A Jewel in the Crown II

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12. Polarization

*Thomas G. Brown*

Polarization encompasses the vector character of light and is an academic subject over two hundred years old. Even at the founding of The Institute of Optics, much was already understood about how to measure, control, and make use of the polarization of light in optical instruments. With the invention of the laser, as sources of polarized light became more ubiquitous, faculty at The Institute of Optics and eventually the Laboratory for Laser Energetics relied more and more heavily on polarization-based optical science and engineering.

**Polarization and Coherence**

When Emil Wolf died in the summer of 2018, the optics world and The Institute of Optics lost a treasure. Emil was often called the father of modern coherence theory. He spent active years long after the usual retirement age focusing in on fascinating new problems that were emerging in physical optics. By the year 2000, he had already worked a number of years toward a unified theory of coherence and polarization: in Emil’s view, polarization should be described not simply in terms of a local polarization state (the traditional textbook view), but would be properly understood to include the spatial and spectral correlations between vector components that must exist in any real electromagnetic field. As he worked with students, postdoctoral scholars, and colleagues, he began to understand that the vector correlations must propagate in such a way that a quantity such as the degree of polarization and the spatial distribution of polarization states within a field will evolve and change under propagation. Many of these principles were laid out in detail in Mandel and Wolf’s *Coherence and Quantum Optics*, but Emil continued to feel that students could benefit from a shorter book summarizing the principles of classical coherence theory in a way that inclusion of polarization can naturally fit. The result of this project was the 2007 publication of the *Introduction to the Theory of the Coherence and Polarization of Light*. It included work with Olga Korotkova
(polarization and atmospheric turbulence), Govind Agrawal (propagation-induced polarization changes), Taco Visser, Greg Gbur, and many other former students and collaborators. Emil continued publishing in this area and, in his last ten years, proved that (at least in his mind) there remained many unanswered questions. He included some of them in the titles of his papers: “Does a light beam of very narrow bandwidth always behave as a monochromatic beam?” (with his last student, Mayukh Lahiri) and “Can a light beam be considered to be the sum of a completely polarized and a completely unpolarized beam?” (as sole author).

Meanwhile, Miguel Alonso, along with students and collaborators, was building on the mathematical foundations of both Wigner functions and ray-based wave fields to include both polarization and coherence in the radiometric description of optical systems. This work attracted collaborators across the globe who were intrigued by Alonso’s ability to take a complex problem needing four (perhaps five) dimensions to properly describe, and reduce its complexity using geometrical transformations and mathematical insights. Within The Institute, Miguel Alonso’s ability to illustrate his insights using real-time Mathematica computations became legendary.

Inspired by Emil’s infectious interest in experimental science, the Brown group collaborated with the Franco Gori group at Roma Tre (Italy) to construct an apparatus that could provide an experimental map of the correlation function between any two vector components of the field. Dean Brown (PhD student of Thomas Brown) was able to both collaborate with Emil on a measurement of a fully correlated azimuthal beam, and extend both the measurement and theory to better understand the polarization coherence structure of an azimuthally polarized critical or Kohler illumination system. It was around 2010 that Miguel Alonso joined the effort, assisting in the theory and design of an LCD mask–based coherence measurement system that culminated in the publication “Using shadows to measure spatial coherence.” The key recognition was that, within certain mathematical constraints, one could measure the 2D correlation function of a field about a particular point by using an amplitude or phase mask, along with its complement. In 2016, Katelynn Sharma and Greg Costello were able to complete an extension of this measurement to experimentally acquire the 4D polarization correlation matrix of an optical field, repeating Dean Brown’s results and extending the measurement to complex, space-variant polarization coherence functions.

Even in his later years, there was little activity in coherence and polarization at The Institute that did not have Emil’s influence. During Fall 2015, Miguel Alonso organized a seminar course in modern coherence theory (something Emil had taught for many years). It was held in the Physics Department, on a day each week when Emil (now over ninety years old) was on campus and available. Most weeks, Emil took the students and faculty out to lunch at his favorite restaurant. He continued to be intensely interested in their work. The work on polarization and coherence will, no doubt, continue at The Institute; however, we will continue to ask, “What would Emil say about this?” for many years to come.
Polarization in Quantum Optics

The burgeoning field of quantum information has, for the past thirty years, relied heavily on quantum optics. The groundbreaking work of Hong, Ou, and Mandel laid the foundation for studies of single-photon sources, single-photon interference, and two-particle entangled states (e.g., qubits) that rely heavily on entangled polarization states for implementation. One important path to practical, nonclassical sources is the single-photon source. Graduate student Luke Bissell, working with Svetlana Lukishova, Carlos Stroud, and Robert Boyd, demonstrated a room-temperature single-photon source based on fluorescence of dye molecules in a chiral nematic structure. Robert Boyd led several studies incorporating polarization into quantum optical schemes for angular momentum control and sorting, making use of q-plates, chiral materials, and surface plasmon polaritons.

Beginning in 2005, Joe Eberly began asking intriguing questions about classical analogs to entanglement, and whether one could create entirely classical fields that showed the essential mathematical properties of quantum entanglement. In a series of papers with his postdoctoral scholar Xiao-Feng Qian, he explored classical modes that are nonseparable combinations of polarization states and spatial modes. When cast in the language of quantum mechanics, Eberly and colleagues argued (and showed experimentally) that features (such as a violation of Bell’s inequality) can be seen in classically entangled fields. As a 2015 paper stated: “[There is a] growing recognition that entanglement is not exclusively a quantum property, and does not even originate with Schrödinger’s famous remark about it.”

The use of polarization in better understanding the “quantumness” of a light source has become even more intriguing in recent years. Beginning in 2016, Eberly, Qian, and Vamivakas began exploring what they referred to as the “last hidden optical coherence.” It had long been understood that the spin angular momentum of an optical beam was associated with its polarization, and the spatial mode with orbital angular momentum. By linking correlations between time, space, and polarization, the team was able to establish an experimentally tested equality relationship between measures of visibility, distinguishability, and spatiotemporal coherence.

As of this writing, we are seeing even more intriguing links between unconventional classical polarization states and their quantum counterparts beginning to emerge. Some of this is in work related to classical weak measurements led by Alonso, Brown, and recent PhD Anthony Vella. Other clues are found in the broad collaborations by Robert Boyd and Miguel Alonso on links between polarization (spin) and orbital angular momentum and on exploiting these links to find new ways to measure the polarization properties of single photons.

Polarization in Strong Field and Nonlinear Optics

It has long been understood that optical transitions both in atoms and solids are fundamentally polarization dependent. In the strong-field limit, the photons
involved in double ionization need not have the same polarization or phase. Furthermore, the resulting electron correlation in strong-field ionization can yield potentially interesting quantum states of the subsequent electron pairs. Joe Eberly and former PhD student Xu Wang published a series of papers exploring the polarization dependence of double ionization, concluding that the polarization ellipticity can have a strong influence on the ionization probability.

In nonlinear optics, the anisotropy of materials used for frequency mixing (e.g., doubling and downconversion) and the induced anisotropy in soliton interactions can result in nontrivial, and therefore highly interesting, phenomena. In 2007, a list of the most-cited books in physics was released. The most cited was Born and Wolf’s *Principles of Optics*. But also appearing prominently in the top ten were *Nonlinear Optics*, by Robert Boyd, and *Nonlinear Fiber Optics*, by Govind Agrawal. The secret was out: The references familiar to generations of Institute alumni were now appreciated throughout the world.

**Unconventional Polarization States**

It was the early 1990s when Dennis Hall began asking what type of laser modes would exist in a circularly symmetric distributed feedback (DFB) laser. He knew that such a laser would oscillate in the plane of the waveguide, but with an out-coupled beam that would diffract out perpendicular to the surface of the structure. So-called second order or third order DFB lasers were well known, but none emitted a clean circular beam. What was somewhat surprising was that the natural modes of oscillation of such a laser produced a beam with an optical vortex at its center and a tangential polarization distribution about the axis of the beam. Dennis dubbed these “azimuthal polarizations,” and wrote an important paper entitled “Vector Beam Solutions to Maxwell’s Equations,” which laid out the propagation and focusing properties of an azimuthally polarized Bessel-Gauss beam. Meanwhile, Thomas Brown was taking great interest in possible applications of these beams as well as simpler ways of generating them. (Dennis and his group had found that the lithographic precision and control of the gain medium made it difficult to maintain a stable mode profile in the DFB laser.)

Brown also recognized that the homology of Maxwell’s equations required that there be an equivalent solution in which the magnetic field was azimuthally polarized, leading to a beam polarization with an electric field polarized in a radial direction. He and his student Kathleen Youngworth began asking what might happen if such a beam were tightly focused using a well-corrected, high numerical aperture lens. And did there exist simple experimental arrangements to transform a Gaussian beam, such as that coming from a HeNe laser, into a radial or azimuthal polarization? Following Dennis Hall’s description, they called these “cylindrical vector beams”—vector beam solutions to Maxwell’s equations that followed perfect cylindrical symmetry. One of the key results in these early investigation was
the realization that a focused, radially polarized beam could provide a focal field slightly smaller than predicted by scalar wave theory; more significantly, the energy density in the focal region was dominated by the polarization component along the optical axis. This, along with similar studies carried out by the Leuchs group (in Erlangen, Germany) spawned a flurry of activity in the study of descriptions of polarization.

When Lukas Novotny established his world-class nano-optics laboratory at The Institute, he brought with him the knowledge that nanostructures, particularly sharp tips and noble metal nano-antenna structures, were exquisitely sensitive to the 3D polarization structure of a focal field. His work on single-molecule fluorescence microscopy, tip-enhanced Raman microscopy, and nano-antenna design took polarized light to experimental scales that had been inaccessible to previous generations. In a collaborative effort with the Brown group, Lukas was able to show that the 3D orientation of single molecules could reveal the 3D in single-molecule imaging through the creative use of polarized light.

Stress-Engineered Optics and Full Poincare Beams

It was soon clear that radial and azimuthal beams were simply two members of a much larger class of beamlike optical fields that could be created by superposition (interference) or through a space-variant transformation element. Upon the suggestion of former student Stephen Kreger and in partnership with PhD student Alexis Spilman Vogt, Thomas Brown began exploring the use of spatially inhomogeneous stress birefringence as an engineering tool to create radial and azimuthal beams from ordinary, low-coherence sources. They soon found that an ordinary window with three peripheral stress points created a remarkable spatial structure; this finding continues to yield surprising results nearly fifteen years later. Among these results was an observation predicted and analyzed by Miguel Alonso, and carried out by Amber Beckley, that a stress-engineered optic (SEO) could transform an ordinary, circularly polarized Gaussian beam into a beam whose cross section carried a stereographic map of the Poincare sphere, containing every possible fully polarized state of the field within one beam. They coined the solution a “Full Poincare Beam”—in its simplest form, the beam was a superposition of Gaussian

Figure 12.1. Birefringence in a stress-engineered optic from Amber Beckley’s PhD thesis.
and LaGuerre-Gauss beams having orthogonal polarizations, and therefore followed simple, analytic propagation laws in the paraxial regime.

In subsequent investigations, the SEO opened up new avenues for polarimetry—the measurement of polarization. Building on the work of Amber Beckley, MS student Roshita Ramkhalawon showed that an SEO placed in an optical system could produce a point spread function whose shape was uniquely correlated with the polarization state (specifically, the Stokes parameters) of the input field. PhD student Brandon Zimmerman was then able to take this principle, optimize it, and apply it experimentally to a Mie scattering experiment. This opened up the possibility (which Zimmerman demonstrated) of single shot Mueller matrix polarimetry using unconventional polarization states.

**Polarization in Three Dimensions**

The full description and understanding of polarization in three dimensions has remained a subject of active study. Because textbook treatments of degree of polarization, Stokes parameters, etc., deal implicitly with beamlike (2D) solutions, the proper definition of both coherence and polarization in three dimensions remained ambiguous and (to use Emil Wolf’s favorite label) controversial. Emil himself wrote heavily on the subject, as did his former students and colleagues. As with much of his other work, Emil was chiefly concerned with the nature of a fluctuating field. Meanwhile, colleagues at The Institute and elsewhere were equally intrigued by the deterministic and beautiful structure that could be engineered into nearly deterministic fields. One of these was Robert Boyd, who coauthored a paper on the three-dimensional structure of a focused beam (a cousin to a Full Poincare Beam, produced by a so-called q-plate) that was shown to exhibit a type of Mobius strip in the polarization of the focal region. The work was later extended to more complex, knotlike field distributions linked to the topological features of the focal field.

Optical scattering (specifically Mie scattering) by small particles was another case that attracted the attention of Emil Wolf, Miguel Alonso, and Thomas Brown in separate collaborations. Emil addressed problems related to 3D stochastic descriptions, while Alonso, along with students Jon Petrucelli and Nicole Moore, began looking at the Mie scattering of nonparaxial fields using focused radial and azimuthal fields as a starting point. Brown and Youngworth looked at the scattering of axial fields from particles near a surface, and were able to map out axial field components using a confocal microscope illuminated with radially polarized light. Brown and David Biss, in work done for the semiconductor community, explored the scattering of radial and azimuthal fields from edges such as might be important in semiconductor metrology. The result was a new kind of dark-field confocal imaging that could highlight edges of a semiconductor structure in a way similar to that found in differential interference microscopy.
Polarization was an important part of the first beam line at LLE and triggered the Hoppy story made famous in the first edition of *A Jewel in the Crown*: Hopkins had spent much of the night trying to diagnose problems with the beam line, and finally yelled for someone who “knows something about polarization.” At LLE, the electro-optic materials required for q-switched and actively mode-locked lasers were dependent on careful polarization engineering; indeed, the original paper by Donna Strickland and Gérard Mourou laying out the science of chirped-pulse amplification that would eventually win them the 2018 Nobel Prize described in some detail the trick of using a polarization-based system to trap a pulse in a laser cavity for a prescribed number of round trips before releasing the amplified pulse.

Twenty years later, polarization remained a focus of tremendous importance at LLE. To achieve a smooth irradiance profile within a fusion target, it was necessary to spatially scramble both the phase and the polarization of the high-energy, 355 nm wavelength, pulse in each of the beams in the Omega system (and, eventually, its successor the Omega EP). Two parallel efforts were pursued: (1) James Oliver explored and optimized a glancing angle thin film deposition of columnar films; (2) Stephen Jacobs led an effort to produce photoaligned, high-damage threshold liquid crystal materials for patterned polarization conversion in the high-energy line. Meanwhile, Brian Kruschwitz (PhD graduate and instructor at The Institute) incorporated plasma electrodes into the large-aperture Pockels cells in the beam line, thereby allowing an increased aperture and much higher damage threshold for polarization-based high-energy laser elements.

**Polarization in Optics Education**

Ten years ago, there was a growing recognition that the study of polarization in the optics curriculum deserved an upgrade. This has happened gradually, in the undergraduate and graduate courses and laboratories. In Andrew Berger’s shepherding of the course in electromagnetic theory for undergraduates, he spends a great deal of time on understanding polarization, how it changes on reflection and through an anisotropic crystal, and the importance of polarization in optical scattering. On the graduate level, Thomas Brown introduced an MS-level course in polarization (that generally includes undergraduate juniors and seniors), and there has been a renewed interest in laboratories designed around modern polarization measurements. An example of this is the quantum optics laboratory, designed by Svetlana Lukishova, in which students use polarization-entangled states to explore violation of Bell’s inequality and to study single-photon and two-photon interference.

In summary, the contributions of Institute faculty, students, and alumni to polarization science and engineering have been exciting, productive, and fruitful.
over the last fifteen years. The number of students making use of polarization in their dissertations and project work has increased, as have the number of faculty that include polarization in at least part of their research portfolio. What will a review of polarization at year 100 look like? We will perhaps be writing more about the creative use of polarization in integrated quantum photonics, an emerging field here at The Institute and elsewhere. We will, no doubt, be writing about spin and orbital angular momentum in engineering terms; and surely we will be amazed at the new polarization-related physics that is being uncovered each day in ultrafast laser science and engineering. But, if Eberly and Vamivakas are correct, we will no longer be searching for hidden coherences, at least for optical fields.