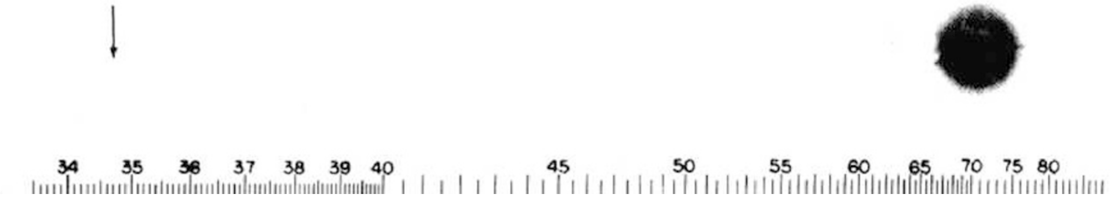

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MILESTONE 10

Optics in harmony

GETTY

The development of the laser (MILESTONE 9) meant that, for the first time, the interaction of huge electric fields with matter could be studied, particularly in the regime where the electrical polarization created by the laser is no longer linearly proportional to the light field. Then, higher-order effects occur, similar to the excitation of higher harmonics in musical instruments.

Indeed, it was only a year after the first laser was built when, in 1961, Peter Franken and colleagues used a seminal experiment to demonstrate the frequency doubling of light from a ruby laser beam focused into a quartz crystal. This second harmonic signal was imaged as a small spot on a photographic plate. Unfortunately, however, that tiny spot was thought by the lithographers at *Physical Review Letters* to be a grain of dust, and was therefore eliminated from the published version of the article.

Nonetheless, the significance of these results was widely recognized, and inspired Nicholaas Bloembergen and his group to enter the field; while waiting for a suitable laser source to conduct their own experiments, they developed the theoretical foundations of the quantum mechanical description of nonlinear optics. This effort was recognized with a share of the Nobel Prize in Physics in 1981.

Subsequently, other nonlinear effects were demonstrated in the early 1960s such as sum-frequency generation and four-wave mixing. An important nonlinear effect that forms the basis for continuously tunable laser sources is optical parametric generation. There, two beams of different energy are generated from one incoming laser beam.

Another class of nonlinear optical effects occurs through the influence of strong light fields on material properties themselves. Since the nineteenth century, the effects of electric fields on the refractive index of a material — the Kerr and Pockels effects — have been known. High-intensity optical fields can achieve a similar effect, which is known as self-phase modulation. In laser pulses this leads to chirp, which is a variation in the frequency spectrum of the pulse, and is therefore an important detrimental effect to consider in many optical systems.

Ever since those early discoveries in the 1960s, nonlinear optical effects have been widely used in applications. Apart from telecommunication applications in which nonlinear effects are an ideal tool to manipulate the short, intense laser pulses in optoelectronic systems, they also form the basis of imaging and sensing applications such as coherent anti-Stokes Raman spectroscopy (CARS) and multiphoton fluorescence microscopes. Second-harmonic generation also plays an important role in the femtosecond frequency combs used for ultrahigh-resolution laser spectroscopy (MILESTONE 20). As in the case of music, the best works are always those that make perfect use of higher harmonics.

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