

The Kerr effect

By Bruce A. Garetz

In 1875, the Scotsman John Kerr discovered that transparent, amorphous substances, such as glass and many liquids, become doubly refracting while subjected to a strong electric field.¹ This phenomenon became the basis for the construction of optically bistable devices and ultrafast optical shutters, and it has become valuable in the study of molecular structure and dynamics.

Actually, the Kerr effect has come to refer to a number of related optical phenomena. In its original sense it meant electric-field induced birefringence in amorphous media. With the development of the field of electro-optics, it came to mean any quadratic electro-optic effect, in crystals as well as amorphous substances.²

More recently, with the advent of nonlinear optics, the Kerr effect has also meant birefringence induced by the oscillating electric field of plane-polarized light (optical or ac Kerr effect), such that the original meaning has become the zero-frequency limit (static or dc Kerr effect).³

From another point of view, the Kerr effect has come to mean any intensity-dependent refractive in-

dex due to electric-field induced molecular alignment.⁴ In a specialized application, it has referred to a number of resonant coherent interactions of a pair of light beams in a nonlinear medium that enhance the optical Kerr effect (e.g., the Raman-induced Kerr effect).³ This article will focus on the Kerr effect in amorphous media.

Static Kerr effect

The basic idea behind the Kerr effect is to make a liquid or glass behave like a crystal. Normally, the molecules of a liquid or solution are randomly oriented. If one applies an electric field to a liquid, the molecules of the liquid tend to align along the direction of the electric field. These aligned sam-

ples share some of the properties of crystalline materials; in particular, they are optically anisotropic and exhibit two indices of refraction (one each for incident light polarized parallel or perpendicular to the electric field), a property referred to as birefringence.

The mechanism for alignment is twofold. For molecules with a permanent electric dipole moment, the external field applies a torque on the dipole, inducing orientation of the molecule along the direction of the field (Fig. 1). For nonpolar, anisotropic molecules, the external field induces a dipole moment in the molecule. Because the molecule is anisotropically polarizable, the induced dipole is not parallel to the external field. Thus the induced dipole experiences a

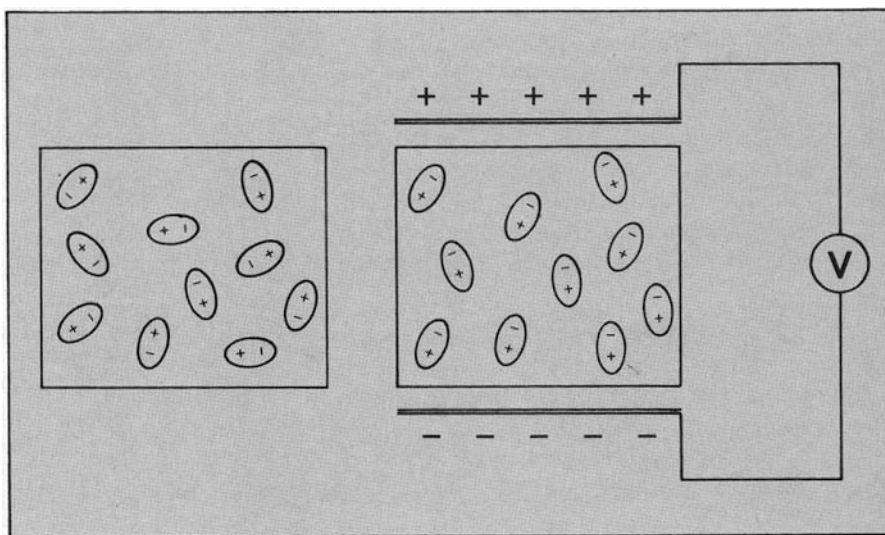


FIGURE 1. Electric field induced molecular alignment.

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torque, causing alignment along the field direction. This induced dipole contribution also occurs with polar molecules, but is considerably weaker than the permanent dipole contribution.

Some materials are more susceptible to the Kerr effect than others. There is a larger difference between the two refractive indices they exhibit. This difference equals a constant multiplied by the square of the intensity of the applied electric field, multiplied by the wavelength of the incident light. The proportionality constant varies from substance to substance. The larger the constant, the greater the Kerr effect due to a given electric field.

For polar molecules, the Kerr constant can be either positive or negative, depending on whether the permanent dipole is parallel or perpendicular to the most polarizable axis of the molecule, respectively. For nonpolar molecules, the Kerr constant is always positive.

Optical Kerr effect

The Kerr effect, as it was discovered in the 19th century, involved the response of a material to a static electric field. A sample was placed between two metal plates that were charged, one positively, the other negatively, creating a constant electric field between them. This device is called a Kerr cell. Today, instead of a static electric field, one can produce a transitory, oscillating field using intense pulses of laser light.

Light is a form of electromagnetic radiation and has an electric field associated with it. If the pulse of light is sufficiently intense, an electric field strong enough to cause alignment of molecules is created. The resulting birefringence is called the optical Kerr effect.

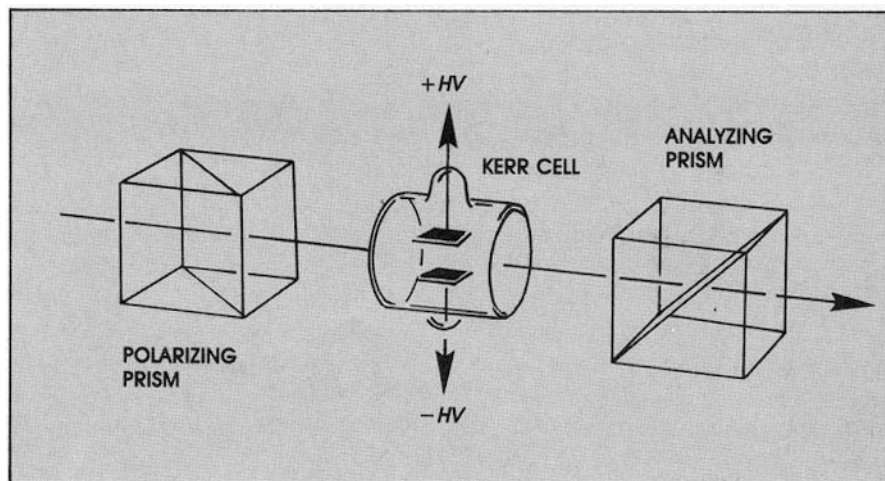


FIGURE 2. Static Kerr shutter

Some materials are more susceptible to the Kerr effect than others. There is a larger difference between the two refractive indices they exhibit.

Only the induced dipole contribution to the Kerr effect survives; the permanent dipole contribution disappears, since the nuclei of the molecule cannot move fast enough to follow the high-frequency oscillations of the field.

Optical shutters

One of the most important applications of the Kerr effect is its use as a fast optical shutter. A Kerr shutter consists of a Kerr cell placed between crossed polarizers (Fig. 2). As long as the medium remains in its randomly oriented state, light passing through the first polarizer cannot pass through the second one. However, when

an electric field is applied to the medium, causing the molecules to align, the medium becomes birefringent and will alter the state of polarization of the original light beam, enabling some of it to pass through the second polarizer.

The amount of light transmitted through a Kerr shutter depends on the Kerr constant of the medium used. Materials with large Kerr constants will permit a greater transmission for a given electric field. Kerr shutters based on the fast, nanosecond switching of the high voltage applied to Kerr cells containing nitrobenzene were used as some of the first laser Q-switches.

A configuration is used so that the shutter is closed while the high voltage (typically tens of kilovolts) is applied. The laser medium is excited while the shutter is closed, allowing the buildup of excess population inversion. When the bias voltage is suddenly switched off, the shutter opens, allowing stimulated emission to occur, resulting in a giant laser pulse.

Today, these Kerr shutters have been largely superseded by Pockels shutters, shutters based on crystals exhibiting a large linear electro-optic effect.

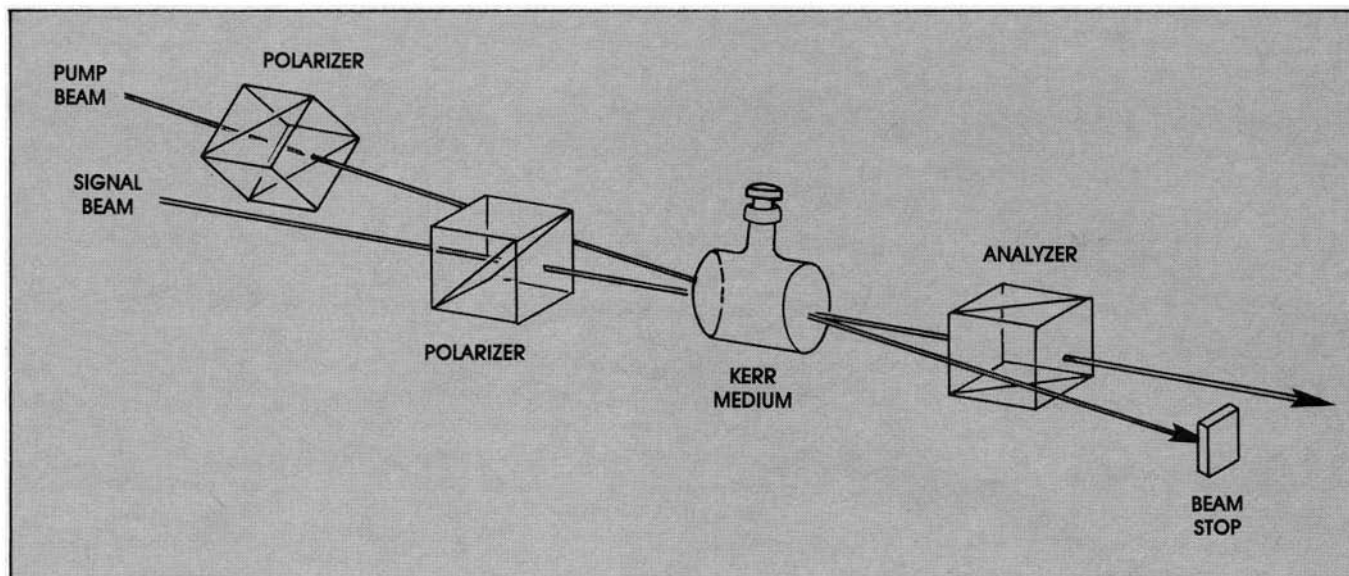


FIGURE 3. Optical Kerr shutter.

However, shutters based on the optical Kerr effect continue to be useful.⁵ Picosecond optical pulses applied to carbon disulfide are used to create picosecond optical shutters (Fig. 3). Such shutters can act as a kind of strobe to freeze ultrafast molecular processes in liquids. Carbon disulfide, because of its large optical Kerr constant, has become a standard used to compare Kerr constants of other liquids and solids.

In a search for liquids with large Kerr constants in our own laboratory, we measured the Kerr constant of carbon diselenide and discovered that it was approximately three times larger than that produced by carbon disulfide, thus making it the largest known optical Kerr susceptibility for a simple liquid.⁶

Today lasers exist which can produce light pulses as short as about 10 fsec. Application of such short pulses to an optical Kerr shutter does not generate a 10 fsec shutter, however. Once aligned, the molecules of a liquid require a finite time to relax to the state of random orientation. This rotational

diffusion time ranges from about a picosecond for small molecules to milliseconds or longer for large macromolecules, so that a picosecond is the ultimate limit for an optical Kerr shutter based on the alignment of molecules.

To go to shorter times, Kerr shutters must rely not on an orientational mechanism, but on a purely electronic mechanism. Such mechanisms exist, but they are generally much weaker, or are effective as shutters only over a limited range of wavelengths of light.

Measurement of rotational diffusion times is, in itself, a useful application of the Kerr effect. This time is proportional to the viscosity of the liquid, and is related to the shape of the rotating molecules. Kerr relaxation measurements of rigid-rod polymer molecules have been useful as a probe of polymer molecule structure.¹

Optical bistability

A pulse of light propagating through a Kerr medium can alter the refractive index that the pulse itself experiences. This is referred

to as an intensity-dependent or nonlinear refractive index. It can give rise to a number of "self-acting" Kerr phenomena such as the self-focusing of a Gaussian laser beam and self-induced rotation of the polarization ellipse.⁴

An application of an intensity-dependent refractive index is in the creation of optically bistable devices, i.e., devices that can be switched between two stable states with different optical properties, analogous to generating a 0 or 1 binary digit. Such a device can be created by placing a Kerr medium between the mirrors of a Fabry-Perot interferometer. The transmission of such nonlinear Fabry-Perot as a function of incident intensity exhibits hysteresis (Fig. 4), so that the device can exist in two states, with transitions between them induced by a small change in the incident light intensity.² These devices are the basis for the new field of digital optical computing.

Traditionally, optical processing has been analog, as with optical Fourier transforms performed with lasers. With optically bistable de-

vices, one can create logical circuits and memories analogous to those used in digital electronic computers. Such optical computers would be faster and require less power than existing electronic computers.

One particular area in which optical computers may have significant advantages over electronic computers is matrix manipulation, where many separate calculations could be performed in parallel. Because a beam of light has spatial extent, different spatial regions of the beam cross section are able to carry different pieces of information, all of which could be processed simultaneously.

While the technology has not yet advanced to the point of building optical computers, this is at present an active area of research. It is conceivable that one could see prototypes within a few years.

Spectroscopic applications

In another application, the optical Kerr effect can be useful as a

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spectroscopic tool. This is done using a "pump" laser to provide a pulse of light which induces the birefringence, and a second "probe" laser to detect the resulting birefringence. The optical Kerr effect can be enhanced if the frequency difference between the pump and probe laser is tuned to a vibrational resonance of the Kerr medium. By scanning the frequency of either laser and recording the transmission of the probe laser through a Kerr shutter, one can ob-

tain the Raman spectrum of the medium.

In our laboratory, we are using this "Raman-induced Kerr effect," or RIKE for short, as a probe of some of the more subtle details of the structure of biological molecules. If one considers a large organic molecule, there is a good chance that one or more of the carbon atoms has four different substituents. Those carbon atoms are called asymmetric. Asymmetric carbon atoms can exist in either a right- or left-handed configuration. The identification of a carbon as being of the right- or left-handed variety is referred to as determining its absolute configuration.

We have developed an extension of the Raman-induced Kerr effect which is sensitive to Raman optical activity.⁷ It would, in principle, allow one to determine the absolute configuration of many asymmetric centers in a molecule.

This by no means exhausts all of the spectroscopic applications of the Kerr effect. The whole area of polarization spectroscopy, which has been applied to double resonance and two-photon as well as Raman spectroscopy, can be considered as a variation of the Kerr effect.

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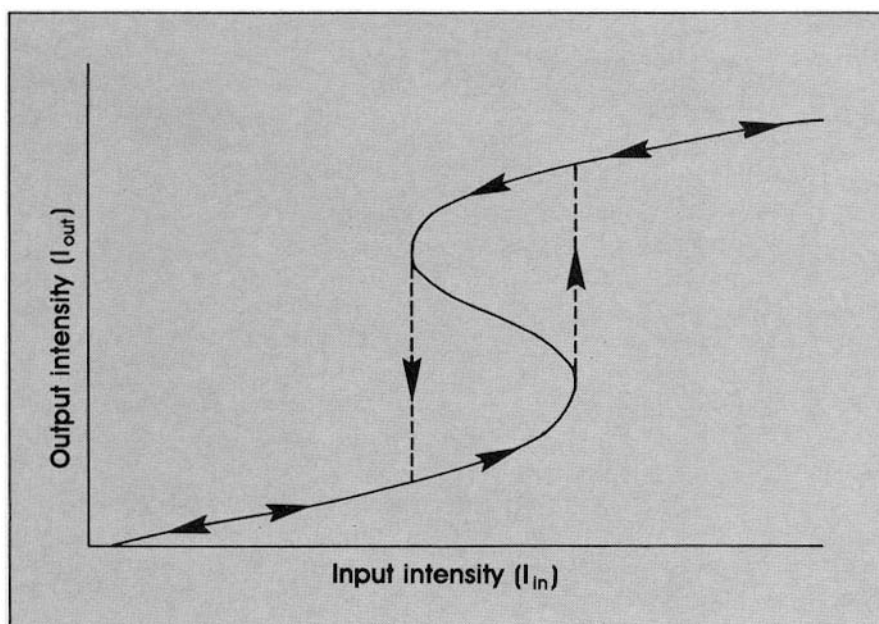


FIGURE 4. Output characteristics of a nonlinear Fabry-Perot interferometer, exhibiting optical bistability.