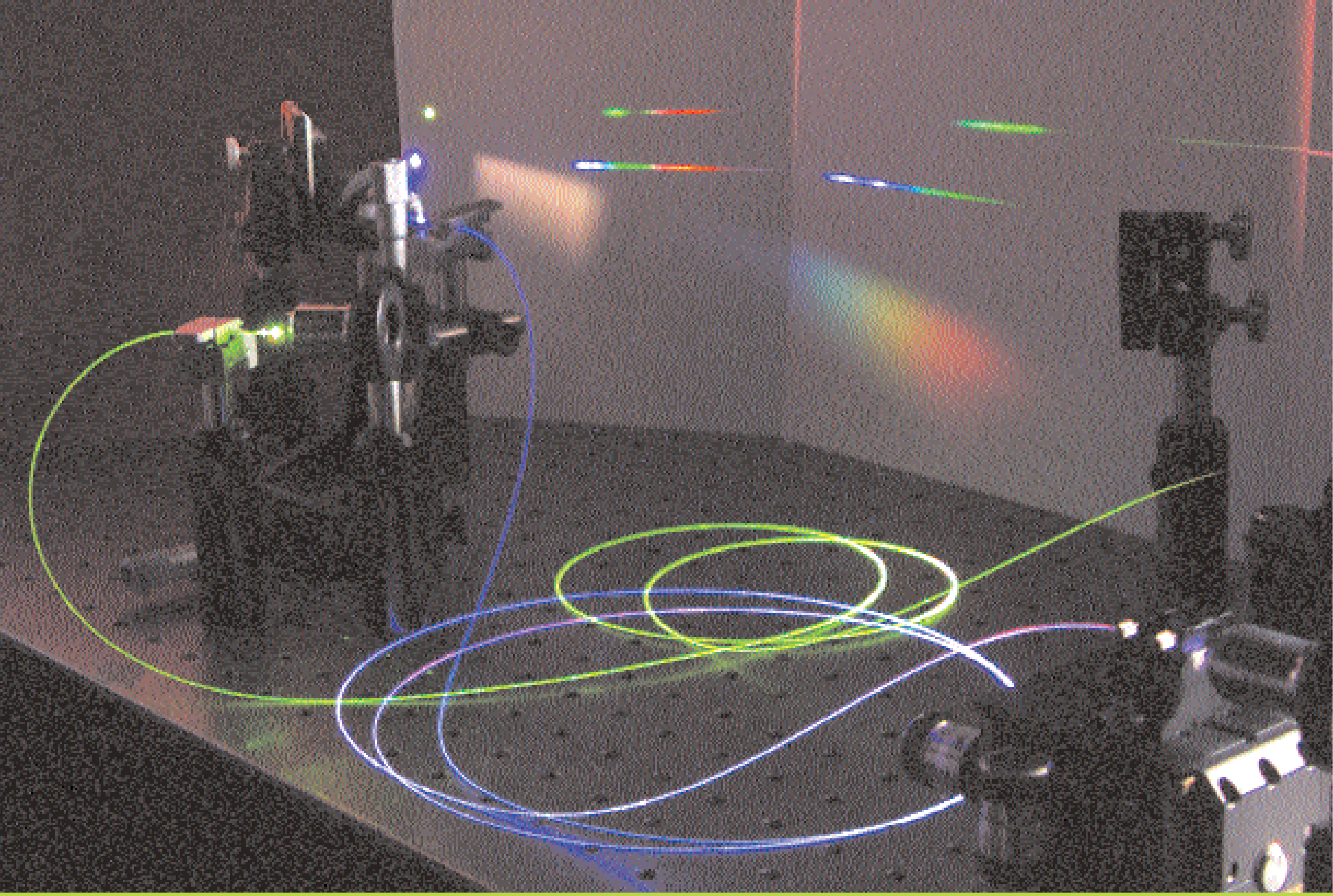

Nonlinear Interactions in Air-Silica Microstructure Optical Fibers

By Jinendra Ranka and Robert S. Windeler

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The development of optical-fiber cables and communications technology has undergone a dynamic revolution over the past decade.[1] The most basic design of an optical fiber consists of silica cladding surrounding a silica core doped with germanium (GeO_2), which increases the index of refraction by up to 2% above pure silica, allowing light to be guided simply by total internal reflection at the core-cladding interface. Over the years, however, this basic geometry has evolved to substantially alter the waveguide properties, especially the dispersion in the 1.3 to 1.6 micron wavelength region. Design variations have included shaping the core index profile and adding down-doped and up-doped rings as well as elliptical cores for polarization-preserving fibers. Just recently, significant new developments—specifically, the use of microstructure air holes around the fiber core—have made possible some incredible new properties, with applications in many fields, from metrology to medicine.

The development of novel transmission fibers has perhaps had its most important impact in the area of nonlinear optical effects in optical fibers.

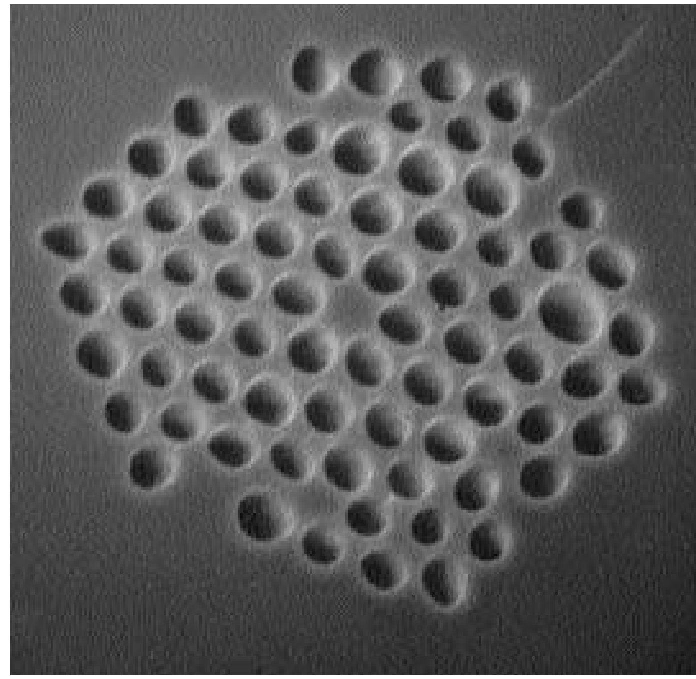


Figure 1a. Please provide caption.

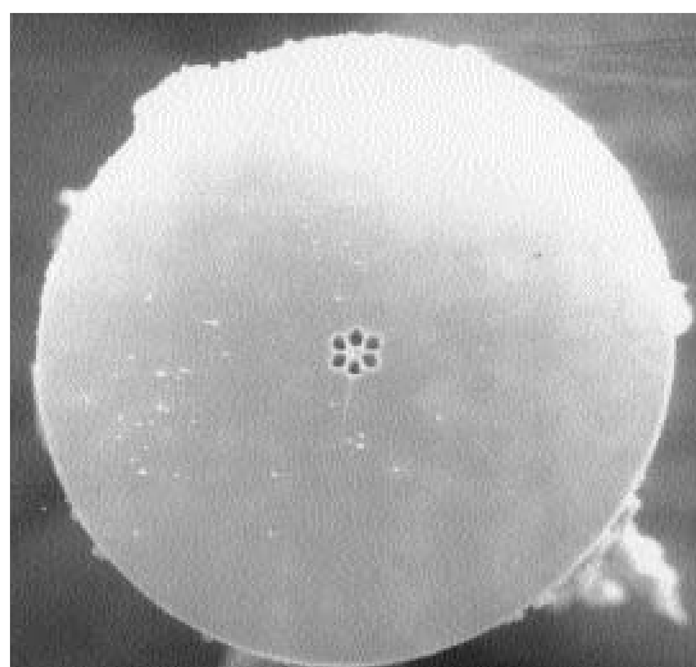


Figure 1b. Please provide caption.

All of these new applications involve consideration of the group-velocity dispersion (GVD) of a material, the phenomenon causing different spectral components of a pulse to travel through the medium at slightly different velocities, and which can result in a temporal broadening of an ultrashort light pulse during propagation. The net GVD of a single-mode optical fiber can be attributed to the sum of two contributions, that from the material itself and that due to the waveguide. The waveguide contribution is a result of the wavelength dependence of the fraction of the light confined within the fiber core. At longer wavelengths, light is less confined by the higher-index core and expands further into the lower index cladding region, lowering the effective index of the guided mode. By properly modifying the core-cladding index difference and the core diameter, the waveguide dispersion contribution can be tailored to shift the zero-dispersion wavelength of a single-mode silica fiber to wavelengths greater than 1300 nm, the material zero-dispersion wavelength of bulk silica. Fibers can also be designed to have large normal dispersion ($< -100 \frac{ps}{nmkm}$) at 1.55 microns) or a net GVD of less than a few ps/(nm*km) across several hundred nanometers. As a general rule of thumb for a step-index fiber, the larger the core-cladding index contrast and the smaller the core diameter, the larger the magnitude of the waveguide contribution; *i.e.*, a small wavelength dependent variation in the mode-field diameter will result in a large effective index change.

The development of novel transmission fibers has perhaps had its most important impact in the area of nonlinear optical effects in optical fibers. Although fused silica possesses a relatively low nonlinear susceptibility, single-mode optical fibers are excellent nonlinear media because of their low loss, small effective areas, and long interaction lengths. A myriad of nonlinear interactions, including spectral broadening and continuum generation, stimulated Raman and Brillouin scattering, and parametric amplification, have been efficiently demonstrated in optical fibers.[1] As the strength of these nonlinear interactions is often limited by pulse spreading (and hence intensity reduction) due to the chromatic dispersion of the fiber, dispersion management through fiber design can also be used to enhance these effects. Unfortunately in the single-mode regime, no conventional step-index silica fiber has been shown to have a zero-GVD wavelength below that of bulk silica. As ultrashort pulse technology is most fully developed in and near the visible wavelength region, with Ti:Sapphire lasers at 800 nm, the large fiber dispersion in conventional fibers precludes a host of interesting nonlinear effects. Dispersive temporal broadening lowers the peak power of the pulses over short distances, substantially reducing the nonlinear interaction lengths.

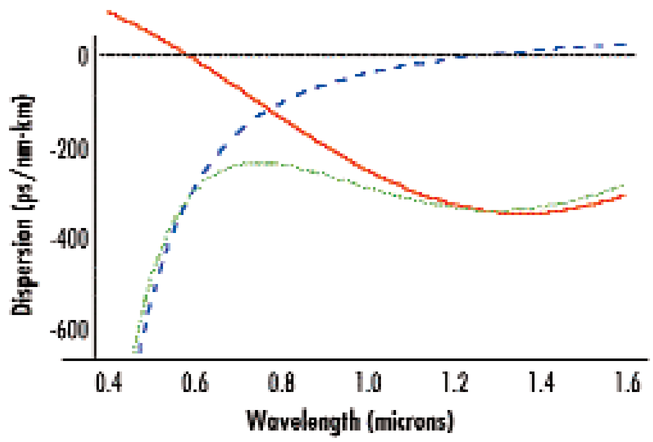


Figure 3. Please provide caption.

Microstructure optical fibers

Recently we have been developing fiber structures that incorporate numerous air holes within the cladding region (Figure 1). These air-silica microstructure fibers, also referred to as holey fibers or photonic crystal fibers, can guide light by several means as the placement and size of the air voids allow for several new degrees of freedom that do not exist in conventional waveguide designs. Initial interest in these structures was focused on their potential to confine light through a photonic bandgap created by air voids arranged in a periodic hexagonal lattice.[2] A silica based photonic crystal optical fiber based on the above idea was recently demonstrated experimentally and a number of theoretical and numerical models are being developed to describe the waveguide properties of these structures.[3,4]

Microstructure fibers that do not require a periodic placement of the air voids, and that guide light through total internal reflection rather than a photonic bandgap, have also been demonstrated.[5] With just a solid silica core surrounded by an air-silica cladding, honeycomb fibers have been shown to exhibit single-mode behavior with negligible bend loss over broad spectral ranges, and theoretical calculations have indicated that the fibers can exhibit unusual dispersion characteristics such as anomalous group-velocity dispersion at wavelengths as short as 1 micron.[4] Using an effective-index model to simulate the air-silica cladding, single mode propagation in honeycomb microstructure fibers has been calculated to be single mode due to a wavelength dependence of the cladding index. Light at shorter wavelengths becomes more confined in the silica core, avoiding the air holes and increasing the effective index of the cladding. For air-filling fractions (the percentage of the cladding that is air) below a few percent, the fiber can be kept single-mode over a broad wavelength range. As the air-filling fraction is increased, the fiber becomes highly multimode.

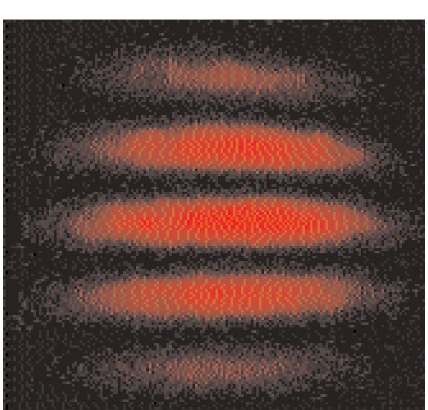


Figure 2. Please provide caption.

Microstructure optical fibers with large difference between the core and cladding refractive indices ("high delta"), where the air-fill fraction of the cladding is greater than ~ 60%, can be considered simply as step-index waveguides, guiding light through total internal reflection. These fibers, similar to earlier single-material optical fibers,[6] approach core-cladding index differences of $\Delta n \sim 0.45$, substantially higher than can be achieved in conventional step-index optical fibers. These fibers will support numerous transverse spatial modes for any reasonable core diameter due to the large index contrast. Such simple step-index multimode fibers however have unique properties that are not possible in conventional optical fibers. The large index contrast and small core diameters result in a large waveguide contribution to the fiber's dispersion and hence dramatically altered dispersive characteristics, such as anomalous dispersion at visible wavelengths! As a result, a number of nonlinear optical effects can now be achieved at visible wavelengths that were not previously possible or were severely limited in conventional silica optical fibers.[7,8]

Unique optical properties of high delta air-silica microstructure optical fibers

One of the first high-delta microstructure fibers we demonstrated consisted of an ~ 1.7-micron diameter silica core surrounded by an array of 1.3-micron diameter air holes in a hexagonal close-packed arrangement (Figure 1a). A small ellipticity in the fiber core results in a strong polarization-maintaining birefringence. Light is completely confined within the first ring of air holes in the structure and the other rings do not appear to play a role. Later versions of our fiber, incorporating only a

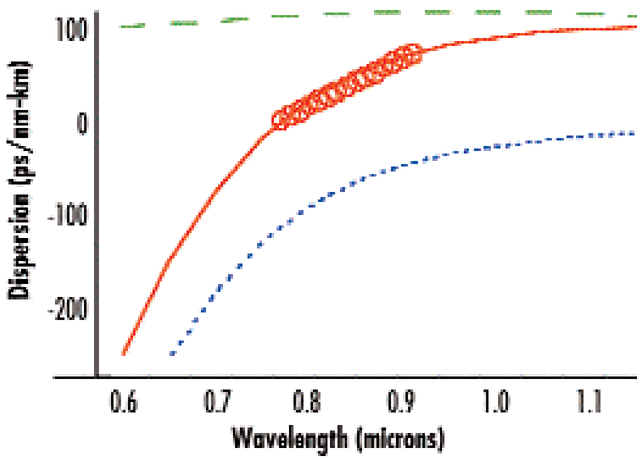


Figure 4a. Please provide caption.

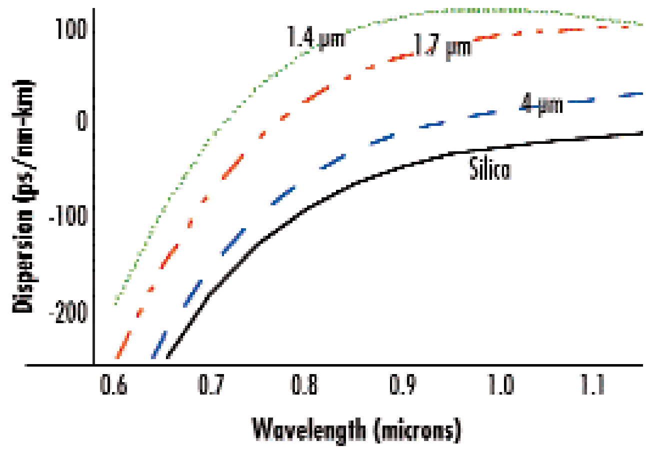


Figure 4b. Please provide caption.

single layer of large air holes with similar dimensions (Figure 1b), show identical waveguide properties. The background loss of these fibers is typically under 50 dB/km at 1 micron, while substantially higher at the water absorption peaks. Through proper manufacturing techniques, fibers with losses less than 10 dB/km are possible. As this is still ~ 50 times larger than for ordinary silica fibers, present day microstructure fibers are primarily suited for applications where short length (~few hundred meters or less) are needed. Several kilometers of fiber are readily drawn from a single preform.

Although the fiber should support numerous transverse spatial modes, experimentally we see that only a single mode can be excited for wavelengths from 500 nm to 1600 nm, and it is not possible to excite higher-order modes by bending or twisting the fiber as is easily done with conventional multimode fibers. Furthermore, the fiber is insensitive to bend loss at wavelengths less that 1600 nm for bends as tight as 0.5 cm in diameter. We easily determine the single-mode nature of the fiber by performing a spatial interference measurement between the output mode of the microstructure fiber with the output of a standard single-mode fiber. In Figure 2, an example of a spatial interference fringe pattern formed with 633-nm light, showing a clear fringe pattern, indicates that only a single transverse mode is present. The unique mode properties are simply a result of the fact that the lowest-order individual guided modes of a high-delta, small effective area waveguide have substantially different propagation constants. As the coupling strength between any two modes is proportional to the difference in propagation constants between the two modes, coupling and mixing is prevented even in the presence of strong perturbations. It is fair to say that although the fiber can support numerous transverse spatial modes, single-mode excitation (not necessarily the fundamental mode) and propagation can easily be achieved.

The dispersion properties for the fundamental mode of high-delta microstructure fibers closely follow the predictions of analogous step-index waveguides. The calculated material and waveguide contributions to the net GVD [$D = d/d\lambda(1/v_g)$, where v_g is the group velocity] for the lowest-order mode of a step-index fiber with a core diameter of 1 micron and with a core-cladding index difference of 0.1, having a single-mode cutoff at ~800 nm, are shown in Figure 3. In the regime in which the fiber supports only a single mode, the waveguide GVD is negative (normal dispersion), resulting in a shift of the fiber

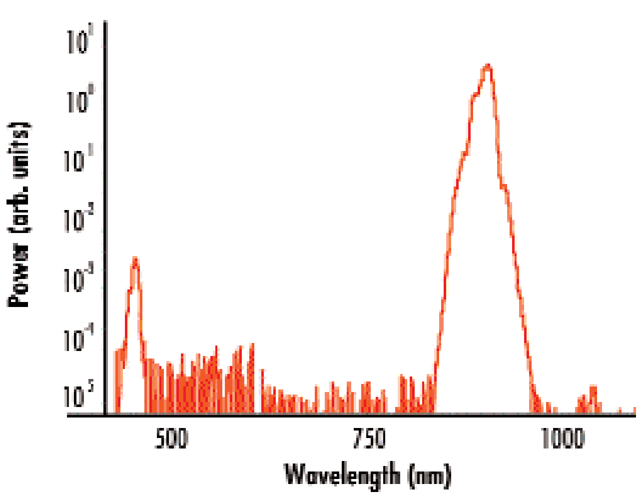
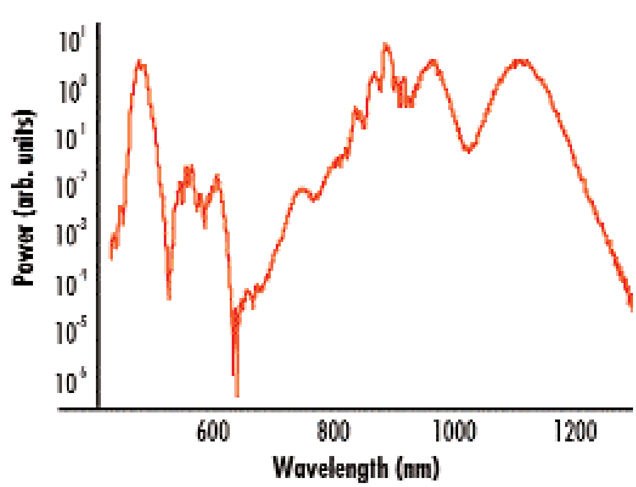


Figure 5a. Please provide caption.



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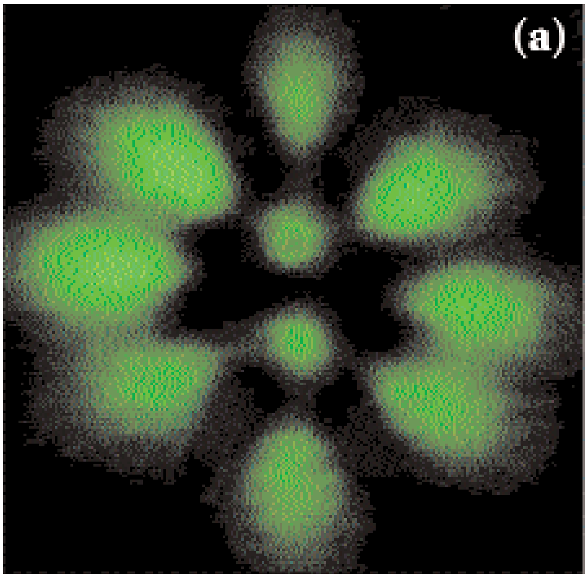

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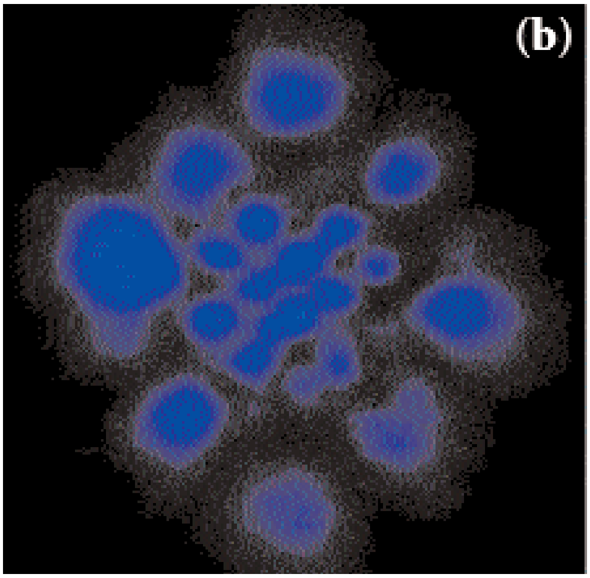


Figure 6b. Please provide caption.

zero-GVD to longer wavelengths. In the multimode regime below ~ 580 nm, the waveguide GVD contribution is positive (anomalous); however the magnitude is substantially smaller than the dispersion of bulk silica. The maximum anomalous waveguide GVD for the fundamental mode increases in magnitude and shifts to longer wavelengths as the core-cladding index difference and the core diameter are increased. The experimentally measured and numerically calculated dispersion values for our microstructure fiber are shown in Figure 4a. The fiber has a zero-GVD wavelength of 767 nm and anomalous dispersion at longer wavelengths, a remarkable result for such a basic structure. By simply scaling the fiber dimensions for larger or smaller core diameters, fibers with zero-GVD anywhere between 650 nm and 1300 nm are possible (Figure 4b). These results were the first experimental demonstration that air-silica microstructure optical fibers can exhibit anomalous dispersion at wavelengths significantly below 1300 nm.[7]

Nonlinear interactions and visible continuum generation

The amazing dispersion characteristics, small core size, and novel mode characteristics of high-delta microstructure fibers open up a world of unique nonlinear and ultrashort pulse interactions at visible wavelengths.[7,8] Soliton propagation was first demonstrated by propagating 100-fs duration pulses at 790 nm through a 20-meter section of fiber. Many classic effects, such as intrapulse Raman scattering, pulse breakup, and self-steepening at high input powers, are also observed. A number of nonlinear effects that utilize birefringent and multimode phasematching in the fiber have also been demonstrated. By launching 100-fs duration pulses at 895-nm with only 250 W of peak power along a birefringent axis of the fiber, an orthogonally polarized second-harmonic component is generated within the first few centimeters. At higher powers numerous other components are observed (Figure 5). Multimode phase matching is seen when 1-kW pulses from a Q-switched Nd:YAG laser operating at 1064 nm are launched into the fundamental mode of a 50-cm section of fiber. The far-field mode patterns of the generated second- and third-harmonic components are shown in Figure 6. Conversion efficiencies well above 5% are achieved. The second-order nonlinearity of the fiber is not clearly understood, and may be a result of stress-induced birefringence or surface effects.

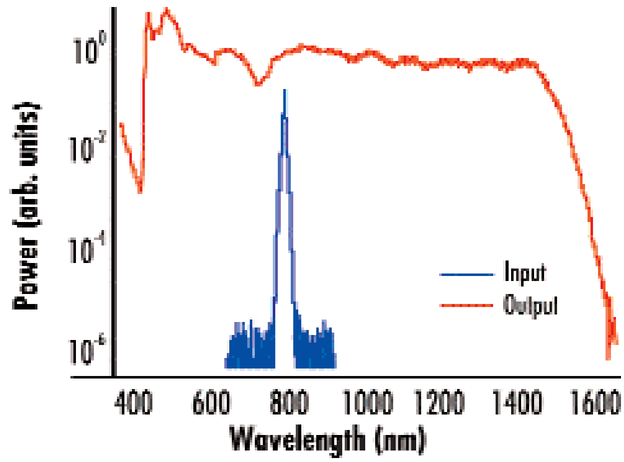
The most amazing result seen to date, however, has been the generation of an ultrabroadband single-mode optical continuum. By injecting pulses of 100-fs duration, 800-pJ energy, and a center wavelength of 790 nm into a 75-cm section of fiber, we were able to create a continuum extending from 390 to 1600 nm (Figure 7). Here the combined effects of self-phase modulation, four-wave mixing, second-harmonic generation, and Raman scattering (a virtual textbook of nonlinear phenomena) in the long length of fiber produce a broad, flat spectrum. By using input pulses of < 30-fs in duration and shorter (~ few cm) sections of fiber, the Raman contribution can be suppressed and a stable continuum, generated primarily through self-phase modulation, is possible. Previous work in continuum generation has required pulses with megawatt peak power or microjoules of energy for generation of similar spectra. The small core diameter and anomalous dispersion characteristics of microstructure fibers allow such a continuum to be achieved with three orders of magnitude less energy, specifically, pulses from a fairly simple unamplified Ti:Sapphire laser oscillator.

Such an incredibly broadband pulse of light poses a serious challenge for anyone attempting to measure it. While measuring its spectrum is straightforward, techniques do not exist for measuring the spectral phase or the time-dependent intensity and phase. Such measurements are important for determining whether this light can someday be compressed to its Fourier-Transform limit—about 1 fs! Indeed, it is also important to determine whether these quantities are the same from shot to shot or highly variable. For example, white light from a light bulb has almost as broad a spectrum, but it has a random spectral phase and hence is uncompressible.

Fortunately, improvements are being developed to existing already sophisticated pulse-measurement techniques, mainly the frequency-resolved-optical-gating (FROG) technique, to allow the measurement of the ultrabroadband continuum. Researchers at the Georgia Institute of Technology have shown the spectral phase to be quite stable by performing a spectrally resolved cross-correlation measurement (often referred to as XFROG) between a ~30-fs reference pulse (characterized separately by the FROG technique) and the continuum.[9] A typical measured spectrogram is shown in Figure 8. Note that the delay versus wavelength is approximately quadratic, which is not particularly complicated, so compression should be possible.

The broadband continuum generated by femtosecond pulses propagating through this fiber has enabled a revolution in optical frequency metrology. While it may be surprising that femtosecond pulses are useful in optical frequency metrology, the very stable train of pulses generated by a mode-locked laser corresponds to a "comb" of regularly spaced frequencies. If this comb is broad enough, it can be used to subdivide an optical frequency into intervals small enough to be directly compared to a cesium clock, which is the primary standard for the definition of the second. Using microstructure fiber to generate the necessary bandwidth, this technique has recently been demonstrated by groups at JILA in Boulder, Colorado and the Max-Planck Institute for Quantum Optics in Garching, Germany.[10] This frequency domain technique also results in stabilization of the phase shift between pulses, which is of interest for time-domain measurements.

Another promising application will be in optical coherence tomography (OCT).[11] OCT is a new imaging modality which is the optical analog of ultrasound and enables the *in situ*, real time cross sectional imaging of materials and biological tissues. In OCT, imaging is performed using low coherence interferometry and the longitudinal resolution is inversely proportional to the bandwidth of the light. In the past, ultrahigh resolution OCT measurements have been performed using state of the art Ti:Sapphire lasers which use double chirped mirrors to generate five femtosecond pulse durations with 300-400 nm bandwidths. The microstructure fibers promise to be powerful sources for OCT imaging since they can generate extremely broadband light that essentially spans the entire visible as well as the near infrared wavelength range. These bandwidths could enable submicron resolution imaging. In addition, the broad spectral bandwidths will be powerful for spectroscopically resolved OCT imaging as well as imaging in wavelength regimes that were previously inaccessible.



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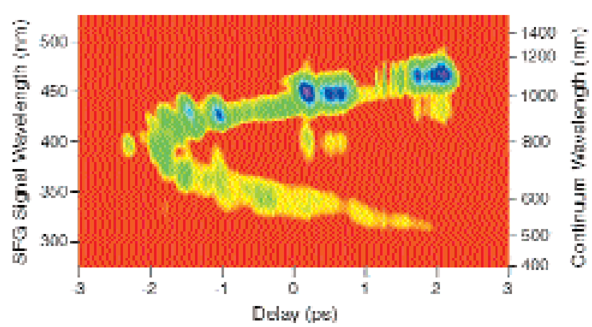

Figure 8. caption needed

Conclusions

Recently demonstrated high-delta microstructure optical fibers have unique properties that are not possible in conventional optical fiber designs. The high-delta and small core diameter of the structure provide for a large waveguide dispersion contribution that results in net anomalous GVD of the fiber at visible wavelengths. Similar results can also be achieved in many other high-delta structures, such as ribbed planar waveguides, where unique highly nonlinear materials can be used. While it is doubtful that microstructure fibers will be used as long-haul transmission fibers, the nonlinear properties of such fibers are well suited for device applications. In just a short period of time, the ability to easily generate a broad, stable continuum has already revolutionized fields such as frequency metrology and biomedical imaging. There is no doubt that we have only just begun to see the potential and benefits of novel microstructure optical fibers.

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