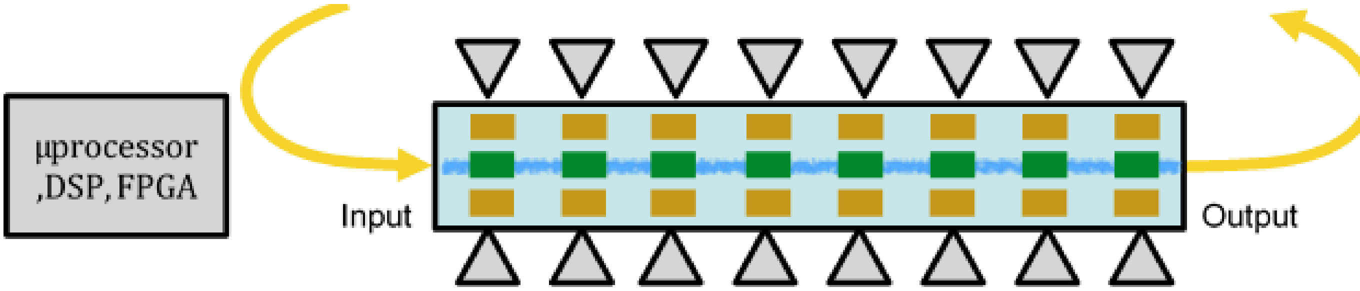


Figure 3: $LiNbO_3$ polcon with schematic drive electronics. Luna control electrodes to form endlessly rotating waveplates of variable birefringence. No HW resets are required. A large library of waveplate polarization functions has be implemented.

placed along the fiber, at different static orientations, to form the PolaRITE III squeezer device, the building block for many Luna polarization control products.

Because it is an all-fiber device and the light never leaves the fiber, the Luna squeezer technology has no back reflection, and has extremely low IL and PDL. With an activation-induced loss of less than 0.01 dB, it is useful in high-precision PDL instrumentation. The squeezer is also very broadband, working equally well for signals ranging from 1260 nm to 1650 nm. With a response time is 30 µs, squeezers are sufficiently fast to track, simulate or mitigate most typical, mechanically induced, polarization fluctuations in the lab and even network polarization changes due to cars, trains, wind, and even diggers along the fiber. However, birefringence range of the squeezer is not endless, but constrained by the range of pressure that can be applied to the fiber. When one squeezer reaches its limit, it can go no farther and needs to be reset. At this point another squeezer element needs to pick up the polarization control. For this reason, a 4-squeezer device, with an extra degree of freedom, is recommended for polarization tracking applications.

The Luna squeezer technology really shines in polarization medium-speed scrambling applications where broad spectrum and low PDL is required. The squeezer is relatively low cost and easily incorporated as an OEM module into optical products designed by other manufacturers. Lastly, because it is an all-fiber device the squeezer is easy to adapt to any wavelength window, by simply swapping the fiber type.

Lithium Niobate (LiNbO3)

For higher performance applications, some polarization products can be based on LiNbO3 controllers. LiNbO3 is a electro-optic birefringent material primarily known for its use in high speed optical communication modulators. The polcon device is fabricated from a LiNbO3 chip. A waveguide is defined inside the chip to guide the light from the input fiber to the output fiber. Over the top of the waveguide are 3 electrodes. The central electrode is usually grounded, and voltages are applied to the electrodes straddling the waveguide, which form an electro-optic waveplate transverse to the waveguide.

The features of the LiNbO3 waveguide waveplates are that:

(1) the birefringence is variable, much like a fiber squeezer

(2) the waveplates can rotate endlessly, with no limits or resets, by the correct application of sinusoidal voltage to the electrodes.

(3) because LiNbO3 has a very fast electro-optic response, the polarization can be modified in <1 µs.

Typically LiNbO3 polcons have 8 waveplates. Since each waveplate has both variable birefringence and rotatable angles there are 16 degrees of freedom.

So the advantages of the LiNbO3 technology are speed, endless, non-resetting control and 16 degrees of freedom. This places the LiNbO3 polcon in a class by itself above other polarization controllers. Any polarization control function that can be described by an algorithm can be coded to drive a LiNbO3 polcon. There are also downsides to the higher performance LiNbO3 polcon. It is more expensive and typical loss is 2.5 to 3 dB with PDL up to 0.3 dB.

Luna's LiNbO3 technology excels in polarization tracking applications where its superior speed, high degree of freedom, and extensive library of control algorithms enable hitless polarization and phase tracking for telecommunications and military applications. As a test and measurement tool, Luna's NRT-2500 has seven test functions, including ones specifically designed for high-speed coherent receiver testing and integrated optics chip testing.

Luna Polarization Control Products

Commercial polcon products fall into three technology classifications, which include multiple waveplates with:

(1) fixed birefringence but variable orientation angles;

(2) fixed orientation and variable retardation; and

(3) both variable retardation and orientation (see Figure 4)

Luna has focused on benchtop test and measurement and OEM modules made from both birefringence squeezers and LiNbO3 waveguide polcons, which are complementary technologies that enable Luna to address more applications than any other polarization solution provider in the industry.

	fixed angle	variable angle
fixed birefringence	Polarization converters (e.g. fixed waveplates, PMF)	 Endlessly-rotatable waveplate and limited-range rotation Paddle Loops (a.k.a. "Mickey Mouse ears") *manual, very slow, 10^0 radians/sec, and least effective polarization control method*
variable birefringence	 Birefringence Squeezers: 4 waveplate limited-range birefringence control *10^3 radians/sec*	 $LiNbO_3$ waveguide polarization controllers: endless angular rotation and limited birefringence range *best & fastest, 10^6 radians/sec, polarization control method*

Figure 4: Comparison of polarization control methods. Luna offers fiber squeezer based variable birefringence technology for price sensitive applications, requiring low IL and PDL. For everything else, the superior LiNbO3 polcon technology is offered. Both come in bench-top for test and measurement and circuit pack modules for OEM.

Looking ahead to the future of polarization

While Luna currently covers the widest spectrum of polarization-control applications in the market today, there are still a number of new applications on the horizon to strive toward, including polarization control function on a silicon chip, and PMD and SOP emulation for stressing coherent detection in the digital domain.

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