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Opinion article

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Fiber optic nanotechnology: a new frontier of fiber optics

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1 Introduction

Nanophotonics is an exciting new field of nano-science that deals with the interaction of light with matter on a micro/nanometer size scale. It is a field in which photonics merges with nanoscience and nanotechnology, providing challenges for fundamental research and creating opportunities for new technologies and applications.

Nanotechnology has spawned new areas of research for fiber optics, namely fiber optic nanophotonics. When we think of optical fibers, we typically think of optical propagation through waveguides of dimensions greater than or similar to the optical wavelength. Conventionally, little attention need be given to sub-wavelength or nanometer size features. However, when nano-features are intentionally incorporated into optical fibers, many interesting phenomena may arise. For example, with nano-features of sufficient refractive index contrast, a properly designed optical fiber can do more than simply guide light from one point to another. Such features can be used to create different types of waveguiding phenomena as well as enabling capabilities for manipulation of light that go beyond conventional optical transport. This additional functionality offers great potential of fiber-based nanotechnology for applications in communications, computation, sensing, biology and chemistry for both waveguides and waveguide-based devices.

Nanotechnology can be exploited in multiple ways. In perhaps the most widely recognized form, nano-features provide an additional mechanism for confinement of light in so-called photonic crystal fiber. The concept of using air-glass structures to guide light was proposed in 1974 as a possible design for low-loss optical fiber. However, the field saw little activity until 1996. A major reason for this was because conventional fibers were so successful commercially that most research efforts were focused on exploiting more conventional fibers. Demonstrations of fibers with photonic crystal cladding, and later photonic band-gaps, in the late 1990s reinvigorated the field and attracted new research interest because air-glass microstructures offer a number of interesting physical effects that do not exist in conventional fibers. Micro- and later nano-structured optical fibers became an extremely active research area while miniaturization pushed toward micro/nanophotonic devices, such as tapers, resonators and interferometer for a wide range of telecommunications and specialty applications.

2 Hollow core fiber

One of the more promising avenues for nanotechnology in fibers has been use of photonic band gap effects to confine light in a hollow core fiber. Such designs provide a number of intriguing optical properties, including: ultralow optical nonlinearity, excellent power handling capabilities, low latency, and even the prospect of ultralow loss. These unique properties cannot be achieved in conventional solid optical fiber. Importantly, they point to a host of exciting application opportunities in telecommunications and high optical power delivery, as well as in new areas such gas based linear/nonlinear optics and particle guidance.

The initial dream that hollow core fibers might reduce optical attenuation by several orders of magnitude spurred a flurry of research. However, the promise has yet to be realized. Despite continued improvement in several areas, critical limitations have caused progress in optical loss to stagnate. Moreover, it appears that the lower latency offered by transmission through air only becomes significant for fiber lengths approaching 1 km. Because of limited power budgets, this requires improvement in optical attenuation from current levels. As a result, emphasis in communications has shifted to the long-term potential for hollow core fibers to provide breakthrough increases in communications bandwidth due to the lower effective nonlinearity. Key advances are required in understanding optical scattering at air-glass interfaces to reduce loss, while further study is needed to understand the basic mechanisms of light confinement in these complex structures. Furthermore, although several groups have suggested that hollow core fiber may offer a breakthrough in chemical sensing technology or other applications that take advantage of the extremely long path length, such applications have been slow to materialize and current research efforts are not widespread. Perhaps this suggests the lack of a high-value application to drive further study. While the optical physics and fiber fabrication technology is fascinating, it is important to find compelling applications for which hollow core technology is the best solution. In turn, this will spur further fiber advances. At this time, it appears that the primary benefit of hollow core fiber is the great reduction in optical nonlinearity, suggesting that such fiber could become important in applications that require high optical intensity and/or long path length.

3 Photonic crystal fiber

In a different design space, adding holes to the cladding of solid-core fibers allows modification of modal properties and offers great flexibility in fiber design. This has been exploited in many directions, such as: (a) to decrease the mode-field size to enhance nonlinear effects, such as for supercontinuum generation, (b) to increase the mode-field size to avoid nonlinear effects for applications such as high power fiber lasers, and (c) to reduce the bend loss of fibers for telecommunications applications, such as in-home wiring. Fibers with air holes have also opened up new possibilities by selectively filling holes with materials such as dyes, liquid crystals or functional polymers. In such cases, the collective composite behavior of the fiber enables an optical mode to experience an equivalent novel material with all-embracing properties. From this, novel material performance and devices are envisaged. Moving even further into the nano domain, when cladding features are on the order of several hundred nanometers, strong wavelength dependence of average index or dispersion occurs. This strong dispersion effect leads to designs of "endlessly" singlemode fibers and enables fibers with extremely low bend loss.

However, initial widespread interest and creativity has recently focused on a handful of activities surrounding specific applications. While photonic crystal fibers have been commercialized for fiber laser and supercontinuum generation, and so-called "hole-assisted" fibers are penetrating the communications market, the vast design opportunities afforded by microstructuring of the cladding of optical fibers does not yet seem likely to achieve commercial significance. Simply creating a clever fiber or device is insufficient and the field needs a compelling application that is optimally addressed using microstructure fiber.

4 Micro-scale and nano-scale photonic devices

Beyond altering waveguide propagation, nanotechnology has also created a platform for the manipulation of light in devices and novel structures. Perhaps the simplest example is miniaturization of optical fibers, i.e., optical micro- and nanowires. Optical fibers with diameters close to the optical wavelength were proposed in the mid-1980s. However, they attracted little attention until around 2003 when low-loss microfibers and nanofibers with diameters far below the optical wavelength were demonstrated. Such nanowires were fabricated by adiabatically tapering a fiber and preserving the original fiber dimensions at the input and output, thereby allowing ready splicing to standard fibers and fiber components. Tapers allow facile coupling and nanowire manipulation without the expensive instrumentation typical of the nano world. These miniaturized optical fibers have sub-micron or nanometer dimensions with tight optical confinement and can be configured into an array of miniature optical components such as evanescent field couplers, resonators, interferometers and filters. These devices offer potential as sensors, switches, delay lines or miniature optical sources, with the opportunity to use the small scale for high spatial density integration.

While interesting and potentially useful devices can be demonstrated with nanostructures, key challenges remain in both robust packaging and integration. A key benefit of nanostructures appears to be the potential for integration into a fabric of devices, such as delay lines and switches for optical computing, but relatively little effort has been devoted to engineering such packaging. Although work has focused on the fascinating physics, it will likely be the applications that will drive further innovation required to reduce the cost of fabricating robust devices or to increase the level of integration necessary for producing arrays of devices.

5 Spatial multiplexing and higher order mode fiber

A final nanotechnology application we consider in fiber-based optics is the use of nano-features to excite specific modal properties of novel waveguides. An early example of this is the use of higher order modes to exhibit dispersion properties unattainable using conventional singlemode approaches. Excitation of higher modes is commonly accomplished using resonant coupling in a waveguide, such as in Bragg or long-period gratings, but other mode-selection schemes (i.e., photonic lanterns and patterned waveguides) are used as well. While a vast body of literature on fiber gratings has been established over the several decades since their invention, a radical new trend combines mode selection devices with novel fiber design. In particular, more conventional singlemode and multimode fiber design gives way to few-mode fibers in which the properties of individual modes can be exploited. This offers potential for new optical properties, such as excitation of modes with optical angular momentum. Here, the key attribute to be exploited is the possibility of optical behavior that cannot be achieved in conventional fibers. This field is relatively new and a wide array of opportunities are yet to be explored. Hopefully, this trend will not follow the same path as other novel specialty fibers and devices, i.e., strong initial excitement centered around the novel opportunities in optical physics was followed by a lack of commercial penetration and the resulting stagnation of the technology. The challenge is to consider the drivers and constraints of real-world technology in addition to the exciting physics.

We have a final thought. Nanophotonic technology is evolving rapidly and holds great promise as photonics penetrates more and more applications and industries. To maintain a robust research environment, one historical pitfall to avoid is the creation of solutions for which there are no transcending problems. For example, photonic crystal fiber offers a wonderful improvement in nonlinear fiber devices, but there are relatively few applications for nonlinear devices. Similarly, there are few applications that require the low latency of hollow core fiber, and few applications as yet which exploit the high peak power offered by air-clad fiber lasers. In many cases, it appears as though the technology has outpaced the need and perhaps the field has been too successful. Advanced optical sensors based on nanofibers may become far more significant once optical sensors in general become mainstream, though optical sensor technology is quite immature at present. Meanwhile, the many studies which forecast an impending bandwidth exhaust in the communications infrastructure have driven the rapid progress in spatial multiplexing using few-mode or multicore fiber, but it will likely be a number years before such advances will be widely deployed. The vast potential inherent in fiber optic nanophotonics will only be realized when applications are developed to drive the demand.

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