# Nonlinear optics: The next decade

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**Abstract:** This paper concludes the Focus Serial assembled of invited papers in key areas of nonlinear optics (Editors: J.M. Dudley and R.W. Boyd), and it discusses new directions for future research in this field.

**OCIS codes:** 190.0190 Nonlinear optics

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## References and links

1. J.M. Dudley and R.W. Boyd, "Focus Series: Frontier of Nonlinear Optics. Introduction," Optics Express **15,** 5237-5237 (2007); http://www.opticsinfobase.org/oe/abstract.cfm?URI=oe-15-8-5237

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Nonlinear optics describes the behavior of light in media with nonlinear response. Its traditional topics cover different types of parametric processes, such as second-harmonic generation, as well as a variety of self-action effects, such as filamentation and solitons, typically observed at high light intensities delivered by pulsed lasers. While the study of nonlinear effects has a very long history going back to the physics of mechanical systems, the field of nonlinear optics is relatively young and, as a matter of fact, was born only after the invention of the laser. Soon after, the study of light-matter interaction emerged as an active direction of research and boosted the developments in material science and source technologies. Nowadays, *nonlinear optics* has evolved into many different branches, depending on the form of the material used for studying the nonlinear phenomena. The growth of research in nonlinear optics is closely linked to the rapid technological advances that have occurred in related fields, such as ultra-fast phenomena, fiber optics, and optical communications. Nonlinear-optics activities range from the fundamental studies of the interaction between matter and radiation to the development of devices, components, and systems of tremendous commercial interest for widespread applications in optical telecommunications, medicine, and biotechnology.

This Focus Serial, being edited during the last two years by two leading researchers in the field of nonlinear optics, Prof. John M. Dudley and Prof. Robert W. Boyd [1], assembled a number of invited papers in key areas of nonlinear optics and identified new directions for future research in this field. *So, where is this field going ?*

Importantly, we notice that research efforts during recent years which focused on both fundamental physics and applications of nonlinear optics demonstrate several major trends. First, the basic concepts of nonlinear optics penetrated into new areas of material science by exploring novel nonlinear materials and nonlinear propagation of light in engineered structures and waveguides. Secondly, we observe further development of novel concepts, such as *tunable nonlinear response*, and engineered and *enhanced nonlinearities*, which should be explored more extensively for developing novel optical tunable nonlinear devices. Moreover, in such novel structures many of the effects well studied in nonlinear optics can be enhanced by the cavity effects, heterostructures, or Fano-type resonances, that enable much stronger nonlinear

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response at lower powers, as well as demonstrate novel sub-wavelength localization phenomena. Slot waveguides, nonlinear cavities, slow-light structures, and ring resonators are expected to become the key building blocks for such nonlinearity-enhanced effects and devices.

The development of *photonic crystal fibers* in the 90's opened new frontiers in the field of nonlinear fiber optics as well as dispersion and nonlinearity engineering. The advantages of photonic crystal fibers for applications in nonlinear frequency conversion have already been recognized. It is expected that the subsequent research will be targeting novel designs of linear and nonlinear properties of such micro-structured fibers, as well as the study of interesting nonlinear parametric effects such as sum-frequency generation and multistep cascading. More importantly, the observation of *supercontinuum generation* in photonic crystal fibers has had revolutionary impact on nonlinear optics. Nowadays more and more groups are employing these new white-light-laser sources for their experiments, which include the studies of self-focusing, shaping, and control of polychromatic light.

One of the recent major advances of nonlinear optics is connected with the miniaturization of photonic devices for confining and guiding electromagnetic energy on a scale of a nanometer. In the last ten years, photonic-crystal technology allowed us to gain at least an order of magnitude factor in the miniaturization of components, such as waveguides and couplers, with respect to conventional optics. However, when the size of conventional optical circuits is reduced to the nanometer scale, the propagation of light becomes limited by diffraction. *Optical nanowires* allow us to trap and guide light in a new way, and represent an ideal optical medium to study novel and intriguing physical phenomena in nonlinear physics and nonlinear optics. By carefully choosing the waveguide dimensions, both linear and nonlinear optical properties of optical nanowires can be engineered. In particular, the relatively low threshold powers for nonlinear optical effects in these wires make them potential candidates for functional on-chip nonlinear optical devices of just a few millimeters in length. In addition, the characteristic length scales of linear and nonlinear optical effects in silicon wires are markedly different from those in commonly used optical guiding systems such as photonic crystal fibers.

Another way to overcome the diffraction limitation is to employ interesting properties of *surface plasmon polaritons*, which are evanescent waves trapped at the interface between a medium with a positive real part of the dielectric constant and one with a negative real part of the dielectric constant, such as metals in the visible range. Even though this phenomenon has been known for a long time, there is renewed interest in this field, mainly motivated by the will to merge electronic circuits with photonic devices. On the other hand, a deeper insight into the physics of *sub-diffractive imaging* through surface plasmon polaritons and the study of the dielectric properties of layered metal and dielectric structures is required for the development of the novel nanometer-scale imaging technology. Nonlinear optics would enable better image resolution as well as imaging at other harmonics, so that it may drive novel potential applications of the imaging technology to nanolithography, with a significant impact on optics community by substantiating realistic materials with effective negative refractive index. It is believed that the fabrication of metal-dielectric composite structures where the dielectric layers possess strong nonlinear response would allow the realization of *tunable nonlinear metamaterials* recently demonstrated at microwaves.

Novel ideas which are developing in *nonlinear plasmonics*, and the trends for the miniaturization of photonic devices renew the interest in the study of nonlinear effects at surfaces. Nonlinearity is known to enhance localization, and this effect has been demonstrated in many settings but for other areas of physics. Similar effects are expected for nonlinear photonic and plasmonic structures. Surfaces are known to provide the crucial background for the plasmon-induced effects such as *sub-wavelength beaming*, but the studies of the nonlinear response modified by geometry and sub-wavelength scales is a new, not yet explored area.

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The important area where the role of nonlinear optics is expected to become more and more pronounced is the creation of *all-optical circuitry* for computing, information processing, and networking which is expected to overcome the speed limitations of electronics-based systems. The design and realization of photonic equivalents of fundamental devices that form basic building blocks in electronic circuits is a primary step towards the practical realization of all-optical circuits. Ultra-fast and ultra-small photonic integrators capable of providing the performance that is required for future applications enabling operation bandwidths in the THz regime is expected to provide an alternative photonic design that would allow integration of arbitrary time-limited optical pulses with bandwidths at least one order of magnitude higher than those achievable previously. The use of novel nonlinear materials (such as chalcogenide glass or InGaAsP) is expected to enhance the key performance of the corresponding devices and circuits by substantially reducing their size and switching power. It is expected that these major tasks will be solved soon and lead to the study of many of *the nonlinear optics effects and devices on a chip*, including bit memory cells for future all-optical packet switching systems.

The concepts and methods of nonlinear optics penetrate actively into other fields. The discovery of *carbon nanotubes* as a new class of materials calls for the study of their optical properties. These materials exhibit unique absorption and emission properties that can be controlled through changing the diameter of the carbon tubes. They also have significant potential through the use of their nonlinear optical properties. These properties are generally observed when high light intensities are present and can be used to control and adapt this light. For example, it is possible to rapidly switch the light on and off, change the wavelength (color) of the light and even form a continuum of light from a short pulse using nonlinear properties of fullerenes and carbon nanotubes. A key point is that this material will be capable of forming both optical as well as thin-film electronic devices using very similar fabrication processes, thereby opening the door towards the low-cost mass manufacture of fully integrated electro-photonic circuits.

As another example of interaction of nonlinear optics with other fields, it is worth mentioning the recent advances in the study of light propagation in colloids and nanosuspensions. A light beam propagating in such *nonlinear soft matter* can display complex nonlinear dynamics due to spatiotemporal variation of the refractive index of this complex fluid. This kind of effect may result in modification of properties of suspension and subsequently affect the optical wave both in space and time. Most fascinating effects would be related to the observation of optically-induced control of nonlinear waves and their instabilities in fluids.

Last but not least, we should mention a rapid development of applications of nonlinear optics to *quantum physics*, the area least reflected in this Focus Serial. In particular, the use of a parametric down-conversion process to generate squeezed electromagnetic states has been demonstrated for several different systems including more recent experiments with cavities in photonic crystals. The amount of squeezing is determined by the correlation functions relating the field quadratures of light coupled into the waveguide or cavity, which enable squeezing well below the shot noise. Also, it looks attractive to design *single-photon sources* based on the emission of cavities in photonic crystals or quantum dots embedded in nanowires which can be engineered to reduce the divergence of the far-field radiation. In addition, the nanowire geometry can be employed for creating efficient tunable nanoantennas. The studies of many other nonlinear effects in quantum systems such as dynamical chaos are expected to become more important, especially for nonlinear optics of ultra-small structures and devices.

The breadth and the depth of the nonlinear-optics research is truly remarkable and, as we believe, is indicative of the fact that the field of nonlinear optics is not showing any sign of saturation even after many years from its creation. Instead, nonlinear optics now spans from micrometer to nanometer scales and from classical to quantum, increasingly becoming an interdisciplinary field of research with many concepts that span beyond the discipline boundaries.

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