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History of Light and Polarization

1.1 Early History of Light

Light is the most important element to the life on Earth, particularly to the existence of human beings. Light not only enables us to “see” for receiving visual information from our surroundings and communicating with others via gestures and expressions, but also provides the energy for living things to grow. The main source of light on Earth is the Sun, which provides the energy for the plants to grow via a process called photosynthesis (Morton 2009). While growing, the plants create sugars and carbohydrates (Stichler 2002), which release energy into the living things that digest them. Buried dead plants can also be turned into coal and fossil fuels by nature as a different form of energy. Another important source of light for humans has been fire, from ancient campfires using woods to last century’s kerosene lamps using fossil fuels, which also originated from the Sun light. With the development of electric lights and power systems, electric lighting has effectively replaced firelight. Interestingly, the origin of the electrical energy is still the Sun light because it is produced by burning the coal or fossil oil, or by the direct conversion using solar panels via photovoltaic effect. Some species of animals generate their own light via a process called bioluminescence. For example, fireflies use light to locate mates, and vampire squids use it to hide themselves from prey.

The most recent form of man-made light is laser beams, which are being widely utilized in human societies today, such as in optic fiber communication networks (the backbone of internet), printing (laser printers), navigation and guidance (optic gyroscopes and Lidar), medicine (laser diagnosis, surgical and treatment equipment), sensor (facial recognition in smart phones and temperature, pressure, and other sensors in industrial, medical, and defense equipment), and manufacturing (laser cutting and laser additive manufacturing), just to name a few. These laser applications have dramatically improved the quality of our lives behind scenes and many of us may not notice them. New laser based developments and applications are emerging almost every day to continue better our lives. That is why twenty-first century is considered the century of optics by many, just as twentieth century was regarded as the century of electronics.

Humans have been trying to understand and utilize light since very early stage of our civilization. The early studies of light may likely be initiated from trying to understand vision because ancient men started to wonder why they could see, while the early man-made optical devices may be for harvesting sun light. For example, the 3000-year old Nimrud lens made with a quartz crystal unearthed in modern-day Iraq was likely a sun-light concentrator for starting fire. Bronze concave mirrors dating back around West Zhou period (c. 1046–771 BCE) unearthed in Shan’Xi, China, from 1972 to 1995 are also believed for concentrating sun light for fire-starting. In fact, it was recorded in

a book called *Etiquette of Zhou* that the government had a dedicated official for using the concave mirror to start fire for religious rituals or ceremonies.

As early as sixth to fifth BCE, **Ancient Indian** developed some theories on light and believed that light rays were a stream of high velocity of *tejas* (fire) particles. In **Ancient China**, **Mozi** (c. 468–376 BCE), a renowned Chinese scientist and thinker during Warring States Period (c. 476–221 BCE) summarized 16 rules (eight each in two separate articles) regarding shadows, pin-hole images, and mirror images in his book *Mojing* (*Mo's Articles*) around 388 BCE, describing the relationships between the shadows and the light source positions, the relationship between the images and pin-hole positions, as well as the relationships between the image properties (size, location, and direction [inverted or upright]) and different types of mirrors (flat, concave, and convex).

Euclid of Alexandria (c. 325–265 BCE) is the first known author of a treatise on geometrical optics. His book, known as *Euclid's Optics*, influenced the work of later Greek, Islamic, and Western European Renaissance scientists and artists. In his book, Euclid observed that “things seen under a greater angle appear greater, and those under a lesser angle less, while those under equal angles appear equal.” In the 36 propositions that follow, Euclid relates the apparent size of an object to its distance from the eye and investigates the apparent shapes of cylinders and cones when viewed from different angles. While Euclid had limited his analysis to simple direct vision, **Hero of Alexandria** (c. 10–70 CE) extended the principles of geometrical optics to consider problems of reflection (catoptrics) and demonstrated the equality of the angle of incidence and reflection on the grounds that this is the shortest path from the object to the observer. On this basis, he was able to define the fixed relation between an object and its image in a plane mirror. Specifically, the image appears to be as far behind the mirror as the object really is in front of the mirror. **Claudius Ptolemy** (c. 323–283 BCE), in his book *Optics* (known as *Ptolemy's Optics*), undertook studies of reflection and refraction of light on flat surfaces in the second century BCE. Both Euclid and Ptolemy believed that sight worked by the eyes emitting rays of light.

Ibn Sahl (c. 940–1000 CE), a Persian mathematician and scientist, is known to have compiled a commentary on *Ptolemy's Optics* and wrote an optical treatise around 984. He studied the optical properties of curved mirrors and lenses, and discovered the law of refraction which was mathematically equivalent to Snell's law. He used his law of refraction to compute the shapes of lenses and mirrors that focus light at a single point on the axis. **Hasan Ibn al-Haytham** (c. 965–1040), an Arab mathematician, astronomer, and physicist, often referred to as “the father of modern optics,” studied the characteristics of light and the mechanism/process of vision, produced a comprehensive and systematic analysis of Greek optical theories, and wrote the influential *Book of Optics*. He was against Euclid and Ptolemy's opinion on eyes emitting light rays and insisted that vision occurs because rays enter the eyes and considered these rays as the forms of light and color. He then analyzed these rays according to the principles of geometrical optics and carried out various experiments with lenses, mirrors, reflections, and refractions to verify his analysis. He was an early proponent of the concept that a hypothesis must be supported by experiments based on confirmable procedures or mathematical evidence – an early pioneer in scientific method five centuries before Renaissance scientists. In the Far East, **Shen Kuo** (c. 960–1279), a Chinese polymathic scientist, was the first to have detailed description of camera obscura or pin-hole imaging in his book *Dreams Pool Essays* in 1088. In the late thirteenth and early fourteenth centuries, **Qutb-al-Din al-Shirazi** (1236–1311) and his student **Kamal al-Din al-Farisi** (1260–1320) continued the work of Ibn al-Haytham, and they were among the first to give the correct explanations for the rainbow phenomenon. al-Farisi published his findings in his book, *The Revision of Optics* (*Kitab Tanqih al-Manazir*), for refining al-Haytham's *Book of Optics*, which signified the beginning for humans to understand another important aspect of light: the color.

The English bishop, **Robert Grosseteste** (c. 1175–1253), may be the most influential figure in the understanding of light during the medieval Europe. He wrote on a wide range of scientific topics on the time of the origin and tended to apply mathematics and the Platonic metaphor of light in many of his writings. His works on light are more philosophical and have been credited with discussing light from four different perspectives: an epistemology of light, a metaphysics or cosmogony of light, an etiology of light, and a theology of light (Lindberg 1976). Grosseteste was the first of the Scholastics to fully understand Aristotle’s vision of the dual path of scientific reasoning: generalizing from particular observations into a universal law, and then back again from universal laws to prediction of particulars. He had read several important works translated from Greek via Arabic and produced important work in optics of his own. In *De Iride* he wrote: “This part of optics, when well understood, shows us how we may make things a very long distance off appear as if placed very close, and large near things appear very small, and how we may make small things placed at a distance appear any size we want, so that it may be possible for us to read the smallest letters at incredible distances, or to count sand, or seed, or any sort of minute objects.” Grosseteste is now believed to have had a very modern understanding of color, as described in his treatise *De Luce* (*On Light*) written in about 1225. In *De Luce*, Grosseteste also explored the nature of matter and the cosmos, and described the birth of the Universe in an explosion, four centuries before Isaac Newton proposed gravity and seven centuries before the Big Bang theory. Other important figures in understanding of light during the medieval Europe include **Roger Bacon** (c. 1214–1294), **John Pecham** (died 1292), **Witelo** (born c. 1230, died between 1280 and 1314), and **Theodoric Freiberg** (c. 1250–1310). Bacon wrote three books on light (*Perspectiva*, the *De multiplicatione specierum*, and the *De speculis comburentibus*) and cited a wide range of translated optical and philosophical works, including those of Euclid, Ptolemy, al-Haytham, and Aristotle. Pecham built on the work of Bacon, Grosseteste, and a diverse range of earlier writers to produce what became the most widely used textbook on Optics of the Middle Ages, the *Perspectiva communis*. His book centered on the question of vision, on how we see, rather than on the nature of light and color. Witelo drew on the extensive body of optical works translated from Greek and Arabic to produce a massive presentation of the subject titled the *Perspectiva*. Freiberg was among the first in Europe to provide the correct scientific explanation for the rainbow phenomenon. Although his work was independent from that of al-Farisi mentioned earlier, both authors relied on the *Book of Optics* by Ibn al-Haytham.

1.2 History of Polarization

Polarization is one of seven fundamental properties of light waves, together with the propagation direction, wavelength, intensity, speed, phase, polarization, and coherence. The early studies of light mostly concerned with the direction, color (wavelength), and brightness (intensity) because they can be directly observed with human naked eyes. For example, the reflection and refraction in the works of Euclid, Ptolemy, Ibn Sahl, and Ibn al-Haytham basically describes how the direction of a light ray changes upon incident on an object. The word “ray” basically implies the involvement of the direction. Similarly, the studies on color were the direct results of humans’ observation of rainbows and other colorful objects, such as flowers, leaves, and sky. On the other hand, the other fundamental properties of light, the speed, phase, polarization, and coherence, could not be observed directly and therefore were not studied until much later. In order not to defocus our attention to the subject of this book, the polarization, we will not go into the details of the other properties of light, but concentrate on humans’ understanding of polarization as it evolved in the history.

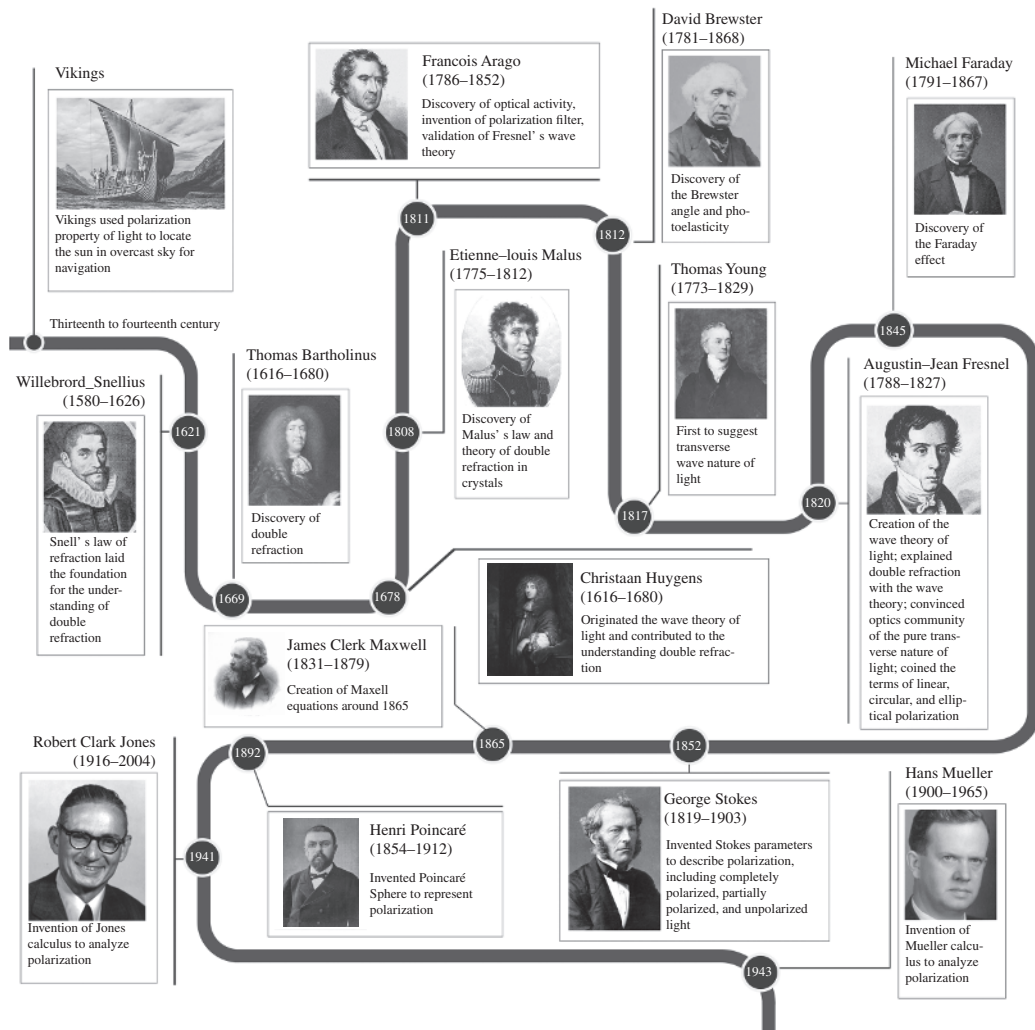


Figure 1.1 Historical milestones in understanding the polarization of light. Sources: Nejrion Photo/Adobe Stock; Unidentified painter/Wikimedia Commons/Public domain; Unknown author/Wikimedia Commons/Public domain; Henry Perronet Briggs/Wikimedia Commons/Public domain; Unknown author/Wikimedia Commons/Public domain; World History Archive/Alamy Stock Photo; ART Collection/Alamy Stock Photo; Photo Researchers/Science History Images/Alamy Stock Photo/Unknown author/Wikimedia Commons/Public domain; John Simon Guggenheim Memorial Foundation.

Figure 1.1 is the chronicles of polarization, showing the important milestones for the understanding of polarization by humankind in the history, manifested by the fundamental discoveries or contributions made by various individuals or group, which had profound impacts on the subject matter. **Vikings** were probably the earliest men who noticed the polarization property of light. In around thirteenth to fourteenth century, they used polarization property of light to locate the Sun in overcast sky for navigation with the aid of Sunstone or Iceland spar (calcite). In 1621, **Willebrord Snellius** (13 June 1580–30 October 1626), a Dutch physicist, astronomer, and mathematician, known in the English-speaking world as Snell, published the Snell law of refraction, which was mathematically equivalent to Ibn Sahl's law of refraction published around 984. Unfortunately, Ibn Sahl's law of refraction was not recognized earlier probably because it was not singled out as a law, but buried in the calculations of lenses' focusing effect in Ibn Sahl's

writings. Although Snell's law was not directly related to polarization, it was important for the understanding double refraction, which **Thomas Bartholin** (20 October 1616–4 December 1680), Danish physician, mathematician, and physicist, discovered and described in 1669.

In 1678, **Christiaan Huygens** (14 April 1629–8 July 1695), a Dutch physicist, proposed the wave theory of light: “Treatise on Light” and described it in 1690, which was regarded as the first mathematical theory of light. The theory was rejected in favor of Newton's corpuscular theory of light, until adopted by Augustin-Jean Fresnel in 1818. Now the theory is known as Huygens–Fresnel principle.

Many people considered **Étienne-Louis Malus** (23 July 1775–24 February 1812), a French physicist, as the father of polarization. His mathematical work was almost entirely concerned with the study of light. He conducted experiments to verify **Christiaan Huygens'** theories of light and rewrote the theory in analytical form. His discovery of the polarization of light by reflection was published in 1809 and his theory of double refraction of light in crystals, in 1810. Malus attempted to identify the relationship between the polarizing angle of reflection that he had discovered and the refractive index of the reflecting material. While he deduced the correct relation for water, he was unable to do so for glasses due to the low quality of materials available to him (most glasses at that time showed a variation in refractive index between the surface and the interior of the glass). It was not until 1815 that Sir **David Brewster** was able to experiment with higher quality glasses and correctly formulated what is known as Brewster's law. This law was later explained theoretically by **Augustin Fresnel**, as a special case of his Fresnel equation. **Malus** is probably best remembered for Malus's law, giving the resultant intensity, when a polarizer is placed in the path of an incident beam. His name is one of the 72 names inscribed on the Eiffel tower.

Francois Jean Dominique Arago (26 February 1786–2 October 1853), a French mathematician and physicist, discovered optical activity in 1811, invented polariscope and polarization filter in 1812, discovered polarized light from the tail of the Great Comet of 1819, and experimentally validated Fresnel's wave theory of light. Nowadays, polarization filters are used extensively in photography to cut out unwanted reflections or to enhance reflection. Interestingly, Arago was one of five judges in the award committee to judge the entries for the biannual physics *Grand Prix* to be awarded in 1819 and eventually wrote the committee's report. The other judges were **Laplace**, **Biot**, **Gay-Lussac**, and **Poisson**, mostly corpuscularists. With the encouragement from **Arago**, **Fresnel** submitted his prize entry titled “Memoir on the diffraction of light” on 29 July 1818, describing using wave theory of light to analyze diffraction. In order to disapprove Fresnel's theory, **Poisson**, a strong supporter of Newton's corpuscular theory of light, exploiting a scenario in which Fresnel's theory gave easy integrals, predicted that if a circular obstacle were illuminated by a point-source, there should be (according to the theory) a bright spot in the center of the shadow, illuminated as brightly as the exterior. Arago, undeterred, assembled an experiment with an obstacle 2 mm in diameter and observed indeed in the center of the shadow a bright spot which was later called Poisson's spot. Arago's verification of Poisson's counter-intuitive prediction passed into folklore as if it had decided the prize and was important to convince the scientific community to accept Fresnel's wave theory of light finally published in 1820.

Jean-Baptiste Biot (21 April 1774–3 February 1862), French physicist, astronomer, and mathematician, discovered optical activity in organic materials in 1815, laid foundation for liquid crystal display (LCD) display. In 1812, Biot turned his attention to the study of optics, particularly the polarization of light. Prior to the nineteenth century, light was believed to consist of discrete packets called corpuscles proposed and advocated by Newton. During the early nineteenth century, many scientists began to disregard Newton's corpuscular theory in favor of the wave theory of light. Biot began his work on polarization to show that the results he was obtaining could appear only if light were made of corpuscles. In 1815 he demonstrated that “polarized light, when passing through an organic substance, could be rotated clockwise or counterclockwise, dependent upon the optical axis

of the material.” His work in chromatic polarization and rotary polarization greatly advanced the field of optics, although it was later shown that his findings could also be obtained using the wave theory of light. Biot’s work on the polarization of light has led to many breakthroughs in the field of optics. LCDs, such as television and computer screens, use light that is polarized by a filter as it enters the liquid crystal, to allow the liquid crystal to modulate the intensity of the transmitted light. This happens as the liquid crystal’s polarization varies in response to an electric control signal applied across it.

Thomas Young (13 June 1773–10 May 1829), a British polymath, known for his double-slit experiment, experimentally demonstrated wave nature of light and laid the foundation of Fresnel’s wave theory of light. He was also the first person to suggest to Arago that the light waves were pure transverse in order to explain Arago’s experimental results, which could not be explained with Fresnel’s wave theory when light wave was believed to be longitudinal as **Huygens** assumed. In 1807, he invented the name “index of refraction,” which was called by Newton as “proportion of the sines of incidence and refraction” and by Hauksbee as the “ration of refraction.”

David Brewster (11 December 1781–10 February 1868), a Scottish scientist, discovered Brewster angle, which is one of the most important quantities related to polarization. He is principally remembered for his experimental work in physical optics, mostly concerned with the study of the polarization of light, including the discovery of Brewster angle. He studied the birefringence of crystals under compression and discovered photoelasticity in 1815, thereby creating the field of optical mineralogy. For this work, William Whewell dubbed him the “father of modern experimental optics” and “the Johannes Kepler of optics.”

Augustin-Jean Fresnel (10 May 1788–14 July 1827) perhaps is the most important figure in the history of polarization, as well as in optics. Fresnel was a French civil engineer and physicist whose wave theory of light published in 1820 completely won over Newton’s corpuscular theory. By supposing that light waves are purely transverse as suggested by Thomas Young, he explained the nature of polarization, the mechanism of chromatic polarization, and the transmission and reflection coefficients at the interface between two transparent isotropic media. By generalizing the direction–speed–polarization relation for calcite, he accounted for the directions and polarizations of the refracted rays in double-refractive crystals of the *biaxial* class (those for which Huygens’ secondary wave-fronts are not axisymmetric). The period between the first publication of his pure-transverse-wave hypothesis and the submission of his first correct solution to the biaxial problem was less than a year. Later, he coined the terms linear polarization, circular polarization, and elliptical polarization, explained how optical rotation could be understood as a difference in propagation speeds for the two directions of circular polarization, and (by allowing the reflection coefficient to be complex) accounted for the change in polarization due to total internal reflection (TIR), as exploited in the Fresnel rhomb. Not only Fresnel correctly predicted the pure transverse-wave nature of light in his wave theory of light in 1820, but he also correctly described “direct” (unpolarized) light wave as “*the rapid succession of systems of waves polarized in all directions*” in 1821, and gave the modern explanation of chromatic polarization. According to this new view, he wrote, “*the act of polarization consists not in creating transverse motions, but in decomposing them in two fixed, mutually perpendicular directions, and in separating the two components.*” Defenders of the established corpuscular theory could not match Fresnel’s quantitative explanations of so many phenomena on so few assumptions.

Despite the great success, there still remained a last weakness with the wave theory of light: the light waves, like sound waves, would need a medium for transmission and there was still no experimental proof that the hypothetical substance *luminiferous aether* proposed by Huygens in

1678 existed. This issue was not resolved until the wave theory of light was subsumed by Maxwell's electromagnetic theory in the 1860s. In the period between Fresnel's unification of physical optics and Maxwell's wider unification, a contemporary authority, Humphrey Lloyd, described Fresnel's transverse-wave theory as "the noblest fabric which has ever adorned the domain of physical science, Newton's system of the universe alone excepted."

An important development in the understanding of light is due to **Michael Faraday** (22 September 1791–25 August 1867), an English scientist, who discovered Faraday Effect in 1845 describing polarization rotation in certain media caused by a magnetic field. Nowadays the Faraday Effect is successfully used for sensing magnetic field and electrical current with light, particularly with optical fibers. Perhaps more importantly, it inspired **James Clerk Maxwell** (13 June 1831–5 November 1879), a Scottish scientist, to realize the linkage between the magnetic field and light, and led to the creation of Maxwell's electromagnetic theory (known as Maxwell Equations) between 1860 and 1871, the second great unification in physics unifying electricity, magnetism, and light, after the first one realized by **Isaac Newton** (unification of gravity). Maxwell's equations firmly establish that light is alternating electrical and magnetic fields of transverse waves, a view well accepted in the scientific community today. The last weakness of wave theory of light was finally overcome by Maxwell's electromagnetic theory of light: no medium is required for the light to transmit because the oscillating electrical field induces magnetic field, and vice versa as the light propagates in space or vacuum.

Note that Fresnel's wave theory was an amplitude description of light, completely successful in describing polarized light. However, the interference experiments by Fresnel and Arago were carried out with unpolarized or partially polarized light. Although Fresnel, together with Arago, summarized their interference experiment results as the four interference laws (Fresnel–Arago interference laws), unfortunately he was not able to mathematically describe the unpolarized light or to provide the mathematical statement of the interference laws until his early death in 1827. In the next 35 years, the mathematical description of unpolarized light and the Fresnel and Arago interference laws still remained unsolved.

In 1852, **George Gabriel Stokes** (13 August 1819–1 February 1903), an Irish physicist and mathematician, published a remarkable paper titled "On the composition and resolution of streams of polarized light from different sources," reporting a novel approach for mathematically describing not only the polarized light, but also partially and totally unpolarized light. He abandoned his predecessors' fruitless attempts to describe unpolarized light with amplitudes; instead, he used four measured intensities, or observables, known as Stokes parameters to define the polarization properties of light. With this approach, the mathematical statements of unpolarized light, partially polarized light, and completely polarized light, as well as Fresnel–Arago interference laws could be written within the framework of the wave theory of light. **Stokes** practically completed the unfinished task of Fresnel on the wave theory of light, but unfortunately his great paper was practically forgotten for nearly a century till it was re-discovered by the Nobel laureate, **Subrahmanyan Chandrasekhar** (19 October 1910–21 August 1995) who used Stokes parameters to describe the effect of polarized light in his study of radiative transfer published in 1950. Nowadays, Stokes parameters are widely used to describe the polarizations of both coherent and incoherent lights with the introduction of Mueller matrix calculus by **Han Mueller** in 1943.

Another important development in polarization optics is the **Poincaré Sphere**, the three-dimensional spherical volume with which any state of polarization and degree of polarization can be represented was credited to **Jules Henri Poincaré** (29 April 1854–17 July 1912), a French polymath. Poincaré made contributions in many areas of mathematics as well as astronomy and physics. The Poincaré sphere representation was first introduced in 1892 in Poincaré's book

Théorie Mathématique de la Lumière. Poincaré apparently was not aware of the Stokes parameters because he did not present the sphere as being generated using the Stokes parameters as values along orthogonal axes in a Cartesian coordinate system, a representation we often used today.

Robert Clark Jones (30 June 1916–26 April 2004), a researcher at Land Corporation and a Harvard professor, invented Jones vector and calculus to calculate polarization states after passing through optical elements in 1941. The work was published in a series of eight papers in the *Journal of the Optical Society of America* from 1941 to 1956. Nowadays Jones vector and calculus, sometimes referred to as Jones matrix formulation, are widely used in scientific research and engineering designs.

Hans Mueller (27 October 1900–10 June 1965), a Swiss–American physicist at the Massachusetts Institute of Technology (MIT), invented Mueller matrix calculus to manipulate Stokes vectors in 1943. Born in Switzerland and obtained his degrees from the Eidgenössische Technische Hochschule in Zurich, he came to MIT in 1925 and remained there for the next 40 years. Mueller matrix calculus is also widely used around the world today, especially when dealing with partially polarized or partially coherent light.

1.3 History of Polarization in Optical Fibers and Waveguides

1.3.1 The History of Optical Fiber

The history of polarization in optical fibers and waveguides could not even start without the history of guided light, which relies on a phenomenon called total internal reflection (TIR). The discovery of TIR was generally attributed to Johannes Kepler (27 December 1571–15 November 1630), a German astronomer, mathematician, and astrologer, who published his findings in his *Dioptrice* in 1611. Although Kepler did not find Snell's law of refraction (which was discovered 10 years later by **Willebrord Snellius**), from his extensive experimental studies on refraction between air-to-glass and glass-to-air, he concluded that when a ray is incident from glass-to-air at an angle beyond 42° , it could only be totally *reflected* (Total internal reflection – Wikipedia). This 42° angle was later termed as the critical angle of glass.

The first time that light was ever guided by the TIR was demonstrated in 1841 by Swiss physicist **Daniel Colladon** (15 December 1802–30 June 1893) in his attempts to show the speed of sound in water jets to the audience. In order to visualize the sound wave in water jet, he collected sunlight and directed into the water jet. The light was trapped by the TIR in the water jet and curved with it. A sound wave traveled in the water jet would disturb the TIR especially at the curved sections and cause glows to be seen. Colladon reported this experiment in 1842 to a wider audience in the *Comptes Rendus*, the French Academy of Sciences' journal. He later taught the tricks to **Louis Jules Duboscq**, a famous Paris instrument maker hired by Paris Opera, who then deployed them for special effect stage lighting, first appeared on stage in “Elias et Mysis” in 1853 as background fountains and later in Charles Gounod's opera “Faust” in 1859 to show the devil making a stream of fire flash from a wine barrel. With the successes on the stage, Duboscq published a catalog of luminous fountains aimed at the upper class, which even included rotating color filters to change colors, with list prices from 50 to 1000 French francs. In the International Health Exhibition held in 1884 in London, eight London water companies jointly built a huge luminous fountain to show their sparkling clean water. The fountain was designed and operated by **Sir Francis Bolton** with color changing filters and earned “unqualified admiration” remarks from *Nature*. More refined luminous fountains were later exhibited in Royal Jubilee Exhibition in Manchester in 1887 and in Universal Exhibition in Paris in 1889.

Around 1842, a French Physicist **Jacques Babinet** (5 March 1794–2 October 1872), the inventor of Babinet compensator, independently demonstrated light guiding in Paris by the TIR in water stream by focusing candlelight on the bottom of a bottle and pouring the water from the mouth of the bottle. In his article in *Comptes Rendus* per Arago's invitation to describe his experiments, he first reported light guiding in a curved glass rod to deliver illumination to the inside of a mouth. In 1854, a man named **John Tyndall** (2 August 1820–4 December 1893) demonstrated light guiding in water jets at the suggestion of Michael Faraday that made the topic more common knowledge. Tyndall also wrote about the property of TIR in an introductory book about the nature of light in 1870. In 1888, **Dr. Roth** and **Prof. Reuss** of Vienna used bent glass rods to illuminate body cavities for dentistry and surgery and realized Babinet's suggestion in practice. In 1889, **David D. Smith** of Indianapolis applied for patent on bent glass rod as a surgical lamp. In October of 1926, **John Logie Baird** applied for a patent on transferring images through glass rods and hollow tubes, and in December of 1926, **Clarence Hansell** proposed a fiber-optic imaging bundle in his notebook at the RCA Rocky Point Laboratory on Long Island, and received American and British patents later. Then in the 1930s **Heinrich Lamm** used the technology developed by Hansell and Baird to conduct internal medical examinations.

Circa 1949, **Holger Møller Hansen** in Denmark and **Abraham van Heel** in the Netherlands started to investigate image transmission in glass fiber bundles, and in 1951, Hansen filed a Danish patent application to propose applying a cladding for glass and plastic fibers with a transparent low index material. In October 1951, **Brian O'Brien** of the University of Rochester suggested to van Heel to apply a transparent cladding for improving transmission of fibers in his imaging bundle. On 12 June 1953, Dutch-language weekly *De Ingenieur* published van Heel's first report of clad fiber. On 2 January 1954, *Nature* published van Heel's paper on clad fiber bundles (van Heel 1954), and **Harold Hopkins and Narinder Singh Kapany's** paper on bundles of unclad fibers for image transmission next to each other (Hopkins and Kapany 1954, 1955). In 1956 **Basil Hirschowitz, C. Wilbur Peters, and Lawrence E. Curtiss** patented the first fiber optic partially flexible gastroscope, which was licensed to American Cystoscope Manufacturers Inc. in 1957. In early 1958, **Will Hicks** of American Optical (AO) Company developed practical fiber-optic faceplates for military imaging systems and later in the same year he, together with **Paul Kiritsy** and **Chet Thompson**, left American Optical to form the first fiber-optic company, Mosaic Fabrications in Southbridge, Massachusetts, the same town where American Optical is located.

In a job interview at American Optical (AO) in 1958, **Elias Snitzer** (27 February 1925–21 May 2012) was shown with a picture of the end of fiber-optic faceplate and he immediately recognized waveguide modes because he was very familiar with the mode patterns in dielectric microwave waveguides when he consulted with a firm called High Voltage Engineering on a proposal for Stanford Linear Accelerator to calculate wave-guide mode propagation in linear accelerator type applications. In 1958, working with Hicks, AO produced the first single-mode fiber and **Elias Snitzer**, after hired by AO, started to develop the dielectric waveguide theory using the Maxwell equations to describe waveguide modes in thin optical fibers with cores on the order of wavelengths, because the geometrical optic treatment of optical fibers was no longer sufficient for such small glass core fibers. He first reported his theory (Snitzer 1959a, paper TB36 by himself) and related experiment (Snitzer et al. 1959, paper TB37 with his colleagues **H. Osterberg, M. Polanyi, and W. Hicks**) at Optical Society of America's (OSA) annual meeting in October 1959. He even developed the well-known coupled mode equations to describe optical coupling between two parallel waveguides and reported the work in the same conference (Snitzer 1959b, paper TB38). **Snitzer** recognized the importance of single-mode transmission and applied for a patent with Hicks in 1960. In 16 May 1960, **Theodore Maiman** demonstrated the first laser at

Hughes Research Laboratories in Malibu, California. In October 1964, **Charles Koester** and **Elias Snitzer** described the first optical amplifier using neodymium-doped glass. In 1965 **Manfred Börner** demonstrated the very first fiber-optic data transmission system, and one year later, in 1966, he patented this new innovation that should be considered as a serious alternative to copper wires.

Charles K. Kao (4 November 1933–23 September 2018) is perhaps the most critical figure in advocating optical fiber for communication and was recognized by being awarded with a Nobel Prize in Physics in 2009. In December 1964, Kao took over Standard Telecommunication Laboratories' (STL) optical communication program when **Antoni E. Karbowiak** left to become chair of electrical engineering at the University of New South Wales. Kao and **George Hockham** soon abandoned thin-film waveguide in favor of single mode clad optical fiber. In the fall of 1965, Kao concluded that the fundamental limit on glass transparency was below 20 dB/km, which would be practical for communications and Hockham calculated that the radiation loss in clad fibers should sufficiently low. They prepared a paper proposing fiber-optic communications. In January 1966, Kao announced to the Institution of Electrical Engineers in London that glass fibers could be made with loss below 20 dB/km for communications, and in July 1966, Kao and Hockham published the paper proposing optical fibers for communications with convincing evidence in *Proceedings of the Institution of Electrical Engineers* (Kao and Hockham 1966). In their theory they showed the attenuation (light loss) could go below 20 dB/km if the correct materials were used. However, at the time of this determination, optical fibers commonly exhibited light loss as high as 1000 dB/km and even more. In 1968, Kao and **M.W. Jones** measured intrinsic loss of bulk fused silica at 4 dB/km, the first evidence of ultra-transparent glass, prompting Bell Labs to seriously consider fiber optics.

In the summer of 1970, **Robert D. Maurer**, **Donald Keck**, **Peter C. Schultz**, and **Frank Zimar** produced an optical fiber with 16 dB/km attenuation at 633 nm by doping titanium into fiber core and two years later in 1972, they were able to produce multimode germanium-doped fiber with attenuation levels as low as 4 dB/km, with much greater strength than titanium-doped fiber. Around 1970–1971, **Dick Dyott** at British Post Office (Dyott and Stern 1971) and **Felix Kapron** of Corning (Kapron and Keck 1971) separately discovered that pulse spreading caused by dispersion was lowest at 1.2–1.3 μm , and in 1965, **Dave Payne** and **Alex Gambling** at University of Southampton confirmed that pulse spreading should be zero at 1.27 μm . In early 1976, **Masaharu Horiguchi** and **Hiroshi Osanai** of Japan made first fibers with a low loss of 0.47 dB/km at 1.2 μm . In the summer of 1976, **Horiguchi** and **Osanai** of Japan discover third fiber-optic transmission window at 1.55 μm . Late in 1976, **J. Jim Hsieh** made the first indium-gallium arsenide phosphide (InGaAsP) lasers emitting continuously at 1.25 μm , providing the light source required for the 1.2–1.3 μm communication window. In late 1978, **NTT Ibaraki lab** made single-mode fiber with record 0.2 dB/km loss at 1.55 μm . Such low levels of attenuation and dispersion made optical fiber a very practical choice for communications and triggered a series chain effects in the commercialization of the technology. For example, **Bell Labs** publicly committed to single-mode 1.3- μm technology for the first transatlantic fiber-optic cable, TAT-8 in 1980; **ITT** signed consent agreement to pay **Corning** and licensed Corning communication fiber patents in the same year; **British Telecom** transmitted 140 Mb/s data through 49 km of single-mode fiber at 1.3 μm in 1981; **MCI** leased right of way to install single-mode fiber from New York to Washington operating at 400 Mb/s at 1.3 μm in December 1982. After these notable discoveries and commercialization efforts described earlier, little bits of research here and there have accumulated into the modern day optical fiber we know and love.

1.3.2 History of Polarization in Optical Fibers

The first mention of polarization in optical fibers was perhaps by **W. Hicks** representing both Mosaic Fabrication and American Optical, and **R.J. Potter** of University of Rochester, in their attempts to develop an electromagnetic theory of optical fiber reported at OSA's annual meeting in October 1959 (Hicks and Potter 1959, paper FB39). In the abstract, they outlined their presentation to include “a few comments about the splitting of momentum levels due to polarization, a discussion of bent fibers and cones and cross coupling between modes...” Interestingly, Potter and Hicks were also working on the geometrical theory of optical fibers, as reported in the related work at the same conference (Potter and Hicks 1959, paper FB38). Apparently, Hicks was very familiar with the theoretical work of **Elias Snitzer**, and had collaborated with Snitzer on the experiments (making the fiber for Snitzer) to observe the modes predicted by Snitzer's electromagnetic theory (Snitzer 1959a, paper TB37). Hicks and Potter might have realized the limitations of their geometrical theory and started to develop their own theory with the similar electromagnetic wave approach. Clearly, Snitzer was much more advanced in the efforts because he presented three reports (Snitzer 1959a, 1959b; Snitzer et al. 1959, papers TB36, TB38, TB37) in the same conference describing his theoretical and experimental work on the electromagnetic wave description of waveguide modes in optical fibers with much more solid results.

Elias Snitzer is the first to report solid theoretical and experimental studies of the polarization of light in optical fibers, particularly associated with waveguide modes. In May 1961, **Snitzer** published his detailed electromagnetic theory of optical fibers, titled “Cylindrical dielectric waveguide modes,” in the *Journal of the Optical Society of America* (Snitzer 1961). In the paper, he started with Maxwell Equations to derive expressions for different waveguide modes in optical fibers and plotted electrical and magnetic fields inside the fiber, which was the first description of polarization in optical fibers. In the same issue of the journal, together with his colleague **Harold Osterberg**, Snitzer also published his experimental results titled “Observed dielectric waveguide modes in the visible spectrum” to verify his theoretical findings (Snitzer and Osterberg 1961). This paper shows that he is the first to measure the polarization of different modes in the fiber. At the end of the paper, Snitzer acknowledged Hicks for helpful discussions and for providing the special fibers in the study.

In January 1971, **L.G. Cohen** of Bell Labs published a paper in *The Bell System Technical Journal* titled “Measured attenuation and depolarization of light transmitted along glass fibers” describing his measurements of Stokes parameters and depolarization of a linearly polarized input light after passing through different multimode optical fibers (Cohen 1971). He observed significant depolarization due to light coupling into multiple waveguide modes and attributed the cause of the circularly polarized components to the cross-sectional ellipticity caused by squeezing during the fiber drawing process. In February 1972, **Felix Kapron**, **Nicholas Borrelli**, and **Donald Keck** of Corning published their detailed theoretical and experimental studies titled “Birefringence in dielectric optical waveguides” (Kapron et al. 1972) to describe polarization evolution in a single mode optical fiber under the influence of birefringence at 633 nm (He–Ne laser wavelength). They described polarization having some anomalous behavior which could be explained in terms of birefringence varying locally along the fiber, observed a depolarization about 1% per km, and estimated an upper information rate of over **1000 Gb/s** due to the birefringence. They finally concluded that because of the rotating fast-axis effect along the fiber, the overall phase retardation would not increase indefinitely with length, and that the guide dispersion rather than birefringence would limit the data rates. Concurrently, **W.O. Schlosser** of Bell Labs published his theoretical study on

the data rate limitation imposed by birefringence in a paper titled “Delay distortion in weakly guiding optical fibers due to elliptic deformation of the boundary” in February 1972’s issue of *The Bell System Technical Journals* (Schlosser 1972). This birefringence on the data rate limit is in fact the polarization mode dispersion (PMD) as we know today. Although the manuscript submission date of Schlosser’s paper was two months later than that of Kapron’s (13 September 1971 vs. 7 July 1971), we believe it is fair to credit the discovery of PMD effect to Kapron, Borrelli, Keck, and Schlosser. Note that Kapron’s conclusion that “the overall phase retardation would not increase indefinitely with length” is not exactly accurate. It is more proper to say that “overall phase retardation would not increase linearly with length, but rather increase with the square root of length.”

The first report on light induced birefringence in a single mode optical fiber via optical Kerr effect was first reported by **R.H. Stolen** and **A. Ashkin** in 1973 in a paper titled “Optical Kerr effect in glass waveguide” (Stolen and Ashkin 1973), in which a single mode fiber with a length of 0.58 m was used. A pulsed Xe laser at 535.3 nm was used to induce the birefringence change while a He–Ne laser at 632.8 nm was used to sense polarization rotation caused by the induced birefringence.

As the optical fibers became generally available, some researchers started to turn their attentions to using the optical fiber for sensing in which understanding the polarization properties was critical. In October 1975, **A. Rapp** and **H. Harms** from Siemens AG first reported the polarization maintaining capability of an optical fiber in their paper titled “Polarization optics of index-gradient optical waveguide fibers” (Rapp and Harms 1975) by launching a linear polarization into the fast axis of a graded-index fiber having a fairly large linear birefringence that resulted from mechanical stress created during fabrication. They found that the exit polarization can be rotated with the fiber output end. They are also the first to visually observe the polarization evolution along the fiber by looking at the Rayleigh scattering of light from the side perpendicular to light’s propagation direction inside the fiber, although they might have mistakenly attributed the scattering as the Tyndall scattering. In particular, light scattering in the glass fiber is preferentially normal to the polarization direction and no scattering can be seen by looking into the direction of linear polarization. Therefore by launching the input polarization 45° from the fast axis, the polarization would evolve from linear to elliptical, circular, elliptical, and finally back to linear along the fiber periodically, and the Rayleigh scattering of He–Ne red light viewed from the side would show such periodic change in intensity. In March 1976, the same group in Siemens, **H. Harms**, **A. Rapp**, and **K. Kemper**, first reported the magneto-optic properties in an optical fiber (Harms et al. 1976) and presented the theory to describe the polarization evolution of light under the influence of both Faraday Effect and linear birefringence inside fiber.

In 1976, **V. Vali** and **R.W. Shorthill** (Vali and Shorthill 1976) demonstrated the first optic fiber Sagnac interferometer for rotation sensing (the first fiber-optic gyroscope), pointing out the need for maintaining polarization in optical fibers for optical fiber interferometers. In October 1976, **R.A. Steinberg** and **T.G. Giallorenzi** first reported the performance limitations of waveguide switches and modulators imposed by polarization (Steinberg and Giallorenzi 1976), further elevated the need for polarization maintaining fibers. One approach was to make fibers with extremely low birefringence. In October 1978, a research group at Siemens published the results of their efforts in making an ultra-low birefringence fiber in their efforts to maintain polarization in optical fibers for current sensing and fiber-optic gyro applications (Schneider et al. 1978) with a linear retardation about $10^\circ/\text{m}$, five times better than the lowest reported previously. A year later, a University of Southampton group, **S.R. Norman**, **D.N. Payne**, and **M.J. Adams**, in England achieved a low birefringence fiber with a retardation of $2.6^\circ/\text{m}$ (Norman et al. 1979).

Another approach for maintaining the polarization was to make high birefringence fibers following **A. Rapp and H. Harms'** initial demonstration in 1975. From 1978 to 1982, several research groups were quite active in making such polarization maintaining (PM) fibers. The Bell Labs group included **Ivan P. Kaminow, Roger H. Stolen, V. Ramaswamy, R.D. Standley, D. Sze, W.G. French, J.R. Simpson, H.M. Presby, P. Kaiser, and W. Pleibel**, investigated different ways to introduce birefringence, including using non-circular fiber cores (dumb-bell and elliptical cores), non-circular claddings, and anisotropic strains. In March 1978, **Ramaswamy and French** first concluded that the birefringence produced from non-circular shape of the core was not sufficient to maintain the state of polarization when the fiber was subject to bend, twist, and pressure and anisotropic strain to increase the birefringence was suggested (Ramaswamy and French 1978), pointing to new directions for PM fiber development. Six months later, Stolen, Ramaswamy, Kaiser, and Pleibel reported a first PM fiber using non-circular cladding to cause the anisotropic strain and hence increase the birefringence (Stolen et al. 1978). In February 1979, **Kaminow and Ramaswamy** first theoretically predicted that non-circular cladding fibers could be fabricated from the usual low-loss high-silica glasses to have a strain birefringence as large as 5×10^{-4} resulting from the large differential thermal expansion between a silica outer jacket and a cladding-core region of silica doped with boron, germanium, or phosphorous (Kaminow and Ramaswamy 1979). In a short period of seven months, **Kaminow, Simpson, and Presby** successfully achieved a modal birefringence of 3×10^{-4} using the differential thermal expansion in a germanosilicate fiber with a circular core but the non-circular exposed-cladding. Measurements of birefringence agree with earlier calculations (Kaminow, Simpson, and Presby 1979). These studies paved way to the rapid development of PM fibers in the years followed.

Other groups included **R.B. Dyott, J.R. Cozens, and D.G. Morris** from Andrews Corporation of USA and Imperial College of England, **Luc B. Jeunhomme and M. Monerie** of CNET Lab, France, **S.R. Rengarajan and J.E. Lewis** of University of New Brunswick, Canada, **T. Hosaka, K. Okamoto, T. Miya, Y. Sasaki, and T. Eda** of NTT, Japan, and **T. Katsuyama, H. Matsumura, and T. Suganuma** of Hitachi, Japan. The Dyott group concentrated on using elliptical cores or elliptical cladding to introduce birefringence inside the fiber core, while Jeunhomme's group first proposed (Jeunhomme and Monerie 1980) circular core polarization maintaining fiber. After realizing from the stress analysis that the contribution of the stress-induced strain birefringence to modal birefringence was much larger than that of the geometrical anisotropy, the NTT group led by Hosaka started to investigate introducing birefringence using strain rods and reported the results in 1981 (Hosaka et al. 1981), the first PANDA fiber as we know it today.

As single mode fiber became generally available, many researchers also started to explore using fibers for sensing. Inevitably, understanding polarization variations in optical fibers became increasingly important. In January 1978, **A.M. Smith** of Central Electricity Research Laboratories in England reported the first use of a single mode fiber for current sensing (Smith 1978) and his study on the Faraday Effect induced polarization change in the fiber. Two years later, he also published the detailed studies on pressure induced birefringence (Smith 1980a) and on bend and twist induced birefringence in single mode fibers (Smith 1980b).

In **May 1979, G.B. Hocker** of Honeywell first proposed using optical fiber interferometers for temperature and pressure sensing (Hocker 1979).

The Max-Plant group led by **R. Ulrich**, with members including **A. Simon, M. Johnson, S.C. Rashleigh, W. Eickhoff, and A. Kumar**, was most active and productive in polarization related research in optical fibers from 1977 to 1981. They mostly focused on understanding polarization changes induced by bend, pressure, twist, magnetic field, and how to control or manage the state of polarization. Their studies on the fiber bend and twist induced birefringence in a single mode

fiber were reported a few months earlier than those by A. Smith. It is important to point out that Rashleigh and Ulrich were the first one to coin the term polarization mode dispersion (PMD) to describe the relative group delay between two orthogonal polarizations caused by birefringence in a paper titled “Polarization mode dispersion in single-mode fibers” (Rashleigh and Ulrich 1978). They also demonstrated the first passive PMD compensator by using a $\pm 68^\circ$ double twist at the center of the fiber, as reported in the same paper. It is also important to point out that M. Johnson made the first polarization controller using electro-magnet based fiber squeezers in 1978 (Johnson 1979) and Ulrich was the first to stabilize the output state of polarization in an optical fiber using such a polarization controller and a polarization detector in a feedback loop in 1979 (Ulrich 1979). In 1981, Kumar and Ulrich published their study on birefringence of optical fiber pressed into a V-groove, which concluded that in the absence of friction, the induced birefringence could be zero for a V-groove angle of 60° (Kumar and Ulrich 1981). Note that Rashleigh later joined US Navy Research Laboratory to develop fiber-optic sensors.

There have been tremendous advancements of polarization optics in optical fibers every year by many scientists and engineers working in the field since 1981. The history for this booming period is not covered in this book and may be covered in the second edition of the book.

1.3.3 Chronicles of Polarization Optics in Optical Fibers from 1959 to 1981

October 1959: Elias Snitzer, R.J. Potter, and W. Hicks reported initial investigation of polarization related issues in optical fibers at 1959 OSA annual meeting.

May 1961: Elias Snitzer of American Optical Corporation published the first electromagnetic theory of optical fibers, titled “Cylindrical dielectric waveguide modes,” in the *Journal of the Optical Society of America* (Snitzer 1961) with the plots of polarization distribution of different modes.

May 1961: Snitzer and Harold Osterberg published the results of the first experimental measurement of polarization directions of different fiber modes in the same journal.

January 1971: L.G. Cohen of Bell Labs published a paper in *The Bell System Technical Journal* titled “Measured attenuation and depolarization of light transmitted along glass fibers” describing his measurements of Stokes parameters and depolarization of a linearly polarized input light after passing through different multimode optical fibers.

February 1972: Felix Kapron, Nicholas Borrelli, and Donald Keck of Corning and **W.O. Schlosser** of Bell Labs first reported investigation of PMD effect on data transmission limit of fiber-optic communication systems and estimated an upper information rate of over **1000 Gb/s** due to the PMD. **Felix Kapron, Nicholas Borrelli, and Donald Keck** first reported linear birefringence induced by transverse stress and circular birefringence induced by twist in single mode fibers and the polarization evolution along a single mode fiber with the induced linear and circular birefringence.

March 1973: R.H. Stolen and A. Ashkin of Bell Labs first reported light induced birefringence in a single mode optical fiber via optical Kerr effect.

October 1975: A. Rapp and H. Harms of Siemens AG first reported the polarization maintaining capability of an optical fiber by launching a linear polarization into the fast axis of a graded-index fiber having a fairly large linear birefringence that resulted from mechanical stress created during fabrication.

March 1976: H. Harms, A. Rapp, and K. Kemper of Siemens AG first reported the magneto-optic properties in an optical fiber and presented the theory to describe the polarization

evolution of light under the influence of both Faraday Effect and linear birefringence inside fiber.

October 1977: A. Simon and R. Ulrich first reported a study of the polarization evolution along a single mode fiber with both electro-optic effect induced linear birefringence and Faraday Effect induced circular birefringence.

January 1978: A.M. Smith of Central Electricity Research Laboratories in England reported the first use of a single mode fiber for current sensing using the Faraday Effect.

March 1978: V. Ramaswamy and W.G. French first concluded that the form birefringence resulting from the non-circular shape of the core was not sufficient to maintain the state of polarization in single mode fibers.

August 1978: S.C. Rashleigh and R. Ulrich of Max-Plant Institute first coined the term polarization mode dispersion (PMD) to describe the birefringence induced group delay between two orthogonal polarizations in a single mode fiber in a paper. They also reported a **first PMD compensator** using the $\pm 68^\circ$ double twist midway of a single mode fiber in the same paper.

October 1978: Stolen, Ramaswamy, Kaiser, and Pleibel reported a first PM fiber using non-circular cladding to cause the anisotropic strain and hence increase the birefringence.

December 1978: M. Johnson submitted the report on the first polarization controller using electro-magnet based fiber squeezers to Applied Optics and the paper was published in May 1979.

February 1979: Kaminow and Ramaswamy first theoretically predicted that non-circular cladding fibers could be fabricated from the usual low-loss high-silica glasses to have a strain birefringence as large as 5×10^{-4} resulting from the large differential thermal expansion induced strain.

July 1979: R. Ulrich and A. Simon of Max-Plant Institute first reported twist induced birefringence in single mode optical fibers and described the $\pm 68^\circ$ double twist for interchanging the fast and slow polarization modes.

October 1979: Kaminow, Simpson, and Presby successfully achieved a modal birefringence of 3×10^{-4} using the differential thermal expansion in a germanosilicate fiber based on earlier prediction.

October 1979: R. Stolen of Bell Labs first reported polarization effects in fiber Raman and Brillouin Lasers.

December 1979: R. Ulrich of Max-Plant Institute reported the first polarization stabilizer using the polarization controller of M. Johnson.

June 1980: R. Ulrich, S.C. Rashleigh, and W. Eickhoff of Max-Plant Institute reported first bend induced birefringence in single mode optical fibers.

August 1980: A.M. Smith of Central Electricity Research Laboratories in England first reported polarization evolution in a fiber with both bend and twist.

September 1980: A.M. Smith reported detailed study on pressure induced birefringence.

November 1980: Luc B. Jeunhomme and M. Monerie of CNET Lab, France, first proposed circular polarization maintaining fiber.

July 1981: T. Hosaka, K. Okamoto, T. Miya, Y. Sasaki, and T. Eda of NTT, Japan, reported the first PANDA fiber which used differential thermal expansion of strain rods to introducing birefringence in the fiber core based on the earlier work of Bell Labs.

December 1981: Kumar and Ulrich found that for an optical fiber pressed into a V-groove, the induced birefringence could be zero for a V-groove angle of 60° in the absence of friction.

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