PRE–1940

1941–1959

1960–1974

1975–1990

1991–PRESENT

Introduction: Advances in Optical Science and Technology

Paul Kelley

World War II and the Start of the Cold War

The decades of the 1940s and 1950s saw tremendous change. The United States entered the war as the leading industrial power. It became even more dominant as the war progressed and the European Allies and the Axis Powers suffered great damage. The Cold War, which started shortly after World War II, led to further changes in the industrial outlook of the United States and the world in general. The harnessing of science in the national interest had become a priority prior to the war, and the Cold War and the development of nuclear weapons made its application even more imperative. At the same time, increased industrial sophistication led to more reliance on science to facilitate change and to the application of the tools of science in everyday industrial activity. A diverse group of scientific entrepreneurs developed new technological applications in academia, small start-ups, and corporate research laboratories. Optics and applications of optics played an important role in this progress.

In war time, the United States could not rely on Germany for optical materials and sophisticated optical designs. This had occurred in the First World War, and the U.S. did not want to have this problem repeated. Through the National Defense Research Committee (NRDC) a robust capability was developed for designing and manufacturing innovative optics for aerial reconnaissance. Optical scientists and engineers also contributed to the development of gun sights, range finders, and submarine periscopes. Anti-reflection coatings, which had been introduced in the 1930s, were developed and applied to military optics. Camouflage was another important area of optics that rapidly progressed during the war.

In the 1950s Edwin Land and James Baker persuaded President Eisenhower to develop the U-2 for surveillance of the Soviet Union. Baker had been a leading designer of aircraft reconnaissance cameras. His skill at optical design together with Land's close collaboration with the aircraft designer, Kelly Johnson of Lockheed, led to a well-integrated, optimal system still in use today. The U-2 was designed to fly above the existing intercept altitude of Soviet antiaircraft missiles and the U.S. was quite surprised when the USSR deployed a more capable missile system.

In 1947 Land introduced instant photography. In the black-and-white process, two sheets of paper are employed, one to produce a negative image, the other a positive. The same basic method as in conventional photography is used to produce a negative image. The negative paper is coated with small crystals of silver halide. Exposure to light produces some free silver atoms on the crystallites. After exposure, liquid chemicals are released that begin the development. The free atoms act as a nucleus for further free silver production, turning the exposed crystallites dark. Some of the silver halide crystals that are not initially exposed to light are transported to the adjacent second sheet of paper and then developed to produce a positive image. The Polaroid camera soon became very popular because of the excitement of instantly seeing one's photographs. Polacolor that produced color prints was introduced in 1963.

Applied spectroscopy, which saw increased application during the war, blossomed after the war as manufacturing became increasingly complex and diverse [1]. Synthetic rubber was crucial to the military, and infrared spectroscopy played a vital role in the rubber manufacturing process. The entry of Perkin-Elmer and Beckman into the spectrometer business was motivated by the use of their equipment in rubber manufacturing and fuel refining. Chemists, biologists, and other scientists soon came to embrace the use of physical measurements, most particularly optical spectroscopy in the infrared region. In 1950, the first Pittsburgh Conference on Analytical Chemistry and Applied Spectroscopy (Pittcon) was held. Optical techniques continue to play a central role in this enormous conference, which in 2015 had 16,000 attendees, 925 exhibitors, and more than 2000 sessions.

In 1957 fiber endoscopes were used for medical imaging by Hirschowitz employing bundles of clad fibers developed by Peters and Curtiss at Michigan [2,3]. In 1930 Heinrich Lamm demonstrated the concept of imaging through fiber bundles, H. H. Hopkins developed the fiberscope using coherent fiber bundles in the early 1950s [4], and, also in the early 1950s, A. C. S. van Heel proposed the use of cladding to avoid crosstalk between fibers. Fiber endoscopes are now widely used in clinical medicine, and fiber optical communication relies on the use of clad fibers.

In 1961 Xerox announced the first Xerox copier, which was based on an invention by Chester Carlson in 1938. The basic idea was to use optical transfer to produce an electrostatic pattern or image on a drum. This pattern then attracted black material (toner), which could be transferred to paper. Other printing technology developments in the 1940s and 1950s included phototypesetting, inkjet printers, and dye sublimation printing. A somewhat related area, photolithography of semiconductor circuits, was initially developed by Andrus and Bond at Bell Labs [5,6]. This was based on techniques used to make printed circuits. In one of its first large-scale applications, the printed circuit had been used during World War II for proximity fuses. The work of Andrus and Bond was quickly followed by efforts at Texas Instruments and Fairchild to miniaturize silicon circuits, an effort that would lead to the microelectronics revolution.

The most revolutionary invention in the century of optics, the laser, was first realized just after this period ended. Its precursor, the maser, came in the 1950s. Gordon, Zeiger, and Townes reported [7] the operation of the ammonia maser in 1954; this was followed by the development of solid state masers used in radio astronomy [8]. In 1958 Schawlow and Townes published a paper [9] describing the physics of masers and lasers and a proposed method for making a laser. The next year a conference was held at Shawanga Lodge in New York State, where further discussions were held concerning the possible operation of the laser [10]. The race was on.

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Inventions and Innovations of Edwin Land

Jeff Hecht

Edwin Land was the Thomas Edison of twentieth-century optics, a prolific inventor and entrepreneur. His milestone introduction of instant photography, at an Optical Society spring meeting in New York on 21 February 1947, often overshadowed his other contributions, ranging from 3D movies to surveillance satellites.

Land's first transformative invention was the plastic sheet polarizer in 1928, when he was not yet 20. Fascinated by polarization, he tried growing large sheets of iodoquinine sulfate, a polarizing material invented in the nineteenth century. That did not work, but he found he could make polarizing sheets by applying an electric or magnetic field to align tiny crystals of the material, then embedding them in a celluloid film. Later he invented a process for making polarizing sheets by stretching the plastic to align the polarizing crystals. Those plastic sheet polarizers became the foundation of the Polaroid Corporation.

Land also invented a polarizing filter system that he hoped could solve a major highway safety problem—headlights blinding other drivers at night. He proposed applying polarizers aligned one way to headlights and orthogonal polarizers to windshields. Light scattered from the environment would lose its polarization, so the windshield polarizer would transmit it. But the polarized windshield would block light directly from the headlights, so only a few percent would reach the driver's eyes. It sounded great, but the auto industry never embraced it.

Instead, the polarized film found other applications. In 1934, Eastman Kodak contracted to buy it for photographic filters. Kodak was also interested in polarizing sunglasses, but Land got a better deal from American Optical and in 1935 signed a contract to supply them with polarizing film bonded to glass for sunglasses.

Meanwhile, Land invented polarization-based stereoscopy for 3D movies. The first generation of 3D movies projected overlapping images in two colors, which viewers watched through glasses with red and green or red and blue filters. Land realized that glasses with a pair of polarizers, one horizontal and the other vertical, could give the same effect for overlapping images projected in horizontal and vertical polarization. A short polarized 3D film at the Chrysler Pavilion was a hit at the 1939 New York World's Fair. World War II interrupted 3D movie development but created a need for stereoscopic surveillance imaging that was met by the vectograph, a transparency-based process invented by Joseph Mahler and Land at Polaroid. Polarized 3D movies returned after the war to produce a brief boom in the early 1950s, including the first color 3D film, *Bwana Devil*.

A prescient question asked by Land's young daughter during a 1943 vacation launched his quest for instant photography. Why couldn't she see the photo he had taken right away? Land's logical mind realized it was a matter of chemistry, so he invented a self-developing film that combined exposure and processing of the negative and transfer to a positive. In early versions, the photographer pulled a paper tab or leader after exposure, starting a series of events. Inside the camera, a pair of rollers pressed the positive and negative sheets together and spread a processing fluid between them. This then emerged from the camera and, after a brief specified waiting time, the photographer pulled the two sheets apart to display the image. Afterward, brushing a final coating across the image could preserve it.

The first Polaroid cameras had input rolls of negative and positive monochromatic film. Color film followed in the late 1950s. Polaroid introduced film packs combining both types in the early 1960s, simplifying handling. Instant photography delighted amateurs, and also found many other applications—notably, recording oscilloscope traces in research labs. Theodore Maiman's notebook recording the first laser includes Polaroid prints of laser pulse traces.

Land's success lay in hiding the messy chemistry inside the film package. The most refined version was the SX-70 color film introduced in 1972, in which each photo was a separate dry plastic package ejected by the camera after exposure. The image area was pale green when ejected, then took on its final color over several minutes. It marked the pinnacle of Polaroid's instant-photography success; a 1977 effort to introduce Polavision instant movies was a commercial failure.

Behind the scenes, Land was a pioneer in optical surveillance from aircraft and satellites. In 1952 he served on a panel that recommended flying a spy plane at 70,000 feet over the Soviet Union to photograph military facilities. He drew on that experience in 1954, when he was named to the steering committee that proposed the U-2 spy plane, which performed exactly that mission, collecting the first reliable data on Soviet nuclear and missile activity. Land was among the scientists that President Eisenhower assembled days after the 1957 Sputnik launch to discuss its implications. That led to Land's involvement in the Corona series of photographic surveillance satellites, described elsewhere in this book, which provided hard evidence that debunked the myth of a missile gap, a key step in stabilizing Cold War tensions.

Birth of Fiber-Optic Imaging and Endoscopes

Jeff Hecht

Fiber-optic imaging had a surprisingly long prehistory before its birth as an important optical technology in the 1950s. One fundamental building block, the concept of light guiding by total internal reflection, was already well over a century old. A second, the idea of image transmission through arrays of light guides, went back decades. But it took the invention of low-index cladding to successfully launch fiber-optic imaging and endoscopes.

Swiss physicist and engineer Daniel Colladon was the first to describe light guiding by total internal reflection in 1842 [1]. He demonstrated the effect by illuminating a water jet, an experiment later repeated by John Tyndall. French physicist Jacques Babinet noted that light guiding could also be seen in bent glass rods, but he gave no details. Light guiding in water jets helped light up the "luminous fountains" of the great Victorian exhibitions in the late nineteenth century, and by the early 1900s, glass and quartz light guides were illuminating microscope slides and the mouths of dental patients [2].

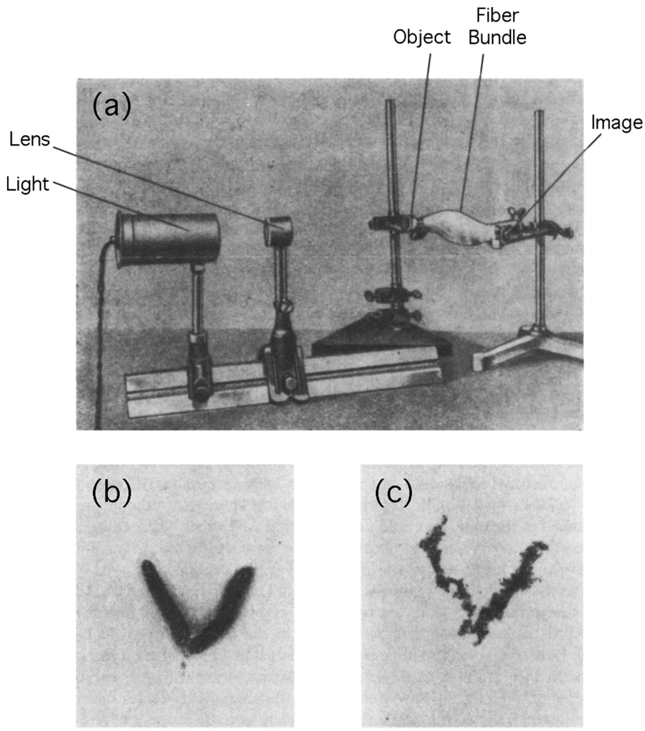
The late nineteenth century also saw the first interest in "remote viewing," or what we now call television. Henry C. Saint-René, who taught physics and chemistry at a small French agriculture school, realized that one way to transmit an image was to project it onto one end of an array of thin glass rods so it could be viewed at the other end of the bundle. He recognized that light would mix within each rod, so the rods had to be tiny to give a good image. In 1895, he wrote to the French Academy of Sciences: "The whole array gives a complete illusion of the object if the diameter of each point does not exceed 1/3 millimeter when the viewer is at a distance of one meter from the image" [3]. The idea was simple and elegant but probably was impractical at the time, and no further records of his work have been found.

In 1926, a British pioneer of mechanical television re-invented the concept. John Logie Baird filed a patent on a method "to produce an image without the use of a lens" by assembling an array of thin transparent tubes. His patent also covered using "thin rods or tubes of glass, quartz, or other transparent material [which] could be bent or curved, or in the case of very fine quartz fibers, could be flexible [4]." He tried to transmit images through an array of 340 metal tubes of 0.1-in. diameter and 2-in. length but abandoned it in favor of spinning disks for mechanical television.

At almost the same time, a young American radio engineer and inventor named C. W. Hansell thought of a new way to read instrument dials that were out of sight. In a notebook entry dated 30 December 1926, he outlined his plans for using a flexible bundle of glass fibers. When his employer, the Radio Corporation of America, applied for a patent, he expanded on his original idea, proposing to use fiber bundles in periscopes, endoscopes, and facsimile transmission. Crucially, he realized that the fibers on the two ends had to be aligned in the same pattern to transmit the image properly. The patent issued in 1930 [5], but by then Hansell had moved on to other ideas.

The first person to make an image-transmitting bundle was a medical student named Heinrich Lamm at the University of Munich in Germany. Lamm had studied with Rudolf Schindler, who had developed a semi-rigid gastroscope that could be bent up to 30 deg. Lamm thought a bundle of glass fibers would be much more flexible and persuaded Schindler to buy him some glass fibers from the Rodenstock Optical Works in Munich.

Lamm combed the glass fibers so they lined up from end to end of the bundle and projected an image of a lamp filament onto one end. In 1930 he recorded an imperfect but recognizable



▲**Fig. 1.** Heinrich Lamm, M.D., combed thin glass fibers and packaged them in a short bundle (a), then focused the image of a light bulb filament (b) onto one end. The fibers were well enough aligned to transmit a recognizable image of the filament (c) to the other end. Both filaments are shown in negative images. (Courtesy of Michael Lamm, M.D.)

image on the other end (Fig. 1). It was enough to prove the principle, although Lamm conceded that the images were not bright or sharp enough to be usable. He tried to apply for a patent, but the German Patent Office told him that a British version of Hansell's patent had just issued.

Lamm described his experiment, but could go no further [6]. The world was sinking into the Depression, and soon Lamm had to flee Nazi Germany. World War II followed. The concept of fiber image transmission did not reappear until around 1950—when three people developed it independently, two of them well connected in optics and the third an independent inventor.

The postwar Dutch navy turned to one of its leading optics specialists, Abraham C. S. van Heel, to develop a new type of periscope as it tried to rebuild its submarine fleet. The German optics industry was in ruins, and neither the United States nor Britain wanted to share their periscope technology with Holland. A professor at the Technical University of Delft, van Heel thought he could solve the problem by guiding light through thin rods of glass or plastic. But his experiments with bare fibers initially got nowhere because of light leakage and scratching.

In neighboring Denmark, engineer and inventor Holger Møller Hansen, like Hansell, wanted to peer into inaccessible places. He thought of using a flexible fiber bundle to transmit images after looking at insects' segmented eyes. An avid experimenter, he first tried drawing his own fibers, then bought some fibers to test. He also discovered that light leaked between fibers if they touched but realized that he could solve that problem if he clad the fiber with a material having a lower refractive index. However, when he sought a material with index close to one, the best candidate he could find was margarine, which did not work well.

Meanwhile, in 1951, British optical physicist Harold H. Hopkins found his inspiration at a dinner party where a physician discussed the horrors of trying to use a rigid endoscope [7]. Hopkins decided that a bundle of flexible glass fibers could do a better job and applied for a research grant to support a research student. When the money came through, he assigned the project to a young student from India, Narinder Kapany.

Hansell's patent had been forgotten and expired in 1947. But the Danish Patent Office found it after Møller Hansen filed his own application in 1951, and rejected the filing. With no support and no luck in finding a good cladding material, he gave up and turned to another invention. With more support, van Heel and Hopkins persevered.

When van Heel sought help with his fiber periscope design, the Dutch government referred him to Brian O'Brien, OSA president in 1951 and director of the University of Rochester's Institute of Optics. The two knew each other as leaders in the parallel worlds of American and European optics; at the time, van Heel headed the International Commission on Optics. As it happened, O'Brien had already been experimenting with light guiding, and he recommended cladding the outside of the fiber with a lower-index material, so no dirt or scratches spoiled the total reflection, and light could not leak out if fibers touched. He had gotten the idea from his studies of light guiding in retinal cells, which had earned him OSA's Frederick Ives Medal in 1951 [8]. Van Heel quickly embraced the idea, and the two promised to keep in touch after their October 1951 discussion.

When he returned to Delft, van Heel tried coating fibers with beeswax and plastic. Both cladding materials improved fiber transmission, and the following year he sent light through a fiber bundle half a meter long, well beyond what Lamm had achieved. Then van Heel encountered another complication. On a visit to Britain, fellow Dutch optical physicist Frits Zernike discovered that Hopkins and Kapany were also making fiber bundles. To establish his priority, van Heel quickly wrote a long article for the Dutch-language weekly *De Ingenieur* and a short letter to the British weekly *Nature*. He also airmailed a letter to O'Brien, alerting him to the planned publications. The Dutch weekly published the paper in its 12 June 1953 issue [9], but *Nature* uncharacteristically sat on the short letter for months. Neither mentions O'Brien, who evidently never replied to van Heel's letter.

Why O'Brien failed to reply is a mystery, and so is why *Nature* delayed publication of van Heel's letter until 2 January 1954 [10], when it appeared in the same issue as a longer paper that Hopkins and Kapany had submitted in November [11].

O'Brien was busy with other projects, including moving to head American Optical's new research laboratory in Southbridge, Massachusetts, in 1953. He never published on clad fibers, but he did apply for a patent through American Optical's lawyers in November 1954. The patent office duly granted the application [12], but it was overturned in court because of a blunder by the lawyers. With a year to file the patent after publication of the *De Ingenieur* paper, they interpreted the date 12/6/53 marked on O'Brien's copy as the American style with the month first, rather than the European style with the date first, and missed the deadline.

In 1954, as today, *Nature* was one of the world's best-read research journals, so the two papers collectively put fiber optics into the public eye. Yet neither Hopkins nor van Heel could secure funding for further development.

Things were different in America. A young South African gastroenterologist working at the University of Michigan named Basil Hirschowitz was excited by the idea of making a flexible fiber-optic endoscope. The Central Intelligence Agency picked up on an idea mentioned in van Heel's paper—that fiber bundles might make unbreakable image scramblers. And Kapany landed a research post at Rochester.

At Michigan, Hirschowitz teamed with his supervisor Marvin Pollard and optics professor C. Wilbur "Pete" Peters on the project in mid-1955. They hired Lawrence E. Curtiss, a physics student interested in medical instruments, to do the leg work. Hirschowitz did not know that Curtiss was just starting his sophomore year.

Curtiss ran into problems when he tested bare fibers that Hirschowitz had bought. Cleaning the fibers improved their light transmission, but every time he touched the fiber, transmission dropped about five percent. The mysterious loss came from fingerprint oils, which dry to leave a residue with a refractive index of 1.5, close enough to the glass index to spoil total internal reflection. Drawing their own fibers from glass rods with refractive index of 1.69 overcame that problem, but the bundled fibers scratched each other, again increasing losses.

Peters suggested applying a plastic or lacquer cladding, but that reduced light transmission. Curtiss suggested threading a high-index rod through a low-index tube and drawing the two into a clad fiber, but the older physicists said it would never work. For a few months he heeded their advice, and he and Peters made a three-foot-long bundle, which they described at an OSA meeting in Lake Placid, New York, in October 1956. But Curtiss still thought rod-in-tube fibers would work better. When Peters was away at a conference on 8 December 1956, Curtiss bought some tubes of soft glass from the chemistry supply office, put rods in them, and drew the clearest glass fibers that had yet been made.

Curtiss had been lucky. Drawing good rod-in-tube fibers requires very clean rod surfaces, and they had happened to buy fire-polished rods. Nonetheless, they had a breakthrough, and the project went into overdrive. Hirschowitz wasted no time applying for a patent, and by February the group had assembled the first fiber-optic endoscope.

Meanwhile, the CIA pressed American Optical to develop fiber-optic image scramblers for encoding and decoding secret documents. When O'Brien did not get the project going quickly enough, the CIA hired Will Hicks, a young physicist from Greenville, South Carolina, and sent him to build image scramblers for American Optical. Like the Michigan group, he tested plastic and glass cladding, but he took a different course and developed rigid bundles of fused fibers suitable for image scramblers.

Image scramblers turned out to have a fatal flaw—they always scrambled images in the same way, so an enemy who intercepted enough of the scrambled images could eventually work out the key. Hicks was the first to spot the flaw, but through a friend he also came up with a new use for the fused fiber bundle technology, as fiber optic faceplates to guide light between stages of an image intensifier.

Rigid or fused fiber bundles opened technological possibilities that were different from those of flexible bundles. Melting bundles of fibers together and stretching them made the light-guiding cores of the fibers thinner than the cores of isolated fibers, and groups of fused fibers could be stacked together and drawn again, to make them even thinner. Hicks noticed that fused bundles with the finest fibers showed odd colored patterns on their cut and polished ends. American Optical managers showed the odd pattern to Elias Snitzer when he interviewed for a job, and Snitzer recognized them as mode patterns, produced because the fibers had been drawn so thin that their cores were transmitting only a single optical mode. Snitzer got the job and became the first to describe single-mode transmission in an optical fiber [13]. Single-mode fibers would eventually become the backbone of the global fiber optic communications network.

Kapany took a different course at Rochester, writing a series of papers outlining the principles of fiber optics. First published in *Journal of the Optical Society of America*, they became the core of the field's first textbook. The 46 papers he published through 1966 accounted for 30% of the field's entire literature during the period, including reports on medical treatment.

Hirschowitz and Curtiss helped American Cystoscope Makers develop the first fiber optic endoscope in 1960. It quickly replaced earlier semi-rigid endoscopes because it was far more flexible and much safer to use, and it greatly expanded the use of endoscopy. American Optical and a spinoff company formed by Hicks in 1958, Mosaic Fabrications, developed fused fiber bundles into military and commercial products. Fused and flexible fibers soon found a range of applications, from reading punched computer cards and inspecting the innards of NASA's massive Saturn V rockets to decorative lamps. But none of them were transparent enough for communications.

Note: This essay based on material from [14].

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Xerography: an Invention That Became a Dominant Design

Mark B. Myers

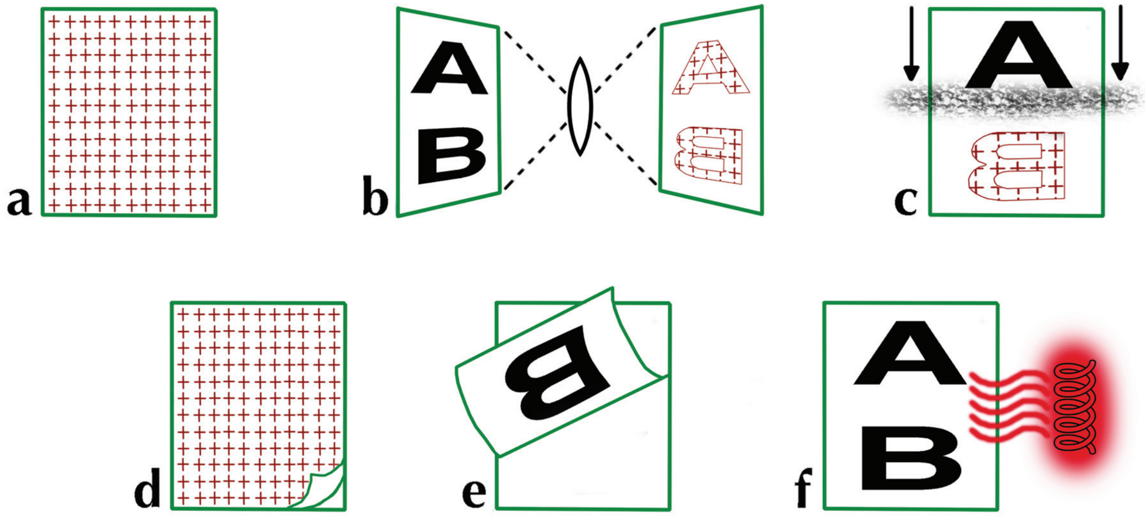
Introduction

Xerography, or electrophotography, was one of the great inventions of the twentieth century. It was invented in 1938, 78 years ago, and remains in wide use today. The copier has become a common presence in our workplace, and its availability is assumed. Prior to its invention an office worker would type an original with sheets of carbon paper and copy paper sandwiched behind it in the typewriter carriage. Legibility limited the number of copies that could be made. If more copies were required, the typing process would be repeated or a master would be typed and offset printing would be employed. The xerographic copier radically changed all of that work and created a whole new communication chain between office workers and their organizations with the multiple copies of a copy sharing the remarks of the respondents.

Xerography's creation and application closely parallels the 100-year history of The Optical Society. It was invented as a novel imaging system, which had no existing competitors. One of its first public demonstrations was at The Optical Society's Annual Meeting held in Detroit, Michigan, on 22 October 1948 [1,2]. Although seen as highly novel, the observers could not see the future value of the technology. That was not unusual: the leading industrial laboratories of the time had previously been offered the opportunity for the development and commercialization of the technology, but all had declined [3].

It would be 1959, owing to the combined efforts of Battelle Memorial Institute and the small company Haloid that would become the Xerox Corporation, when the Xerox 914 copier made its phenomenal market introduction. It would take the efforts of the inventor Chester Carlson, the Battelle Memorial Institute, and Xerox people over a period of 21 years to reach this 914 success—and what a success it was! It is estimated that in 1955 before the introduction of the 914 about 20 million copies per year were made worldwide, largely by typing carbons. In 1964, five years after the introduction of the xerographic copier, 9.5 billion copies per year were made, and in 1985 the number had grown to 550 billion [4]. The revenues of the small Haloid-Xerox Corporation based on the 914 and the follow on products would grow at a 44% rate compounded annually for the decade 1960 to 1970 to be greater than $1.5 billion. It was the fastest sustained corporate growth rate in history up to that time.

When invited to write this brief chapter on the history of the invention of xerography, the author was confronted with the question of what more can be usefully said that has not been previously written. Two comprehensive books were published on the subject in 1965 by the key early participants, namely, *Xerography and Related Processes* by John Dessauer and Harold Clark [5] and *Electrophotography* by Roland Schaffert [6]. There are at least four other texts [7–10] written by practitioners over the period 1984 to 1998 as well as numerous scientific papers and popular press reviews in the same period written by scientists who researched the key processes during the further development of the technology. The value the author brings is that of an early participant in the decade following the introduction of the 914. These are the observations of a young scientist joining Xerox in 1964 to work with the individuals from Xerox and Battelle who created that first product success.



▲ **Fig. 1** Six-step process.

The Invention

Xerography is a photoelectric imaging process that creates high-fidelity copies. It is distinguished for its ability to image directly onto plain paper without the use of wet chemical agents, which were common to silver halide and other sensitized paper photography. How xerography works is demonstrated in the following six-step process (see Fig. 1.):

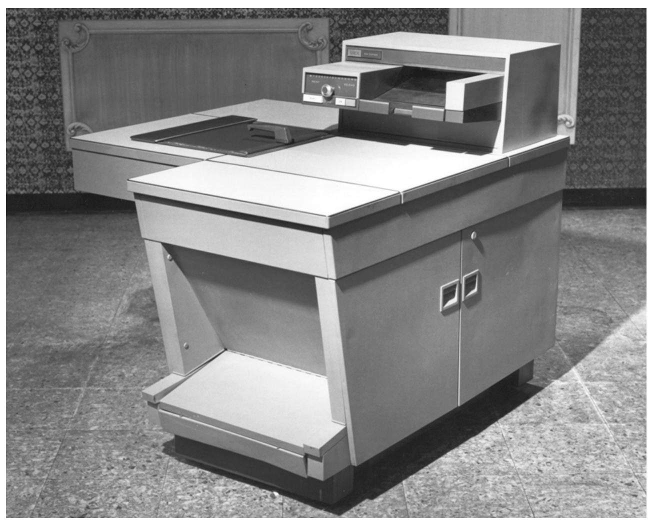
1. An insulator photoconductive sheet attached to an electrode substrate is uniformly electrostatically charged.
2. The photoconductive sheet is imagewise exposed with light. The electrical conductivity of the photoconductor's exposed areas is greatly increased and the surface charges are discharged through the photoreceptor, leaving a latent electrostatic image on the unexposed areas.
3. Pigmented polymer particles charged to the opposite polarity of the latent image are cascaded over the surface. The pigmented particles are electrostatically attracted and tacked to the charged image area, whereas the particles do not stick to the uncharged areas. The latent image is now visible.
4. Plain paper is placed on top of the powder image, and a charge is applied to its back surface with sufficient voltage to de-tack and transfer the image to the plain paper.
5. The plain paper is stripped away from the photoreceptor surface with the image.
6. The polymer toner image on the paper is fused by heat. The photoreceptor surface is cleaned and readied for the next imaging.

This six-step process is the formulation of the basic Chester Carlson 1938 invention as filed in his patent application of 4 April 1939 and which was issued in 1942 [11]. The process has been so robust over time that it still is the core design of all xerographic copiers and printers produced, 77 years later.

The first commercial implementation of this process was the Xerox Model A processor introduced in 1949 (Fig. 2). It was a totally manual operation where the operator carried out each of the above process steps. As a new Xerox employee, the author was introduced to xerography with this machine by working through all of the steps described above. The experience was reminiscent of an introductory physics lab, interesting to the technically trained but bothersome for office workers.

The time between these products, 1949 to 1959, required intensive improvements by the Battelle and Xerox teams in both process physics and materials. The major new challenge to realizing the potential of this technology was the automation of the process steps requiring their systems integration and the creation of a manufacturing capability for these new machines. The operating advances by the engineers were remarkable. The 1949 Model A could produce one copy every four minutes in the hands of a skilled operator. The 914 would produce seven copies per minute with a press of the "green" button in 1959 (see Fig. 3). In 1968, the Xerox 3600 would produce copies at 60 pages per minute, or one every second. The automated xerographic six-step process is shown in Fig. 4.

▲ **Fig. 2.** Xerox Model A, 1949. (Courtesy of Xerox Corporation.)



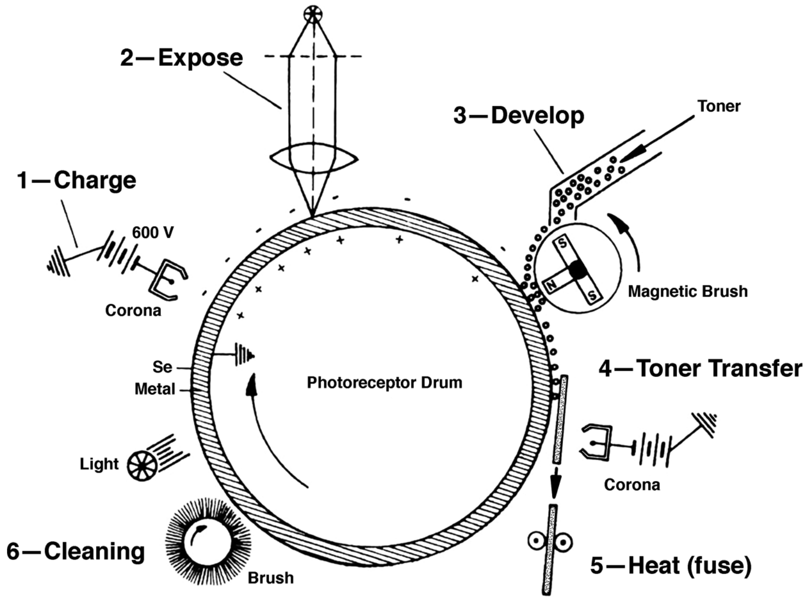
▲ **Fig. 3.** Xerox 914, 1959. (Courtesy of Xerox Corporation.)

The Inventor

Chester Carlson by every measure is the model for the aspirations of all independent inventors: he created a great invention that had tremendous societal benefits as well as providing him with great personal wealth. He is the individual inventor's dream.

His story is compelling. He grew up as an only child in a family of very limited resources. In his early years he became the sole provider for his parents. Living in a suburb of Los Angeles, he worked his way through two years at the Riverside Junior College, from which he transferred to California Institute of Technology for his final two years and graduated with a degree in physics. He started his career in Bell Labs in New York, but was laid off during the depression. He became a patent attorney after attending the New York University law school. It was his work as an attorney that drove his sense of purpose to find a solution to the need for copies.

Chester Carlson first filed a patent application for his invention in October 1937 and reduced it to practice in October 1938 reproducing the image "10–22–38 ASTORIA." At this time he had funded an assistant, Otto Kornei, to help with the laboratory work. This experimental process was his basis for working out the basic six-step process that was the core of his invention. The photoconductor they employed was amorphous sulfur, and they developed the image with dyed lycopodium powder. Charging was done by rubbing a cloth imparting a triboelectric charge on the sulfur film and shaking the powder in a container to impart a triboelectric charge of the opposite sign. The developed image was fused by heat from a Bunsen burner.



◀ **Fig. 4.** The automated xerographic process using the six-step process. In brief, the original is scanned and projected synchronously onto a charged rotating photoreceptor drum. A toner development station develops the image on the photoreceptor and the copy paper is fed to transfer the image from the photoreceptor. The image is detached from the photoreceptor and then passed through toner fuser rolls.

Chester Carlson would contact over 20 companies to try to establish interest in his invention over the period of 1938 to 1944, with no success. In 1944 he had the opportunity to describe the invention to Russell Dayton of the Battelle Memorial Institute. Dayton was visiting Carlson seeking counsel on an unrelated patent matter and became interested in the idea. Battelle and a yet to emerge small company, Haloid, would transform his ideas into a phenomenal success.

Working with both of these organizations, Carlson would relocate to Rochester, New York, and make the Haloid (to become Xerox) labs his professional home. He would maintain an office there through the 1960s. His original xerographic patent would expire in 1955 just before the introduction of the 914. He actively protected his and Xerox's interests by filing over 20 additional xerographic patents, with the final one granted in 1965. The author recalls his presence in the labs. He was a highly honored figure for the new and growing research staff. He was very shy, so few knew him well personally. When he was seen walking the hallways, on second glance he would be gone, a ghostlike figure.

Chester Carlson's wealth from his invention would reach $150 million. At the time of his passing in 1968, that amount would be worth over $1 billion in today's money. He spent the final period of his life giving away his wealth to causes that supported peace and social justice.

Battelle Memorial Institute

Carlson was invited to come to Columbus, Ohio, to demonstrate the concept to members of Battelle's management and research staff, and although the invention was in a very early state, they were interested. A working agreement was concluded in 1944 for Battelle to undertake the development of xerography for a license on future revenues. The Battelle researchers undertook the investigation and selection of the key technology components of the six-step process to enable the system to work. Key advances were the use of amorphous selenium as the photoreceptor, the design of corotrons for the charging processes, and the invention of the two-component development and fusing systems to fix the image.

Battelle was innovative both in their research and in their willingness to break their own business model. They were a contract research organization to which clients brought their problems and purchased the necessary research and development. Battelle did not fund research on ideas from outside inventors, but they changed this in the case of Carlson and xerography. In a sense they were modeling a role that venture capitalist investors would play much later. They would address the challenge of getting to market by forming a partnership with Haloid in 1947. The rights that had been acquired from Carlson would be sold to Haloid for an equity position in the growth of the business. Battelle additionally gave exclusive rights to the xerographic patents that they had been granted from their development efforts. At the conclusion of the Battelle and Xerox relationship in 1970, Battelle had increased the wealth of their endowment manyfold.

The Haloid Company (to Become Xerox)

In 1944, John Dessauer, the head of Haloid research, and Joseph C. Wilson, who would soon assume the Haloid presidency, were looking for new directions for the company. Dessauer came upon an article describing electrophotography in the July 1944 addition of the *Radio News*. He shared the article with Wilson, and they agreed that a closer look was warranted.

▲ **Fig. 5.** Dr. John Dessauer, Haloid head of research to the left, Chester Carlson, and Joseph C. Wilson, president of Haloid, examining a xerographic printer prototype in the late 1940s. (Courtesy of Xerox Corporation.)

Haloid was a small Rochester, New York, company formed 1906 by a group of individuals who had left Eastman Kodak (see Fig. 5). For many years they had a small but successful business producing high-quality specialty silver halide photographic paper. They operated in the shadow of the much larger Kodak Company, which limited their growth potential in photographic paper. In time, other competitors eroded the competitive advantage of their specialty product. The future of Haloid was in doubt, and they needed a new vision and marketplace.

John Dessauer and Joseph C. Wilson, the soon-to-be president of Haloid, visited Battelle in Columbus, Ohio, in December 1945 to see the technology demonstrated. They approached Battelle early in 1946 to request an exclusive license to the technology and to propose a joint development program. Battelle most probably would have preferred a more promising partner, but they, like Chester Carlson, had not found any company interested. An agreement was reached to take effect 1 January 1947.

Joseph C. Wilson was the head of Haloid and Xerox in the period 1946 to 1967. He was from a wealthy Rochester family and was the third in the line of Wilsons to be the head of Haloid. He graduated from the University of Rochester, where he studied literature, and received an MBA degree from the Harvard Business School. He was an exceptionally eloquent business speaker. He loved poetry, and many of his speeches would either begin or end with a poem by Robert Frost.

He also was a man who was willing to take actions that had large risks. The Haloid Company represented most of his family's wealth. He invested $12.5 million in the 914-product development, which amounted to all of the company's profits for a decade, and he borrowed more. If the 914 had failed, the company would have gone under. After the great success of the 914 he would speak of one of the few disappointments. He spoke of friends who had offered to invest money for the development and how they would later be unhappy with him because he declined their offer as he felt that the risk of failure was too great. He is honored at the Harvard Business School by named chair, the Joseph C. Wilson Professor of Entrepreneurship.

John Dessauer was a chemical engineer, educated in Germany, who had immigrated to the United States in the 1930s as a result of the social upheavals that were taking place in his native country. He joined the Haloid Company in 1935 as part of an acquisition that the company had made. He became the first director of research for Haloid, and it was his insight that brought Chester Carlson, Battelle, and Xerox together.

John Dessauer would make another important contribution to xerography. Over the period 1960 to 1970, he would start the building of a Xerox research organization in Webster, New York, dedicated to evolving the company from the dependence on a core xerographic technology based on speculative invention to a predictive science base. The Xerox scientists and engineers would be challenged by the lack of relevant information to support increasingly sophisticated applications of the technology. The underlying sciences of triboelectricity, photo-generation, and charge transport in wide-bandgap semiconductors, controlled corona discharge in ambient atmospheres, physics of surface charge states, and the thermal flow characteristics of pigmented polymers were not widely practiced in the external scientific research of that time.

John Dessauer showed a personal interest in the new research recruits joining the organization. He would drop into the individual scientists' labs to establish connection through wide-ranging conversations. Dessauer developed a close consultative relationship to guide his organization building effort with John Bardeen, Nobel Laureate, of the University of Illinois, who served as an advisor and who would become a member of the Xerox board of directors from 1961 to 1974.

The research capability would continue to grow under the leadership of Jack Goldman, George Pake, and William Spencer with the establishment of Xerox PARC and Xerox Research Center of Canada. From 1981 to 1991, the work of the three centers would rank Xerox among the ten most influential academic and industrial research institutions in the United States as measured by reference to their scientific papers [12].

Xerography, a Dominant Design

Xerography has shown the characteristics of a dominant design [13]. Early in its history it established a competitive edge with respect to alternative technologies, thus becoming the customer and industry choice. Many competitive firms became committed to its usage, offering improved versions. Finally, the technology has shown the capacity to grow in capability and not hit limits leading to early obsolescence.

This does not mean xerography did not have serious competition from alternative technologies. Many organizations including Xerox invested in copying and printing technologies that if successful could have become replacements. They included drop-on-demand inkjet, continuous-stream ink jet, photoactive pigment electrography, and ionography. They all had merits, but only the drop-on-demand inkjet had major market impact. In the drop-on-demand inkjet case, it was a new market for color digital photography home printing that drove the demand. It was a market in which xerography would not be competitive.

A number of market and technological factors have greatly extended the useful life of xerography. The following key events are suggested:

- There was a benefit to the expansion of xerography by offerings of new competition. Xerox established through its relationship to Carlson, Battelle, and its own investments a patent position that limited competitive offerings. This patent exclusion was set aside in 1974 by a consent decree agreement with the U.S. Federal Trade Commission. It required that Xerox license to all competitors its xerographic patents for period of ten years and any new patents issued in that interval. This created an explosion of competitive offerings particularly from Japan.

- An important advance in 1969 was the invention of computer-driven laser writing onto a xerographic photoreceptor [14]. This opened a new market for xerography in electronic imaging and printing. Xerox introduced the 9700 in 1977, which printed single-sheet, 300-spi (samples per inch), single-sheet images at 120 pages per minute. Hewlett Packard introduced desktop laser 300-spi printing in 1984 working at eight pages per minute. Both products revolutionized their respective market places. Most importantly, the application of xerography was transformed from its analog imaging role to become part of the emerging digital imaging future.

- Canon introduced the concept of a low-cost personal copier with a customer-replaceable consumable cartridge in 1982. They creatively collected all of the high-maintenance elements of the xerographic processes into a customer-replaceable unit, thereby removing the need for frequent service. This would open a new market, and desktop copying and printing and would become a design standard for the industry.

- Organic photoreceptors [15,16] offered a breakthrough to a cost barrier, as they could be coated with much-lower-cost manufacturing, and they could be made into highly flexible belts rather than the selenium alloys, thus offering new printer architectures for digital color. In 1975, Kodak introduced its Ektaprint 100 copier/duplication based on an organic photoreceptor. Xerox followed suit in 1982 with its active-matrix organic photoreceptor in its 10-Series 1075 and 1090 duplicators.
- Canon, Hewlett Packard, Fuji-Xerox, and Xerox introduced very-high-quality digital color reprographic and printing devices that extended xerography into the color printing and graphics marketplace.
- The Total Quality Movement practiced by Japan manufacturers greatly improved the reliability of xerographic machine designs. Xerox improved its design and manufacture through its learning from Fuji-Xerox.

It is the nature of dominant designs that they are not simply replaced by an alternative technology. Their dominance will end with a radical transformation of the market they serve. A current example of the decline of a dominant design is analog silver halide photography and its iconic Kodak yellow box. The magic was in the chemistry of the film and its later processing. The analog film businesses of Kodak rapidly declined with the ascendency of a whole new paradigm of consumer photography: the digital camera, the smart phone, and inkjet printers. Dominant designs do have lifetimes.

Similar changes are appearing for prints on paper. The internet, personal computing devices, and social media are reshaping the world of publishing newspapers, magazines, and books. Challenges to the future use of print are seen in the processes of banking, legal, and other businesses.

Xerography is clearly in the mature stages of its lifetime. There still remain active literature creation and patent issuance every year, and there are at least a dozen companies producing products and services. Whether xerography prospers or fades into the sunset will depend on innovation extending its application into new markets.

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U.S. Peacetime Strategic Reconnaissance Cameras, 1954–1974: Legacy of James G. Baker and the U-2

Kevin Thompson

James G. Baker contributed to optics, optical design, and, as this chapter describes, was a pivotal player during the development and deployment of the U-2, and the optics of the U-2. To briefly mention some of his contributions outside of the U-2 is itself a challenge. He graduated from Harvard in 1942 with a Ph.D. in Astronomy and Astrophysics, advised by leading astronomer Harold Shapely, and went on to make innovative contributions for nearly 70 years including developing ray tracing and optical design code using the second largest computer ever built (the first one was delivered to Richard Feynman for the Manhattan Project). He not only designed large format cameras for reconnaissance but also fabricated and tested the large aspheric components personally. He is perhaps best known in the public for his design of the Baker–Nunn tracking cameras and for designing and supporting the fabrication of the first freeform surface in mass production as part of the Polaroid SX70 camera, to name a few examples.

This chapter features his work not only as the optical designer for the optics for the U-2, but also his lesser known contributions as a leading member of the group that convinced then President Eisenhower to authorize the U-2 program. The sources for this chapter were selected to be as original as possible, and are dominantly CIA reports that were developed by the CIA History Staff in the 1980s and released as classified reports within the CIA. These were later declassified with redactions when the existence of the National Reconnaissance Office (NRO) became known to the public in the late 1990s. All of the material in this chapter comes from Baker's personal files that were made available to the author by the Baker family.

Baker's involvement in reconnaissance cameras began in 1941, when he was invited by Major George Goddard to spend two months at the Wright Field in Dayton, Ohio [1]. Perhaps the most succinct introduction to Baker's role in the U-2 and related programs is from an NRO press release that announced the first "Pioneers of National Reconnaissance" on 18 August 2000. The release states: "James G. Baker, Ph.D.—A Harvard astronomer, Dr. James Baker designed most of the lenses and many of the cameras used in aerial over-flights of 'denied territory,' enabling the success of the U.S. peacetime strategic reconnaissance policy" [2].

To write only on his technical accomplishments for reconnaissance cameras would overlook a key role Baker played in bringing President Eisenhower to authorize the U-2 to carry the camera. The first section of the chapter will highlight Baker's roles in that area—roles that often consisted of leading key technology committees, which led to the authorization of the U-2 program specifically as described in [3]. In the context of the U-2 program, these roles began in 1951 with the establishment of what came to be called the BEACON HILL Study Group, named for the location of the study group headquarters on Beacon Hill, in Boston. The group was made up of chairman Carl Overage, a physicist at Kodak, Baker, Edward Purcell from Harvard, and a total of 12 others that included Edwin Land of Polaroid, Richard Perkin of Perkin-Elmer, and significantly, Lt. Richard Leghorn from the Wright Air Development Command, who later became the founder of ITEK where the CORONA program was developed in later years. This group toured airbases, laboratories, and companies every weekend for two months in January and February of 1952. From there the members invested three months preparing a classified document they presented on 15 June 1952—the BEACON HILL Report. The report, with 14 chapters, discussed various technologies from radio to photography including infrared and microwave reconnaissance systems. One of the key recommendations from the report was the need to develop high-altitude reconnaissance.

Reaction to the BEACON HILL Report came a year later, in the summer of 1953, after Dwight D. Eisenhower became president. The specific timing of the president's interest was driven by an early report of a new Soviet intercontinental bomber, designated "Bison" by NATO. This was a B-52 class bomber (the B-52 was just entering production in the U.S.). This report was validated at the Moscow May Day air show. In July of 1953, the Intelligence Systems Panel (ISP) was established, chaired by Baker, to advise both the Air Force and the CIA on ways to implement the construction of high-flying aircraft and high-acuity cameras. In parallel, during World War II (WWII), Baker had established a full-scale optical laboratory, the Harvard University Optical Research Laboratory. After the war, Harvard asked that the laboratory end its relationship with the university and it was moved to Boston University to become the Boston University Optical Research Laboratory (BUORL), with the move funded by the Air Force. Baker, however, elected to stay at Harvard where he continued to design lenses for use in photoreconnaissance. BUORL was destined to become ITEK in 1957 under the leadership of Richard Leghorn.

At the first meeting of the ISP on 3 August 1953 the discussion centered on the fact that the best intelligence on the interior of the Soviet Union was based on German aerial photos taken near the end of WWII. Discussions continued to review incremental modifications that either were being attempted or planned to create a high-altitude airframe from existing production aircraft. At the third ISP meeting on 24–25 May 1954, a critical outcome was to establish that to be successful, a high-altitude aircraft would need to fly above 70,000 feet, something that could not be achieved with modifications to existing airframes. The other pivotal event at this meeting was that the panel learned of a lightweight, high-flying aircraft that was being developed at Lockheed Aircraft Corporation. Baker dispatched a member of the panel to learn more about the project. The plane was conceived by the now legendary Kelly Johnson, leader of the Skunk Works, who had designed essentially a single engine jet powered glider, which was called at the time the Lockheed CL-282. On 24 September 1954 Baker convened the ISP panel to discuss the new airplane. The panel moved to support the CL-282, but the Air Force, which had been aware of the CL-282, had already made a decision not to fund the development of the aircraft.

Somewhat independently, on 26 July 1954, President Eisenhower commissioned another panel of experts, led this time by James Killian, then the president of MIT. This panel had 42 of the nation's leading scientists, including Baker, segmented into three project groups. This group met 307 times over nine months and included field trips and conferences. Baker was a member of the Project 3 committee, which was led by Edwin (Din) Land of Polaroid. Land believed the optimal committee size was one that could fit into a taxi and, as a result, this was a small group consisting of Baker and only a few others, including notably mathematician John W. Tukey. In mid-August 1954, Land and Baker went to Washington where Land was shown the details of the CL-282, after which he is quoted as having phoned Baker to say, "Jim, I think we have the plane you are after." Following a somewhat convoluted path that was dominantly political and too lengthy to describe here, Land and Killian met directly with President Eisenhower in November 1954 and the president directed that CL-282 be developed by the CIA. Even with the president's support, the competitive situation was complicated, but a key deciding factor in the end was that Kelly Johnson promised to deliver the plane in eight months for $22 million, which he did, under budget. A final contract was signed on 2 March 1955 with Lockheed to deliver 20 planes between July 1955 and November 1956. To give some perspective on the priority of the project, Richard Bissell of the CIA wrote a check to prestart the work and mailed it to Kelly Johnson.

With this background on how the U-2 airframe, a version of which is shown in Fig. 1 [3], came to be authorized, this section will present Baker's work on some of the lenses that were considered or used on cameras that flew on the U-2. This material is based on [4] and from the article written by Baker [5].

Fig. 1. U-2R (World Air Power Journal, Vol. **28**, Spring 1997 published by AIRtime Publishing, 10 Bay Street, Westport, Conn. 06880).

To frame the challenge, the dominant aerial cameras that were used in WWII were the Fairchild K-19 and K-21 framing cameras with focal lengths from 24 to 40 inches. In the period that the U-2 was authorized, a typical ground resolution was 7–8 meters when flying at 10,000 meters. For the U-2, due to the new objects of interest, there was a need for 3-meter ground resolution from >20,000 meters, or a 4× improvement. In the mid-1940s, Baker, working with Richard Perkin of Perkin-Elmer, had developed a 48-inch focal length scanning camera that was installed in a B-36 that resolved two white softballs on a green from 10,000 meters. However, this camera weighed more than a ton and the weight budget for the U-2 was near half of this.

Baker began work on a "radical new camera" in October 1954, but quickly realized that it would take more than a year to design, even with his computer access, whereas the plane needed a camera well before this. Consulting with Richard Perkin, the decision was made to base the improved camera on the Hycon K-38. This camera, with weight reduction implemented by Perkin-Elmer and improved optical design developed by Baker in a few weeks, became the A-1 camera working at f/8 that was used in the first flights in mid-1955. A high-impact innovation at this stage was that instead of flying three cameras, one down-looking and two oblique, Rod Scott of Perkin-Elmer developed a rocking mount to gather the oblique and down-looking images with one camera.

As soon as there was a plan set for a camera to support the early U-2s, Baker began work on a totally new concept, the B-camera. This was a 36-inch focal length f/10 lens with aspheric surfaces, personally polished and tested by Baker. The use of aspheric lenses was essentially unheard of in this era and is one of the reasons Baker's lenses set a new standard for high-acuity cameras. Developed in

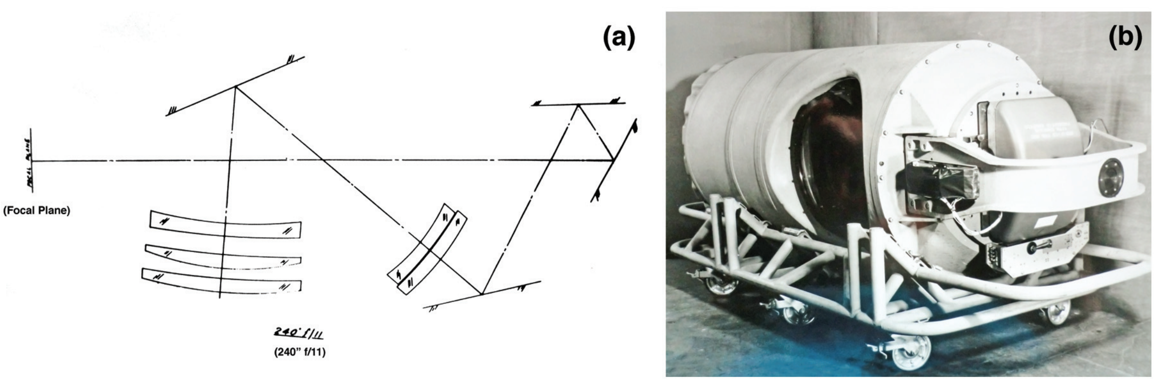

Fig. 2. (a) Layout of a proposed Camera-C (this version at f/11), (b) an assembled Camera-C, 240" EFL, with a final configuration at f/12.

collaboration with Rod Scott of Perkin-Elmer, the B-camera used only one panoramic imaging lens with 18 × 18 inch format frames. This lens, and variations on it, became a key component of all cameras throughout the U-2 program.

Independently, Baker's concept for the ultimate U-2 camera, called the C-camera (see Fig. 2 [6]), was a 240-inch focal length lens to be operated at f/20. However, in conversation with Kelly Johnson he realized this format would never be small enough or light enough for the U-2. Eventually he developed a 180-inch focal length lens operating at f/13.85. While this design would typically have taken years to complete in that era, his state-of-the-art computer allowed it to be completed in 16 days. However, in a test flight of the Hycon manufactured lens, the conclusion was that the 5× longer focal length made the lenses too sensitive to vibration. Apparently this result was never relayed to Baker, who learned of it years later. When he learned of the source of the decision to not use the C-camera, he wrote a terse letter stating he had solved that, should they have bothered to ask.

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History of Optical Coatings and OSA before 1960

Angus Macleod

Introduction

The full history of any scientific subject is impossibly complex, and any account can only be a simplified one. Like other technologies, optical coatings developed over a broad front in many countries with many workers and over a long time. Some discoveries were made and then forgotten and rediscovered later; others were simultaneous but independent. This account is intentionally heavily biased toward The Optical Society, and so, although we will try to retain some breadth in the story, we will concentrate on those workers who were significant in the Society. Others, many of whom we will not mention, were also involved in and made significant contributions to the field.

Beginnings

No one knows exactly when the technology of optical coatings started. As far as optical instruments are concerned, the earliest was probably the simple mirror, and by 2000 B.C. mirrors were common all over the world. Early mirrors were made from anything that could be polished, and their reflectance was simply that of the particular material. Obsidian, jade, bronze, silver, or gold, even pots of water, were all used. The idea of using a coating to improve the reflectance was a later development. We know that the Romans employed many different techniques for mirror manufacture, including some that we can classify as thin films. Glass was a common substrate. Mass production of cheap mirrors involved pouring molten lead over glass, yielding irregular fragments that had somewhat raised reflectance from the lead that stuck to the glass, but quality was generally poor. Better, but more expensive, glass mirrors had films of mercury or gold leaf. Metal mirrors often carried layers of polished tin. Outstandingly clear glass was developed in Murano in the middle of the fifteenth century, and the production of what we would describe as the first modern mirrors followed soon after. These mirrors carried a coating that was primarily a mercury amalgam of tin, although small amounts of other metals were also sometimes added. Thus by the sixteenth century there was a well-established thin film coating industry but the coatings were solely of metals.

The development of interference coatings took rather longer. Of course, nature was first in the use of thin film interference. Color in transparent thin films must have been observed at a very early stage of human development, but it was Isaac Newton who, in the late seventeenth and early eighteenth century, painstakingly established the relationship between film properties and perceived color [1]. He realized that the same effects he saw in his thin films were responsible for many colors in nature and, mistakenly, thought that such effects were responsible for all colors. Not much happened in thin film optics from then until the beginning of the nineteenth century.

Two major events in the early 1800s were the 1802 proposal by Thomas Young that light is a wave [2,3] and the publication in 1810 of Goethe's great book on color [4].

Young was not the first to propose a wave theory for light, and, indeed, for a time the theory was not generally accepted. It took the 1818 work of Fresnel on diffraction [5] to convince the field. The wave theory of light paved the way for the understanding of interference phenomena. Fresnel and Poisson developed the idea of the absentee half-wave and the quarter-wave perfect anti-reflection coating [6]. By the end of the nineteenth century interference in thin films was well understood, had been recognized in nature, and was known to be responsible in the form of tarnish layers for an increase in the transmittance of high-refractive-index lenses.

Goethe's book contained in its first edition a chapter by Seebeck, missing from subsequent editions, dealing with experiments on precipitates of silver chloride where illumination was followed by exhibition of reflection of the very colors used for illumination. Wilhelm Zenker [7] realized that this was an interference phenomenon that could be used in photography and also recognized that half-wave spacing of repeated features should give high reflectance at the corresponding wavelength. Zenker's work was the precursor to the Lippmann emulsion that won Gabriel Lippmann the 1908 Nobel Prize in Physics.

Metallic reflecting coatings had also considerably developed during the nineteenth century. Justus von Liebig's [8,9] development of a wet chemical deposition process for silver in the middle of the century had transformed the production of reflectors of all kinds. Interferometers required beamsplitters with semi-transparent reflectors. Astronomy adopted mirrors constructed from stable glass with silver coatings rather than the older, somewhat unstable, speculum metal. Sputtering was sometimes used, but the general view was that it tended to distort the substrates and so it was not much in favor. Then an important paper by Pohl and Pringsheim in 1912 [10] suggested a vacuum process using what was then called distillation, but nowadays thermal evaporation, for mirror coatings. A great advantage of this method was that with a substrate exhibiting a sufficiently high quality of surface finish, the coatings would immediately form a mirror of equal quality without any further need of polishing.

At the beginning of the twentieth century, thin film applications were largely in photographic emulsions and in metallic reflectors. There was as yet no real need for other kinds of optical coatings. Also, strangely enough, although mirrors were much in demand, there seems to have been no great rush to adopt Pohl and Pringsheim's technique.

Early Efforts

The first volume of the *Journal of The Optical Society of America* appeared in 1917. The second issue (numbered as 2 and 3) contains two papers that would appear of great significance to us today but, from their citations, seem to have received little notice at the time. The first paper, on what we would now describe as an interference optical coating, was by Herbert Ives [11], who modified the treatment of a Lippmann emulsion to produce a narrowband reflecting filter of high efficiency that we would now call a notch filter. In the same issue Otto Stuhlmann [12] described his technique for depositing metallic mirrors and beamsplitters by thermal evaporation from wire sources. Later, in volume 2, Frederick Kollmorgen describes a spinning process for the protection by lacquer of silver films, solving the then current problem of applying a thin, uniform film to protect silver surfaces from tarnishing [13].

In the late 1920s and early 1930s, John Donovan Strong pioneered work in the deposition of optical coatings. 1930 he joined the California Institute of Technology and teamed with Charles Hawley Cartwright to investigate the deposition of an enormous number of metals and dielectrics [14]. By early 1931 Strong had coated, with quartz-protected silver, a 6-in. (15.24-cm) reflector. The following year he replaced the coating with one of aluminum. Aluminum had two great advantages. It strongly reflected the ultraviolet and it had an innate environmental resistance due, Strong was sure, to a film of oxide that naturally formed over the surface.

Meanwhile progress was being made in Germany and France. At the Carl Zeiss company in Jena Alexander (Oleksandr) Smakula [15], of Ukrainian origin, developed an anti-reflection coating for lenses, which for several years remained a close secret and was used primarily for military applications.

Walter Geffcken at the sister company Schott in Jena, around the same time, produced the first narrowband interference filters [16]. Like Smakula's, most of Geffcken's early advances were kept secret. Alfred Thelen's account of Geffcken's work [17] makes fascinating reading. In France, Pierre Rouard, in a 1932 paper [18], described his observation of a significant reduction in internal reflectance at a glass surface induced by an overcoat of a very thin metal layer. He presented his thesis in Paris in 1936 [19], and it included an iterative technique for optical multilayer calculations.

In the United States, John Strong, completely independently of Smakula, realized that his evaporated dielectric coatings could be used as a replacement for the tarnish layers that were known to improve the transparency of glass elements. His paper [20] in the *Journal of The Optical Society of America* was the first account of such coatings to appear in the open literature. Strong coated the lenses of a Leica camera that was probably the first ever to be anti-reflection coated by a vacuum process.

August Hermann Pfund, 1939 Ives Medalist and President of The Optical Society from 1943 to 1945, also made contributions in thin film optics. In 1934 he published [21] an account of a dielectric beamsplitter based on a thermally evaporated film of zinc sulfide for use in interferometers and other systems where transmission was followed by reflection at the same surface. In general, we see gradually increasing interest in thin film interference coatings, much of it, of course, directed toward anti-reflection.

A particularly interesting individual of this era was Katharine Blodgett. In 1920 she became the first woman to be employed as a research scientist by the General Electric Company, where she began working with Irving Langmuir, who won the Nobel Prize for Chemistry in 1932. In 1926, she became the first woman ever to be awarded a Cambridge Ph.D. in physics. She then returned to GE, where she continued the work that Langmuir had started on thin films. In the course of this work she devised anti-reflection coatings for glass. Her Journal publications primarily reported films of barium stearate mixed with stearic acid the acid being removed later by soaking in benzene to leave a barium stearate skeleton behind. Very low reflectances could be obtained in this way. Her 1940 patent [22], however, involved the anti-reflection of soda-lime window glass by adding to it a layer of glass containing a metal such as lead or barium that could then be leached out by acid treatment to leave an etched layer of lower refractive index that acted as an efficient anti-reflection coating and, of course, was environmentally resistant.

In 1937, Arthur Francis Turner and Hawley Cartwright began their ground-breaking research in interference coatings including anti-reflection coatings at MIT. The process they used was vacuum evaporation and the materials for the anti-reflection coatings metallic fluorides, magnesium fluoride being specifically mentioned in claim 6 of their 1940 patent [23]. The publication of this patent induced Germany to publish the Smakula patent that had been kept secret. Turner and Cartwright made other advances in anti-reflection coatings including multilayers. Cartwright described to OSA the advantages of anti-reflection for camera lenses [24], while Miller did the same for the moving-picture community [25]. Then Turner joined Bausch & Lomb in 1939, where he ran the Optical Physics Department until his retirement in 1971.

War Years

Optical instruments of all kinds including binocular telescopes, submarine periscopes, range finders, telescopic gun sights, and aircraft bomb sights were required for World War II. The performance of all of these could be much improved, especially for use at dusk or dawn, by the addition of anti-reflection coatings. All the participants on either side in the war were involved in anti-reflection coatings, yet they were treated everywhere as highly secret.

Richard Denton joined the Frankford Arsenal in early 1942. In 1935 the staff consisted of eleven people. By the end of 1943 the staff numbered 1100. His account of his experiences at the Arsenal [26] paints a vivid picture of the rapid problem solving and innovation that was required by the needs of the conflict. Anti-reflection coatings represented only a part of his responsibilities. Magnesium fluoride had been found most satisfactory, and soon virtually all optics were being coated to improve their transmittance.

Around this time, the importance of heating the substrate during the deposition of the magnesium fluoride anti-reflection coatings was recognized. Cartwright and Strong had included heated substrates during deposition in their investigations at the California Institute of Technology [14] and found the tenacity of silver much improved. Also with Turner he had secured a patent on post-deposition baking of magnesium fluoride [27]. Then Dean Lyon, who had worked on thin films at MIT and now since 1941 was working at the Naval Research Laboratory, "stumbled upon that old idea of heating the elements in a vacuum" [28]. He was eventually awarded a patent for this invention [29]. This process was then used for the remainder of the war. After the war, the Bausch & Lomb company employed the magnesium fluoride process in the production of coated elements, and Lyon sued the company for infringement of his patent in what was a celebrated case at the time and that in 1955 was finally decided in his favor by the United States Second Circuit Court of Appeals.

There was tremendous activity in optical coatings during the war, but little of this appeared in the Society Journal. Frank Jones from the Mellon Institute of the University of Pittsburgh, who had been funded since 1936 by the Bausch & Lomb company to investigate the deterioration of glass surfaces, published with Howard Homer [30] a study of anti-reflection of glass by chemical methods. However, the papers that we would recognize immediately as of fundamental significance in the development of thin film optics were by Mary Banning.

Mary Banning gained her Ph.D. from Johns Hopkins in 1941, and, in the summer of 1941, found herself at the Institute of Optics charged with the creation of an optical thin film laboratory [31]. Faced with such a task nowadays we can turn to the established industry, obtain equipment, and study information in books. She had to start from virtually nothing. Even what methods to use was not clear. She decided on vacuum processes as her primary technique, built and operated the equipment, and published four important papers in the *Journal of The Optical Society of America* [32–35], all of which contain a wealth of practical information and represent very much the foundation on which much of the field was built. One of the papers [34] contains what is still the best and fullest description of the design and construction of an immersed polarizing beamsplitter.

Postwar Years

Now, after the war, the subject expanded rapidly. Part of the reason was the impetus given by the war effort to the field. Many people were involved in optical coating and found it an attractive and rewarding field. But also optics was ready for it. Great improvements could be produced by coating camera lenses. High performance could be obtained from reflecting coatings, avoiding the unpleasantness and unpredictability of the wet chemical processes. Interference filters could be made as easily for one wavelength as another and had enormous energy grasp. Thin film polarizers showed high efficiency without the need for expensive crystals. There were, of course, many military needs, but all of optics was expanding. The chemical industry needed infrared instrumentation, and astronomy needed telescopes and instrumentation and especially narrowband filters for increasing contrast of diffuse nebulosities. Binoculars, photographic cameras, microscoscopes, surveying equipment, and navigational equipment all showed vastly improved performance with anti-reflection coatings.

Optical coatings had developed in Germany during the war, and now the results were being brought back to the United States. In 1946 Howard Tanner, who had been with the U.S. Naval Technical Mission in Europe together with Luther Lockhart, both of the Naval Research Laboratory, published a paper on some of the German anti-reflection coatings. One of the coatings they described in detail was a three-layer one based on a quarter-wave of intermediate index next to the substrate, followed by a half-wave of high index and then finally a quarter-wave of low index. This gives high performance over the visible region. It was further analyzed by Lockhart and Peter King [36], and the idea of the half-wave layer that broadens the anti-reflection performance has since appeared in coating after coating and in many publications and patents.

Accurate calculation of the properties of coatings was of considerable interest, and a good number of the contributions to the Journal at this time were theoretical and concerned optical property calculation. Robert Mooney had two papers in the 1945–1946 volume of the Journal [38]. Antonin

Vasicek, the leading thin film worker in Czechoslovakia, published several theoretical studies [39–42], and Doris Cabellero [43] and Walter Welford [44] also contributed. Most of this work used iterative techniques, but Welford succeeded in putting his method into matrix form. Meanwhile, in France, a young Florin Abelès was gaining his doctorate with a thesis that laid the theoretical foundation of the calculation techniques involving characteristic matrices that we almost universally use for our thin films today [45, 46].

It now becomes difficult to keep track of all that was happening in thin film optics, and we give up completely trying to track all of the significant contributions, even just those to the *Journal of The Optical Society of America*.

Pierre Rouard, in early 1944, had returned as Professor of Physics to Marseille and to optical thin films from a forced two-year absence in Clermont-Ferrand working on acoustics. In 1949 the French Centre National de la Recherche Scientifique, recognizing the tremendous expansion of optical coatings, asked him to organize an international conference on optical coatings in Marseille. This was the first truly international conference devoted entirely to the "Optical Properties of Thin Solid Films." A special July 1950 issue of the *Journal de Physique et le Radium* carried the proceedings in a mixture of English and French. Almost everyone of significance in the field was there. Rouard himself of course, Strong (although now much more in astrophysics), Turner, Heavens, Dufour, Greenland, Ring, Abelès, are just a few of the names. Turner gave a paper [47] describing multilayer anti-reflection coatings, dielectric reflectors, reflection filters, narrowband transmission filters, and frustrated total reflection filters.

At the end of the war, many German scientists were recruited to continue their work in the United States under Operation Paperclip run by the Office of Strategic Services. Two notable ones were Alexander Smakula and Georg Hass. Hass was employed by the United States Army Signal Corps and became director of a significant infrared research activity at Fort Belvoir. He and his group wrote many valuable practical papers dealing with such matters as protection of metallic mirrors and the properties of new coating materials [48–52]. Turner was running his research group at Bausch & Lomb, and he became the recipient of a successful and important series of research contracts for infrared thin film coatings for which Hass was contract monitor. The Fort Belvoir contract reports, long out of print but publicly available at the time, span the period 1950 to 1968 and include anti-reflection coatings, beamsplitters, multiple-cavity filters of many different kinds, and much theory on their designs. Ivan Epstein was working with Turner and was responsible for the ideas of symmetrical periods in filter design that are still used to great effect today [53–55]. There were many other achievements. Turner and Harold Schroeder won a Technical Oscar from the Academy of Motion Picture Arts and Sciences in 1961 for their development of a cold mirror coating for the condenser in movie projectors, much reducing the constant fire risk of the extreme flammability of the film stock. He and Peter Berning [56] introduced the concept of potential transmission and devised the induced transmission filter. More information can be found here [57].

The 1950s marked great progress in optical coatings. Thin films could now be recognized as a discipline with workers who could be described as specialists. Books on the subject began to appear, Herbert Mayer's book on thin films appeared in 1950 [58], followed by Oliver Heavens's in 1955 [59] and Leslie Holland's in 1956 [60]. Then in 1960, Vasicek's book was published [61]. Newcomers to the field now had available excellent compact sources of information for rapid learning.

Astronomers began to be interested in narrowband filters. Many of the nebulosities that they were observing were weak emitters of the hydrogen alpha line at 656.3 nm and were difficult to examine against the broadband light from the night sky. Narrowband filters centered on the hydrogen alpha line were found to improve contrast enormously. The study of solar prominences could also make use of such filters, although for examination of features on the solar disk much narrower filters were required and beyond the ability of the thin film deposition methods available at that time. However, George Dobrowolski showed in 1959 how to manufacture ultra-narrow filters using mica cavities [62].

Contemporary publications show clearly the great barrier to progress that was the volume of calculation necessary in deriving the theoretical performance of an optical coating. The theory had much in common with transmission lines, and Smith Charts were commonly adapted for thin film calculations. Approximate techniques were very popular. Computers existed and were occasionally used—Ivan Epstein was an early user for example—but were cumbersome and not always readily available nor user friendly. Workers in the field tended to use empirical methods, tweaking performance by inspired trial and error in the coating machine. Then in 1958, Philip Baumeister at the University of California at Berkeley [63] showed what might be done in an account of the design of a filter by successive approximations on an IBM 650 computer. This marked the beginnings of the computer-aided design of optical coatings.

By the end of the 1950s we could recognize the modern field of optical coatings. Many companies were producing optical coatings, and there were other companies specializing in the supply of equipment and materials.

Now two very significant events, especially for optical coatings but also for the entire field of optics, occurred. On 4 October 1957 the Soviet Union launched the first artificial earth satellite, *Sputnik 1*, ushering in the Space Age. Then on 16 May 1960, Theodore Maiman achieved successful operation of the first laser. Things were never the same again.

Conclusion

Optics has long reached the stage where optical systems without coatings are unthinkable. Thin film coatings play a variety of roles. In many cases they enable optical components and systems better to perform their function that may be quite different from that of their optical coatings. The anti-reflection coating improves transmission and reduces glare, but the function of the system might be to magnify distant objects. Enabling applications were the main driver for optical coatings in the very early days. Later, with the appearance of the narrowband filter and the thin film polarizer, we begin to see components whose critical performance is purely that of the thin film system, thus extending the role of coatings well beyond that of a purely enabling technology. By 1960 that extension of the role of optical coatings was becoming clear.

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