

SPECIAL ISSUE:

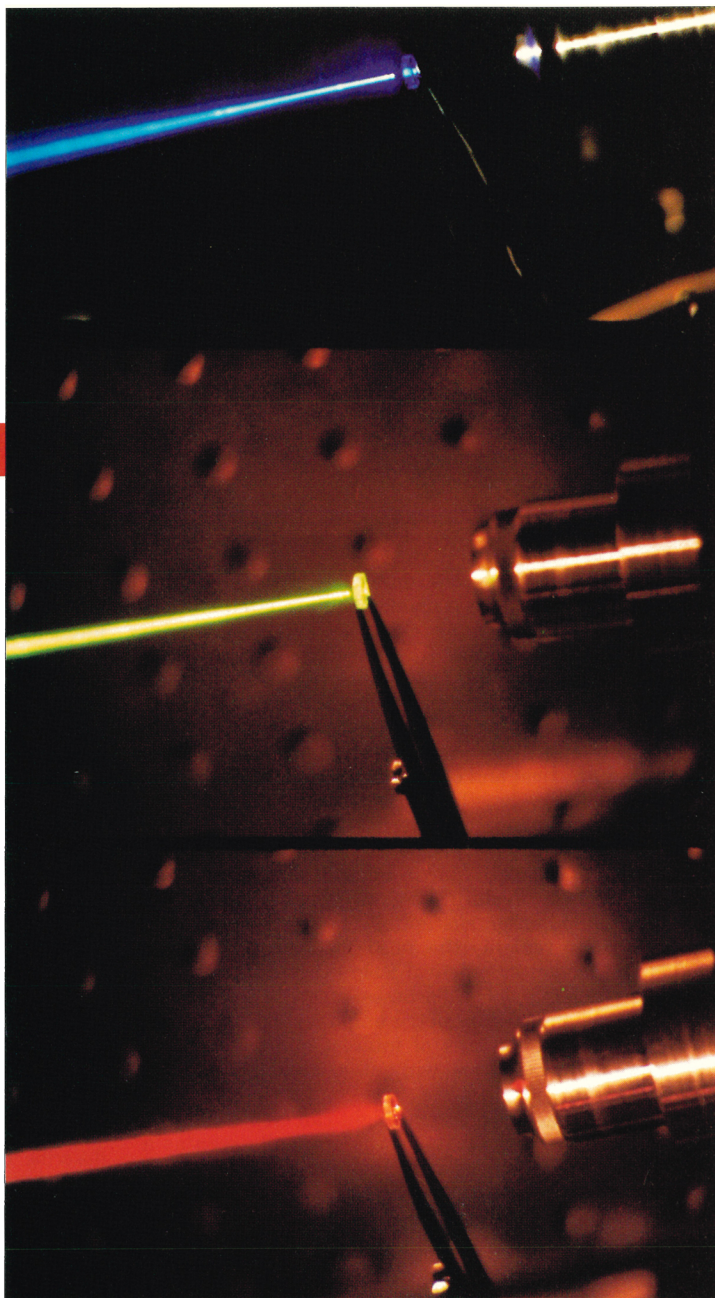
NONLINEAR OPTICS

Before the advent of lasers, transparent optical materials were assumed to be essentially passive, unaffected by light traveling through them. The high powers of laser beams made it possible for the first time to observe that the presence of light can indeed affect the medium. Intense light can, for example, change the refractive index or absorption of an optical material.

When this happens, the light itself is affected by the change, in a nonlinear way. The nonlinear response of the material can convert the laser light into new colors, both harmonics of the optical frequency and, when more than one frequency is present in the input light, sum and difference frequencies.

Nonlinear optics is traditionally introduced by noting that the dielectric susceptibility χ can be expanded in a Taylor series in terms of the oscillating optical electric field. The χ_1 term is the dielectric susceptibility measured at low power. The χ_2 term, linear in the field, multiplies the incident optical field, creating second-harmonic frequencies (as well as dc terms and sum and difference frequencies). The χ_3 term is quadratic in the field, producing third-harmonic frequencies or inducing a change in the index of refraction. The Taylor expansion approach is valid when the optical materials are essentially transparent.

There is a close relation between χ_2 and the electro-optic effect. In that phenomenon, an applied electric field multiplied by the optical field creates an index change through the χ_2 term, so that the index of refraction is controlled by an external applied field. While such optical modulators are not generally con-



Second-harmonic beams of visible light, generated when infrared laser light passes through 1-mm-long crystals of lithium niobate. In each case, the incident ir wavelength is twice the output wavelength. Periodic perturbation during the growth of these optically nonlinear ferroelectric crystals produces periodic reversals of susceptibility, so that the phases of the incident and second-harmonic beams can be matched. A 6.3-micron period, for example, was imposed on the crystal that produces the red (660 nm) beam, and the blue beam (465 nm) is generated in a crystal grown with a 2.1-micron period. (Courtesy of Dieter Jundt, Crystal Technologies Inc.)

sidered nonlinear optics, the materials physics is sufficiently similar that the two phenomena are often studied together.

The generation of new frequency components (from χ_2) is of extreme practical importance because, although there have been an extraordinarily large number of lasers demonstrated, each type of laser typically generates only one or a few optical frequencies, and only a few lasers have proved practical and commercially viable. The needs to achieve new wavelengths and to develop practical tunable coherent light sources have led to the exploration of nonlinear optics. In his article for this special issue of *PHYSICS TODAY* (page 25), Martin Fejer describes the progress that has been made in generating new wavelengths using the second-order susceptibility χ_2 . He notes the challenges that remain—the need for better nonlinear crystals and for better practical lasers that can use these materials efficiently. He discusses progress toward the “holy grail”: an optical parametric amplifier that is tunable throughout all wavelengths of interest and that can be kept running by a novice without a PhD in quantum electronics.

The observation that intense light can create changes that act back on the light itself was originally seen as a problem in the transmission of high-power laser beams through optical material. Depending on the properties of the material, the light could self-focus or self-defocus in the medium, either destroying the material or destroying itself. In recent years researchers have begun to explore ways to use nonlinear optics in information systems to enhance switching, communication and information processing. The third-order nonlinearity χ_3 in transparent media results in an optically induced refractive index change that one can exploit to make optical switches. The nonresonant effect is small but ultrafast, and it has particular potential in ultrawide-bandwidth fiber optics. Mohammed Islam (page 34) outlines the promising devices and applications based on this effect. The picosecond speed with which these devices can switch is beyond the capabilities of electronics.

When the wavelength of incident light lies near an absorption resonance in the material, one cannot describe the nonlinearities with the usual Taylor series. Available

absorption states may fill up under sufficiently intense photoexcitation, causing the absorption to decrease as the intensity increases. In addition there may be an associated index change. My article (page 42) describes how near-resonant nonlinearities, resulting from a moderate amount of absorption, have been particularly accessible in semiconductors and have been used to demonstrate all-optical switching. I also describe nonlinearities that arise from the photomodulation of internal fields. When photogenerated carriers move physically within a medium, the separation of charges provides a screening field that reduces internal fields. The photomodulation of internal fields can create a very sensitive nonlinearity whose origin lies in a second-order nonlinearity χ_2 affected by carrier transport, thereby creating an effectively χ_3 material. One such nonlinearity is photorefractivity.

Organic molecules and polymers recently burst upon the scene as practical alternatives to the inorganic crystals, semiconductors and fibers being used as nonlinear materials. Recent improvements in the understanding of organic molecules, obtained through both modeling and synthesis, show considerable promise for nonlinear optics. Anthony Garito, Rui Fang Shi and Marvin Wu (page 51) describe the rapid acceleration in this field and outline developments in both the second-order and third-order processes.

These articles are snapshots of just a few directions that researchers are exploring in the richly varied field of nonlinear optics. Lack of space precludes discussion of interesting subfields such as stimulated Raman and Brillouin scattering, nonlinear spectroscopy and spatial solitons, as well as some unexpected new results on harmonic generation from fibers and waveguides that have been preconditioned by illumination with blue or ultraviolet light. Emmanuel Desurvire's article on fiber amplifiers (*PHYSICS TODAY*, January, page 20) outlines some of the latest results on nonlinear soliton propagation in fibers, an area that continues to grow in importance. Because of its many applications, nonlinear optics will be a fruitful research area for many years to come.

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