

# how it works

**NONLINEAR OPTICS OFFERS  
A WAY TO EXPAND THE  
REACH OF CONVENTIONAL  
OPTICAL SYSTEMS.**

## Going nonlinear can be a good thing

By Bill Schweber, Executive Editor

**E**NGINEERS OFTEN have mixed feelings about nonlinearities in their designs' signal chains. They try to minimize them in analog circuits, whereas, for some

functions, such as signal conditioners, they deliberately add them to compensate for transducer nonlinearities. In some analog functions, such as mixers, they carefully use them to upconvert, downconvert, modulate, and demodulate signals. And, of course, those digital circuits are the ultimate realization of nonlinear signals and functions.

As electronics and optical functions blend and work together, the discipline of nonlinear optics is becoming more relevant and even necessary. Using such optics, engineers can develop desired optical wavelengths that are difficult or impossible to generate directly. This situation is analogous to the use of nonlinear circuits to create and capture signals that would otherwise be unobtainable or impractical.

You can also use nonlinear optics as sophisticated measurement equipment that helps assess the properties of materials and biological substances. Further, nonlinear optics is not just an enabling principle; it is also a potentially disabling one: It adversely affects some fiber-optic systems with micron-thin fibers handling just milliwatt light levels, due to the relatively high local intensity.

### HOW DID OPTICS GO NONLINEAR?

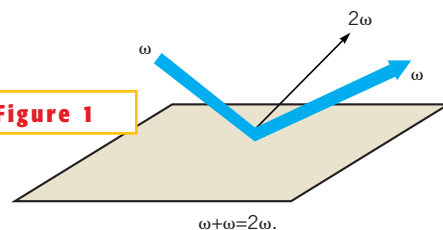
Two nonlinear-optics effects, SHG (second-harmonic generation) and SFG (sum-frequency generation), are especially interesting. In SHG, two identical photons create a photon at twice the energy (Figure 1). (Remember that an individual photon's energy is a function of only its wavelength and frequency.) In SFG, two photons create a photon at the sum of the individual photon energies (Figure 2).

Both of these effects can give information about concentrations, structures, and orientations of molecules at surfaces with which they interact. They can also generate coherent light at shorter wavelengths than the incident light, or you can use them to develop tunable sources in bands in which a direct-output tunable source is unavailable.

It is unsurprising that nonlinear optics exists, because Maxwell's equations dictate optical boundaries in the same way they do with lower frequency electrical and RF signals. However, the generation mechanism for optical nonlinearities is more complex. To understand nonlinear optics, you have to work in both the classical- and quantum-physics worlds, because nonlinear optics operates at the intersection of these two perspectives, where Maxwell's continuous equations meet Planck's discrete perspective (Reference 1). Although Scottish physicist John Kerr and German physicist FR Pockels noted nonlinear-optical effects in the 19th century, our more rigorous understanding began about 50 years ago (see sidebar "The Kerr and Pockels effects" and Reference 2).

A meaningful understanding of the cause of the nonlinear behavior needs complex models and equations (Reference 3). It also requires the application of factors such as the susceptibility of the dielectric medium through which light is passing, which characterizes the medium's index of refraction and its absorption. However, you can get a basic understanding using an analogy.

When light enters a dielectric medium, the electrons of the molecules of the medium absorb the energy and oscillate, which displaces them slightly. Such displacement causes polarization, which is proportional to the electric



**In second-harmonic generation, a new photon created from two identical photons has twice the energy and frequency and one-half the wavelength of the initial photons.**

field of the incident beam of photons. In turn, the polarization sources the light, which then passes through the dielectric medium. The equation that characterizes the polarization response of the material to the applied electric field is an expanded power series with a dc term and higher order terms; each term has decreasing significance, because the susceptibility factor coefficients decrease rapidly.

For modest light intensity, the electrons and their displacements are linear, like masses on springs. In the linear regime, beams of light follow the superposition principle, and different wavelengths of light do not interfere with each other, even though they cross the same territory. As the light intensity increases, the force of the light is strong enough to overcome the force of the molecule and its electron, which is trying to return to its natural equilibrium position. When this return happens, the displaced electron is no longer a mass oscillating with simple harmonic motion on a spring.

This situation doesn't occur in normal ranges of intensity. The electric field of light is as high as 1000V/mm, whereas the field that binds the electrons to their nucleus is  $10^6$  to  $10^9$ V/mm. A laser, especially if you properly focus it, can produce a field strength that rivals that of the inherent molecular field strength.

## CRYSTAL POWER

Creating SHG or SFG effects is not just a matter of having sufficient intensity and energy. For example, the dielectric material must maintain a phase match between the two incident beams to keep the beams together as long as possible as they go through the material and interact. Thus, the material must have a refractive index that is constant at the differing wavelengths or that maintains an even phase difference. In the simplest case, one of the beams can be a dc-applied voltage with a 0-Hz frequency, which induces a birefringence effect that allows control of an incident high-energy laser beam.

Those electronics engineers who think that the only crystal structures that matter in this world are silicon and quartz would find a different situation in the nonlinear-optics world. Researchers have historically used inorganic crystals as the dielectric medium for nonlinear-optics effects. The different internal symmetries, structures, and dimensions of crystals affect their suitability at desired wavelengths. Note that crystals are complex, dividing into seven symmetry classes, which in turn divide into 32 point groups that further categorize the internal structure.

The wavelength-dependent properties of a crystal define its suitability for a nonlinear-optics goal. Many of today's nonlinear-optics researchers focus on using nonlinear optics to produce visible and UV wavelengths because many available laser sources can operate only in the longer wavelength infrared

band. Researchers are experimenting with exotic formulations to produce crystals with the desired physical and optical characteristics. Potassium dihydrogen phosphate (called KDP, although that abbreviation is not its chemical symbol) and its isomorph, called KTP, which has added titanium, are two of the more common crystals that nonlinear-optics applications use. These applications also use  $\text{LiNbO}_3$  (lithium-niobate) because some of its underlying indices change when you heat it to a temperature higher than  $300^\circ\text{C}$ , whereas others do not.

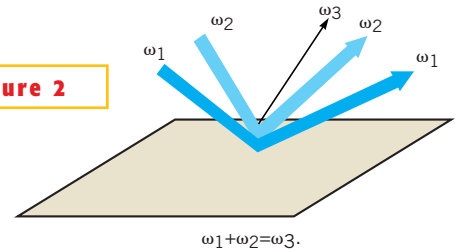
## APPLICATIONS ARE DIVERSE

Nonlinear optics may seem an interesting lab curiosity, but it is much more than that. The science has both emerging and well-established applications. The reasons for using nonlinear-optical systems involve constraints on wavelength, power, and laser sources. Just as with wired- and wireless-communications systems, optical-system designers must balance spectrum and channel issues, oscillator and amplifier technologies and limitations, and other factors that affect the design. Similarly, laser applications, such as drilling holes into steel, exciting fluorescence, curing epoxy, and sensing from remote locations, require specific frequency bands or discrete wavelengths.

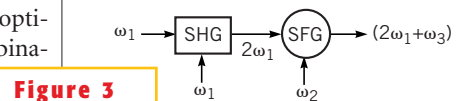
Further, these applications may need a continuously variable or step-tunable source, just as many RF systems do. Yet, the available sources may have insufficient output power, poor efficiency, or some other combination of performance factors that fail to meet an application's needs. Such a scenario is analogous to finding an oscillator or amplifier for RF that meets your design's many conflicting requirements: The part may not exist or may have drawbacks that make it unacceptable. Some nonlinear-optical systems even use a combination of SHG and SFG to develop the necessary wavelengths and tunability, just as analog-electronic-communication channels combine doubling and mixing (Figure 3).

You use SHG to transform the output of solid-state neodymium or ytterbium lasers into a green output, providing relatively low power consumption and a compact source. In another case, the deep-UV-laser sources that small-process-IC production requires is difficult to produce, so engineers use nonlinear-optical sources to

**Figure 2**



**In sum-frequency generation, a new photon is created at an energy value that is equal to the sum of the two initial photons.**



**Figure 3**

**Some systems combine multiple stages of second-harmonic and sum-frequency generation, to develop the desired output photon energy and wavelength.**

produce the required wavelength and power combinations. Some stereolithography systems for prototyping 3-D models use epoxy resins. These systems need wavelengths matched to the characteristics of the epoxy to cure the material, and, in many cases, conventional lasers do not provide these wavelengths; nonlinear-optical-laser systems can.

Some nonlinear-optical applications resemble crime-scene investigations more than they do production case studies. Researchers are adapting these optical systems to perform vibrationally resonant SFG studies of lipids within cell membranes, their response to changes, and the interaction of proteins in pH, temperature, ion concentration, and

toxins. These SFG designs provide direct, in-place information on the structure, orientation, and aggregation of surface-bound proteins. For more about nonlinear optics, including the physics and equations you need for a deeper understanding and appreciation of them, go to Allister Ferguson's Web site on the subject (**Reference 4**). □

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## THE KERR AND POCKELS EFFECTS

Although nonlinear optics is a hot area of research and application, two of its appearances predate our modern solid-state and crystal knowledge. Scottish physicist John Kerr in 1875 demonstrated that an external electric field could cause double refraction in a glass block. In this third-order effect, the electrically induced birefringence is proportional to the square of the applied electric field. Designers use the Kerr Effect to build electrically controlled shutters for light beams, because the change in refractive index shifts and steers the path of the light beam.

German physicist FR Pockels in 1893 discovered that, in some crystals, the change in index of refraction is a larger, second-order effect that is linearly proportional to the applied electric field. Designers often use so-called Pockels' cells, electro-optical crystals, as switches to modulate light and laser beams. The cells cost approximately \$100.

### REFERENCES

1. Schweber, Silvan, *QED and the Men Who Made It*, Princeton University Press, 1994, ISBN 0691033277.
2. Bloembergen, Nicolaas, *Nonlinear Optics*, Fourth Edition, 1996, ISBN 9810225989.
3. Matthews, Stephen J, "The nonlinear response," *Laser Focus World*, February 2003, [www.laserfocusworld.com](http://www.laserfocusworld.com).
4. Ferguson, Allister, *Nonlinear Optics*, March 15, 2001, <http://local.phys.strath.ac.uk/12-370/>.