Nonlinear optics has emerged in the last decade from a basic science discipline that requires large, high power lasers for implementation, to a focus for a number of potential technologies in the information processing area that can be implemented with diode lasers. This rapid transition has been spurred on by two important factors. First, waveguide technology has been developed to the point that high intensities can be maintained over centimeter propagation distances with low losses in interesting (i.e., useful) nonlinear media. Second, new materials and new ways to use existing materials have both been invented. Developing these technologies to their ultimate limits can lead to (1) doublers, and parametric devices in general with sub-milliwatt input powers, and to (2) femtosecond, all-optical switching, logic, etc. devices implemented with tens of milliwatts.

There has been rapid development of efficient waveguide SHG devices. Well-known materials such as KTP, KNbO$_3$, and LiTaO$_3$ have been used in novel ways. The past, the usual Type I and II phase-matching geometries have required that off-diagonal elements of the second order susceptibility tensor $d^{(2)}_{ijk}$ be used. However, the largest coefficients, by factors of 3-20 have been the diagonal elements, and the second harmonic power conversion efficiency scales as the susceptibility squared. For example, quasi-phase-matching (QPM) has allowed these diagonal elements to be used in waveguide geometries, leading to conversion efficiencies in excess of $600\%/W\cdot cm^2$ for LiNbO$_3$ ($d_{33} = 34 \text{ pm/V}$) and KTP ($d_{11} = 18 \text{ pm/V}$). For a 1 cm long device, 50 mw inputs will produce 15 mw of doubled light in a single pass geometry. Here the current challenges are technological in nature—for example, how to fabricate QPM structures with phase-matching over a centimeter, reduce waveguide losses to make resonator structures practical, implement efficient and isolated coupling between lasers and devices.

The other important, but not yet as technically advanced direction, has been the development of useful organic materials. Poled polymers are now achieving susceptibilities of 100-150 pm/V, implying that conversion efficiencies in excess of $5000\%/W\cdot cm^2$ might be possible in suitably phase-matched systems. Actually achieving such levels in stable polymeric devices is one of the greatest challenges for the future. Second order active molecular species with large nonlinearities have already been identified, and the main issues are in the materials processing arena—for example, stability, size of the transparency window, photosensitivity, waveguide losses, etc.

Even better materials are on the horizon in the form of organic single crystals. In poled polymers, only partial alignment of active species is achieved, whereas in single crystals, alignment can be optimized. Materials with activities as large as 600 pm/V have been measured. A great challenge for the materials scientist will be to make such materials with acceptable transmission windows into waveguides, and then to find some way equivalent to QPM for phase-matching. Given the large nonlinearities, clearly the potential for
efficient, low threshold parametric processes is incredible!

The situation for third order materials is just as promising, but the challenges are even more difficult. Until recently, for waveguide devices, only glass in the form of fibers has been found suitable for switching and related devices.\(^4\) This has led to the development of more nonlinear glasses, but always at the cost of much larger linear loss. This obviates one of the strengths of silica glass that has a very small linear absorption coefficient. The challenge here is to develop better glasses with low losses. An open question is whether the current losses in new glasses are due to scattering from imperfections, etc., or are these glasses (sometimes in the form of fibers) already limited by fundamental absorption losses?

Semiconductors, especially carrier and exciton related nonlinearities, have been studied more than any other material.\(^5\) The key question is whether there is too much linear or nonlinear loss to make efficient switching devices. However, multiple quantum wells and quantum dots offer new opportunities, and it is one of the current challenges to show that these materials are actually better in terms of materials figures of merit. To date, the best waveguide semiconductor results have been obtained using photon energies below one half the bandgap to avoid two photon absorption.\(^6\) An obvious question is whether non-direct bandgap semiconductors have better trade-offs for figures of merit.

The largest uncertainties and, therefore, greatest hopes currently lie in the area of organic materials.\(^7\) Unfortunately, the information here is rather sparse. Some very large nonlinearities have been measured and reported. However, the trade-offs between large nonlinearities, and linear and nonlinear absorption are still not clear. Nevertheless, there are a few examples that show considerable promise, especially in single crystals where non-resonant nonlinearities greater than $10^{-12} \text{ cm}^2/\text{W}$ have already been measured. The great challenge here is to build a reasonable and useful database so that the full potential of such materials can be assessed. And then the community must face many challenges about how to make useful devices out of these materials.

There are some interesting, new, non-traditional directions that are being taken to achieve nonlinearities that might be useful for devices. A very promising approach is to use active materials such as optical amplifiers and lasers.\(^8\) For example, large ultrafast nonlinearities have been found in laser amplifiers, opening the possibility for multi-functional devices in lasing systems. Furthermore, gain provided by laser amplifiers has been used to effectively boost device nonlinearities and dramatically reduce operating power levels. An initial example is provided by Er-doped fibers used in a nonlinear loop mirror.\(^9\) In fact, the incorporation of gain in general is certain to become a major factor in nonlinear devices, and poses the question of how best to use it.

Another new idea is to use multiple second order processes, for example, second harmonic generation and subsequent down conversion—to produce nonlinear phase shifts in the fundamental for all-optical devices.\(^10\) The resulting nonlinear phase shifts are proportional to $d_{22}^2 \phi$ and hence can use the large advances in organic second order materials to produce low power (milliwatt) operation. These concepts are in a very early stage of development and many aspects need to be understood—an interesting and high risk challenge.

Given this recent proliferation of new materials and new device ideas, what needs to be done? Success requires five distinct scientific communities: chemistry, materials science, waveguides, nonlinear optics (both characterization and devices), and systems engineers (to define required performance levels). After three decades of nonlinear materials and optics research, the interactions and feedback between these groups are, on the average, still inadequate. Improved interaction is the single factor that would considerably enhance progress in this field.

I believe that the field of nonlinear optical materials and waveguiding devices based on them is very dynamic at this point. Despite the many important advances, much remains to be done in the areas of nonlinear materials, waveguide fabrication, and device implementation before the full promise of guided wave, nonlinear optical devices can be realized.

George I. Stegeman is Professor and holder of the Cobb-Hooker chair at the Center for Research in Electro-Optics and Lasers (CREOL), University of Central Florida, Orlando, Fla.

**References**