# Glass for optical technologies

**By John Ballato**

It cannot be overstated how glass permeates virtually all aspects of modern life in ways other materials or material families do not. This ubiquity is a result of the richness of glass compositions and forming methods that have enabled an equally diverse range of glasses and forms.

From the earliest medieval windows to the first telescopes and microscopes to today's optical fibers that can carry light with intensities that exceed those on the surface of the sun, it is hard to separate the history of glass from the history of light-based technologies (see timeline: *A brief history of glass and light*). In honor of the International Year of Glass, this column celebrates this intertwined history by briefly discussing selected areas of the future impact of optical glasses.

## Glass as a propagator

When it comes to optical technologies, amongst the greatest success stories are the billions of kilometers of (silica) optical fiber that circle the globe and connect nearly all her citizens. Indeed, glass as a carrier of light has enabled the Information Age, whose conveniences we now enjoy nearly all day, every day. But glass is not just in the fiber; glass is central to a great many forms of lasers and optical amplifiers, as well as in the planar waveguide devices that route the light around the optoelectronic chip. And these glasses are not just silica. Phosphate laser glasses, fluoride glass infrared lasers, and chalcogenide planar waveguides are all equally important for their specific purposes. One will see continued explorations and adoption of these glasses into future photonic and laser systems associated with laser fusion, on-chip optoelectronics, quantum computing and secured communications, as well as distributed optical sensors.

## Glass as a protector

In addition to creating and propagating light, the transparency of glass is equally useful for windows, covers, bottles, and displays, applications where the glass transmits light or images and protects that which is inside from the outside. In the future, such uses of glass will become more prevalent based on continuing innovations, for example, chemical strengthening. Efforts to make thinner glass progressively stronger has broad applicability and will support a myriad of products, from covers for phones and tablets to automotive windshields to the glass vials employed for EpiPens and COVID-19 vaccines. Another area where glass acts as a form of protector is in numerous aspects of human health, such as in the growing area of optogenetics, which use glass fibers to optically control the behavior of cells.

## Glass as a projector

Among the first glass-enabled optical technologies were telescopes and microscopes, where lenses permitted us to see objects both far away and small in size. Today, lenses and related glass-based optics remain critical to nearly all optical systems. Some of the most exciting aspects in modern physics rely critically on glass. For example, in the study of gravitational waves, glass beam splitters yield requisite interferometric beams used to detect gravitational waves—ironically, using light to see the dark. Another example of glass as projector are the glass fibers used in high energy/power laser systems. Whether for precision laser machining and manufacturing or directed energy defense applications, light–matter (glass) interactions at extreme intensities and the bounty of nonlinearities that result will be an area of important study and solution for many years to come.

Lastly, but only for reasons of space, is that benefits afforded by the natural diversity of glass compositions and properties beget a paradox of choice: of all these permutations of composition and processing, what glass does one use for an application? To answer this question, the power of artificial intelligence and machine learning will inevitably help crystallize selection. Applying data science to glasses and photonics drives us toward a symbiotic future in much the same way as the 2022 International Year of Glass reflects on the 2015 International Year of Light.

## About the author

John Ballato is professor of materials science and engineering and director of the Center for Optical Materials Science and Engineering Technologies at Clemson University. Contact Ballato at jballat@clemson.edu. ■

# A brief history of glass and light

* Denotes recipients of various ACerS awards.

**Stone Age (~4000–2000 BCE)** First glass known to early humans (obsidian, volcanic glass).

**3500 BCE** Earliest known human-made glass (Egypt and Eastern Mesopotamia).

**400 BCE** Plato's "emission theory" of vision: we see because our eyes emit vision beams.

**399–300 BCE** Founding of Alexandria (331) accelerates development of glass production.

**300 BCE** Euclid writes *Optica*. In it, he proposes that light travels in straight lines and provides mathematical formulae for reflection and refraction.

**100 BCE** Discovery of glass-blowing.

**160 CE** Ptolemy writes about refraction and further expands the emission theory of vision.

**982 CE** First recorded reference to Venetian glassmaking.

**984 CE** Ibn Sahl writes *On burning mirrors and lenses*, which describes how curved mirrors and lenses work. He also discovers a law of refraction equivalent to Snell's law.

Ibn al-Haytham, (965–1040 CE) writes the *Book of Optics*, a seven-volume treatise on optics. Also develops the Intromissionist theory (1021 CE), which posits that vision occurs because light rays enter the eyes. He also proposes that magnification results from refraction and link magnification to glass curvature in lenses.

**1200–1299** Sodium oxide added instead of potash (variety of potassium compounds), which now makes glass easier to form.

Venetian glassmaking moved to Murano (1291), due to risk of fire in Venice.

Earliest known use of (simple) microscopes resulting from more widespread use of glass lenses for eyeglasses.

**1268** Earliest recorded comment on use of lenses for optical purposes. Roger Bacon uses glass spheres for magnification. Discovers light reflecting from objects and not being emitted by them.

**1450** Cristallo glass invented, a very clear soda glass.

**1590–1620** Earliest known examples of compound microscopes, combining an objective lens and an eyepiece. First telescope patent application (Hans Lippershey, 1608). Patent not awarded.

**1604** Johannes Kepler describes how light is focused by the eye.

**1610** Galileo improves telescope design and applies it to astronomy.

Kepler described a more practical telescope using a convex objective lens and a convex eyepiece.

**1615** Willebrord Snellius describes what today is known as Snell's Law (though first described in 984 CE by Ibn Sahl).

**1665–1676** Robert Hooke publishes *Micrographia* (1665). Antonie van Leeuwenhoek achieves 300 times magnification with a single lens microscope. Van Leeuwenhoek reports the existence of microorganisms (1676).

**1668** Isaac Newton credited with building the first reflector.

**1672** Newton uses a (glass) prism to demonstrate how white light is comprised of colors.

**1673** Lead oxide added to potash glass, resulting in clear, heavy glasses that are ideal for cutting and shaping.

**1801** Thomas Young experimentally supports Huygens's wave theory of light.

**1842** Colladon and Babinet invent the "lighted laminar water fountain," which is based on total internal reflection.

**1846** Carl Zeiss founds his microscope company.

**1854** James Clerk Maxwell proposed the "Dynamical Theory of the Electromagnetic Field" and conjectures that light is a transverse electromagnetic wave. John Tyndall formulates the ray picture of optical waveguiding.

**1866** Ernst Abbe is hired by Zeiss and creates new microscope designs that lead to new types of (engineered) glasses.

**1888** Roth and Reuss use bent glass rods to illuminate inside the body.

**1893** Adolph Winkelmann published on the "law of mixtures" for glass composition and properties, creating the foundation of modern glass science.

Otto Schott works with Zeiss and Abbe and collaborates with Winkelmann to extend the understanding of glass composition and optical properties.

**1899** Max Planck's model for black body radiation and the postulation of quanta.

**1900s** Soda-lime glass invented.

**1905** Albert Einstein describes the photoelectric effect and establishes that light consists of quanta, later called photons.

**1930** Heinrich Lamm first demonstrates imaging using glass bundles.

**1932** Publication of Zachariasen's paper "The atomic arrangement of glass" and the first understanding of the amorphous structure of glass.

**1933** First television signals optically transmitted using glass rods.

**1952** Alastair Pilkington invents the float glass process for large scale production of flat glass.

**1953** First maser built by Townes, Gordon, and Zeiger.

**1960** Theodore Maiman demonstrates the first laser.

**1961** Elias Snitzer* reports on the waveguide modes of cylindrical glass waveguides, fabricates a single mode fiber, and demonstrates the first bulk glass laser.

**1964** Nobel Prize in Physics for the maser/laser principle.

Snitzer* demonstrates the first fiber laser/amplifier.

**1966** Kao* and Hockham propose that glass fibers could exhibit transmission lower than 20 dB/km.

**1970** Corning breaks the "20 dB/km" loss mark.

**1975** Discovery of fluoride glasses.*

**1977** First live telephone traffic using optical fiber.

**1986** Erbium-doped fiber amplifier (EDFA) reported.

**1995** First photonic bandgap optical fiber.

**2005** Experiments revived on what becomes Gorilla glass, which Corning had first begun developing chemically strengthened glasses in the 1960s.

**2009** Kao* awarded Nobel Prize in Physics for glass optical fiber for communications.