Externally tunable fibers for tailored nonlinear light sources

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Hybrid-material optical fibers that enable supercontinuum generation show potential for application in widely tunable broadband light sources.

Nonlinear light-matter interactions open up new possibilities for intense light generation, particularly at wavelengths that cannot be accessed using today’s lasers. Supercontinuum generation within highly nonlinear fibers represents one approach to achieving such interactions. This method is particularly effective when such fibers are pumped at wavelengths that fall within the domain of anomalous fiber dispersion. Within this domain, high power pulses can be converted into a series of temporally self-maintaining states called solitons. Solitons can efficiently transfer energy to lower frequencies (i.e., by stimulated Raman scattering) or to higher frequencies (i.e., by the generation of so-called dispersive waves that are temporally phase-matched with the solitons). Exploitation of this phenomenon over the last two decades has led to the development of a vast number of light sources featuring multi-octave bandwidths and high brightness. A greater physical understanding of multi-octave broadening, as well as advances in fiber manufacturing, have resulted in the development of sources with ever-decreasing pump energies. This has given rise to the commercialization of supercontinuum light sources based on silica photonic-crystal fibers (e.g., those developed by NKT Photonics and Toptica Photonics).

Although some success has already been achieved using this approach, the application of fused silica for nonlinear light generation is limited by its relatively weak nonlinearity (2.8 x 10^{-20} m^2/W), narrow transmission window (0.4–2.2 µm), and restricted tunability. Today, emerging applications within the biophotonics and semiconductor industries have driven the demand for light sources that can access new spectral windows, particularly in the UV and IR regimes. This demand has triggered the search for novel, highly nonlinear core materials (i.e., that enable low-power supercontinuum generation in fibers, and even on chip-based platforms), which continues today. Current research in this area is dominated by soft glasses (e.g., chalcogenides,1,2 tellurites,3 and fluorites4). Although soft glasses provide a number of benefits that are inherent to silica (e.g., large nonlinearities, less absorption in the mid-IR, and functional compositions), the optical properties of the fibers are static and generally fixed after fabrication. Only a few case studies show external modulation of the waveguiding properties (i.e., using electro- or magneto-optics).5 Additionally, some soft glasses contain toxic materials, thereby precluding their use in biological applications.

Figure 1. (a) Scheme of a hybrid silver metaphosphate/silica (AgPO₃/SiO₂) fiber. The inset shows an electron microscope image of a cleaved sample. (Reprinted with permission.6 Copyright 2016 Optical Society of America.) (b) Comparison of the group velocity dispersion (GVD) for AgPO₃/SiO₂ fibers, chalcogenide/SiO₂ fibers, and SiO₂ tapers, respectively. The numbers in the plot refer to the core radius (in µm). The red lines mark the main lasing lines of ytterbium (Yb), erbium (Er), and thulium (Tm).
To meet the demand for new materials that can overcome these limitations, we investigated the potential of silver metaphosphate glass (AgPO$_3$) to operate as a linear and nonlinear fiber core material: see Figure 1(a). Because of its good transmission from visible to near-IR (NIR) wavelengths and its flexible glass structure, this material offers an interesting alternative to those mentioned above. Recent studies have demonstrated that AgPO$_3$ exhibits a number of exceptional features, including good solubility of rare earth dopants and the ability to form plasmonic nanoparticles after external treatment. Its use therefore enables the optical properties of the waveguide to be tuned (i.e., the group velocity dispersion, GVD) and nonlinear enhancement to be introduced after fabrication, via post-processing. This feature is particularly useful for active (lasing) and passive (nonlinear) light-generation schemes.

Our dispersion analysis of circular step-index geometries reveals the potential of hybrid AgPO$_3$/silica fiber for supercontinuum light generation. This arises as a result of the special GVD of the hybrid waveguide, which has two zero-dispersion wavelengths (ZDWs). Optical solitons are able to form in this regime, and can transfer energy to two phase-matched dispersive waves (one in each normal dispersion regime next to the pump) in either the visible or IR regimes. In general, the spectral locations of dispersive waves are highly sensitive to changes of the effective refractive index of the core mode and can eventually be tuned by temperature, structural changes to the glass, or before fabrication (i.e., by adjusting the core diameter of the fiber design).

The graphs in Figure 1(b) show that there is a gradual variation in the GVD across core diameters between 1.4 and 2.6μm, where the ZDW can be brought close to prominent laser lines (i.e., ytterbium, erbium, and thulium). Other formerly successful fiber systems, such as chalcogenide/silica fibers or silica tapers, require submicron core diameters to access these laser lines—see Figure 1(b)—which makes handling and optical coupling challenging.

To demonstrate the nonlinear capabilities of our design, we have shown that a hybrid AgPO$_3$/silica fiber can serve as a supercontinuum light source spanning more than one-and-a-half octaves in the NIR for sub-μJ pumping energies. In our design, two ZDWs delimit an anomalous dispersion regime within a small spectral interval at around 1.56μm. Pumping at this wavelength, with a pulse width of 30fs, results in the generation of two phase-matched dispersive waves in the visible and NIR, respectively (see Figure 2).

Liquid-core optical fibers (LiCOFs) are another promising platform for tunable nonlinear light sources. In contrast, gas-filled fibers—known to provide reconfigurability and tunability via changing pressure—require large pulse energies and sophisticated anti-resonant fiber designs. LiCOFs promise similar tunable capabilities, as a result of large thermo-optical coefficients and miscibility of the core material, but can operate at much lower pulse energies and with transmission windows from visible to mid-IR. Additionally, due to their strong noninstantaneous nonlinearities, LiCOFs promise new physical phenomena, such as enhanced dispersive wave generation, enhanced coherence properties, and new soliton dynamics.

We have recently demonstrated soliton-based supercontinuum generation in carbon-disulfide (CS$_2$)-filled silica capillaries pumped with a state-of-the-art thulium-based fiber amplifier system (operating at a wavelength of 1.95μm with a pulse width of 460fs). We observed soliton fission for input pulse energies higher than 3nJ and the generation of a strong dispersive wave at 1.2μm, where the phase-matching condition agreed well with the longest spectral wavelength (i.e., the soliton wavelength at 2.4μm).

In summary, our investigations into the linear and nonlinear properties of novel hybrid fiber systems open new perspectives in relation to the flexibility and capability of optical-light generation in optical fibers. We have developed two such fiber systems that are compatible with biophotonic applications and optofluidic chip designs. These applications represent two significant

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**Figure 2.** Measured and simulated output spectra from a 1.7cm-long AgPO$_3$/silica fiber, pumped at 1.56μm for 30fs with a pulse energy of 575pJ (or 220pJ in the simulation, due to neglected loss). The fiber has a core diameter of 1.9μm, and its output possesses two zero-dispersion wavelengths (ZDWs), thereby separating the normal dispersion (ND) from the anomalous dispersion (AD). Sim: Simulation results. Exp: Experimental results. DW: Dispersive wave.

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motivations that drive our research. It is our aim to create new light-tunable sources at hard-to-access wavelengths. Our future experiments will focus on the use of alternate core materials, detuning the fiber properties by temperature, and novel non-instantaneous soliton interactions. We hope that this work will reveal the potential of hybrid-fiber systems as a platform for efficient and wavelength-selective nonlinear light generation.

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