JPhys Photonics

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To cite this article: John Ballato and Ursula J Gibson 2021 *J. Phys. Photonics* **3** 041001

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IOP Publishing J. Phys. Photonics **3** (2021) 041001 https://doi.org/10.1088/2515-7647/ac159b

Journal of Physics: Photonics

CrossMark

OPEN ACCESS

RECEIVED
14 June 2021

REVISED
2 July 2021

ACCEPTED FOR PUBLICATION
18 July 2021

PUBLISHED
3 August 2021

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PERSPECTIVE

Core opportunities for future optical fibers

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Keywords: optical fiber, semiconductors, optical materials, microstructures

Abstract

Hair-thin strands of glass, intrinsically transparent and strong, of which many millions of kilometers are made annually, connect the world in ways unimaginable 50 years ago. What could another 50 years bring? That question is the theme of this Perspective. The first optical fibers were passive low-loss conduits for light, empowered by sophisticated sources and signal processing; a second advance was the addition of dopants utilizing atomic energy levels to promote amplification, and a third major initiative was physical structuring of the core-clad combinations, using the baseline silica material. Recent results suggest that the next major expansions in fiber performance and devices are likely to utilize different materials in the core, inhomogeneous structures on different length scales, or some combination of these. In particular, fibers with crystalline cores offer an extended transparency range with strong optical nonlinearities and open the door to hybrid opto-electronic devices. Opportunities for future optical fiber that derive from micro- and macro-structuring of the core phase offer some unique possibilities in 'scattering by design'.

1. Introduction

The performance of an optical fiber relies on a delicate interplay between the light, the material from which the fiber is made, and the waveguiding structure. This triumvirate can be seamlessly integrated as exemplified by modern global data communication networks where peta-bit per second capacities will soon become commonplace [1]. However, applications utilizing linear transmission of near-infrared light are only a small part of what is being explored, let alone what is possible, and novel modifications are likely to translate to commercial products in the coming decades.

To anticipate future developments, it is instructive to review the underlying building blocks that define an optical fiber. Light has four characteristic properties: wavelength (or energy or frequency), intensity, polarization, and phase. Contemplating opportunities beyond transmission, devices function by manipulating some number of these properties. An optical amplifier [2], for example, affects primarily intensity. Faraday isolators [3] (magneto-optically) alter polarization to suppress back-reflected intensity. Nonlinear optics [4] involve altering both wavelength and phase, and the range of phenomena falling into this category is continually expanding. A key consideration in the use of fibers for many of these effects has been the ability to maintain high intensities over a significant distance, in contrast to free space optics, where the Rayleigh range limits the intensity-distance product. Fibers have allowed exploitation of weak interactions through propagation over long distances.

Materials are central to development of novel fibers because all optical processes, linear or nonlinear, weak or strong, are predicated on light-matter interactions. The refractive index, band structure and symmetry (in crystalline cores), the presence of dopants and other sub-wavelength inclusions all influence the behavior of a fiber. Glass compositions can be tailored directly to influence properties yielding, for example, intrinsically low, even zero nonlinearity [5]. Furthermore, such amorphous materials (usually) can be softened and drawn into long lengths, a physical characteristic without which global communications

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would look vastly different. Crystalline materials, while more limited in compositional control and formability compared to glasses, compensate with properties such as very high doping levels and, depending on structure, enhanced nonlinearities and electro-optic functionalities. In contrast to glasses, photon interactions in crystals are typically over small bandwidths, and resonances can either be exploited or avoided. As will be discussed in more detail below, combining these two categories of materials—a crystalline core inside a glass cladding—is a relatively recent addition to the optical fiber menu, and one that shows significant promise. Fibers of this type have been used as both passive waveguides over an unprecedented wavelength range [6, 7], as nonlinear devices that allow extreme broadening of the spectrum [8], and as active devices, including solar conversion [9] and thermoelectric performance [10].

In addition, the optical design of the fiber brings its own unique possibilities. By facilitating selected modes, or modal properties, in the waveguide the properties of the transmitted light can be further tailored and controlled. An example of this was the implementation of dispersion-shifted and dispersion-compensated fibers [11–13]. Considerable efforts were undertaken for the better part of the 1990s on optical amplifiers operating at 1.3 μm, since this wavelength corresponded to the zero-dispersion wavelength for the silica comprising the fibers [14, 15]. However, 1.3 μm amplifiers were determined to be insufficiently practical, and the community moved to fibers based on refractive index profiles that altered the dispersion behavior, minimizing chromatic dispersion effects at 1.55 μm where erbium doped fibers amplifiers were mature. In this case, fiber design provided a solution where fiber materials could not. Fibers that exhibit radial microstructure with spatial extent on order of the wavelength of light have opened entirely new doors to optical science and products and, in some cases, are now commercially available [16, 17]. Indeed, the development and maturation of photonic bandgap and hollow core fiber structures is instructive in how novel design and processing techniques permit new opportunities as their performance approaches and, in some cases exceeds, that of conventional (solid core) silica fibers [18, 19].

2. The present

The introductory section discussed each 'component' of optical fiber-based systems individually. As demands for 'more'—more power, more bandwidth, more spatial and spectral extent and agility, etc—have intensified, the fundamental features of the fiber lightguide are being utilized in symbiotic manners.

Some of the most exciting innovations associated with light and its utility focus on scaling to higher optical intensities, accessing broader spectral ranges, and exploiting optical singularities such as vortex states. The interest in these is both fundamental and practical. In the case of high-intensity continuous wave operations, power-scaling to hundreds of kilowatt power levels has direct consequences for directed energy, machining and manufacturing applications [20–22]. In the pulsed regime, including remarkable recent results employing either attosecond pulses [23, 24], or reaching intensities more than 10^{23} W cm^{-2}, permits the exploration of atomic and molecular processes, including strong field quantum electrodynamics [25, 26], as well as frequency conversion to extreme spectral regions [27].

Progress in ultrafast and ultra-high intensity lasers is not the only route to expand opportunities in quantum and nonlinear phenomena. Another topic worthy of note is recent achievements relating to vortex and orbital angular momentum beams [28–35], as well as photon pair generation and entanglement [36–38], which will unquestionably open new doors for the novel use of optical fiber systems. As utilization of quantum light increases, the ability to manipulate modes, and thus alter the entanglement properties is an area of interest, again offering a larger basis set for information encoding [39].

The trends here are clear: utilizing the spatio-temporal qualities of light in greater dimensions, modalities, spectral ranges and bandwidths, and intensities. Phenomena that were once considered parasitic are now purposeful, with nonlinear fiber optics being just one example [40]. Generation of broader spectral ranges and frequency combs using these nonlinear effects are being actively pursued for sensing and other applications.

However, the extent to which one can bring new signal encoding to bear on fiber-based technologies depends very much on advances in the enabling materials.

2.1. New materials, old materials, and no materials

There have been equally fascinating trends in materials that have enabled the increased capabilities of optical fiber. The stunning near-perfection of silica for long-haul communication networks [1, 41], followed by the specialty development of non-oxide glasses such as fluorides and chalcogenides [42, 43] are illustrative. The latter two systems enjoyed initial interest as potential lower loss alternatives to silica. While those promises have not been realized, such fibers now find commercial use in specialty infrared lightguides and fiber lasers [44].

A second trend in fiber materials has to do with the scale of their homogeneity with respect to the wavelength of light. For applications, such as sub-sea cables, where minimizing loss is paramount, homogeneity of the material is critical to reduce scattering. But for specialty applications, where loss is not necessarily as critical, there have been a variety of trends towards materials structuring on scales and dimensionalities not previously possible or thought to be desirous. And, as with light and optics, what was once problematic is now promising. Two exemplars here are glass-ceramic and transverse Anderson localizing optical fibers (TALOFs). Glass-ceramic fibers, in which a secondary, often crystalline, phase is nucleated out of the glass phase, were originally considered for novel fiber amplifiers [45] but have subsequently sparked interest for novel fiber sensor based on the enhanced backscattering [46, 47]. Whereas the secondary phase in the glass-ceramic fibers is randomly arranged within the fiber, in the case of the TALOFs, the secondary phase is random in a cross-sectional view, but longitudinally invariant. Such fibers, in which light guidance occurs via transverse Anderson localization [48], rather than by conventional total internal reflection, permits novel random lasing [49], nonlinearities [50], and image transport and recognition [51, 52].

Lastly, a third trend has to do with the combinations of materials that can be brought together into, and onto [53], optical fibers today. Of note is the molten core method, which has enabled the fabrication of fibers from otherwise thermodynamically incompatible core and core compositions, both from glasses and crystals [54]. Whereas the history of optical fiber materials have almost singularly revolved around glasses, dominantly silica, the composite fibers have both opened the door to the periodic table and further verified fibers as a miniature laboratory to study materials science and the interplay between kinetics and thermodynamics. This has highlighted the increasing importance and utility of phase diagrams in the development of novel optoelectronic fibers [55] and fabrics [56, 57]. Further, following onto the previous discussion of structure, multi-material fibers also now permit novel in-fiber microstructuring, such as optoelectronic junctions [9, 58] and compositional/alloy gratings [59], which are not possible with conventional glass fiber cores. Interestingly, as discussed below, a related trend in optical fiber 'materials' is the move to no material, i.e. hollow core fibers, which have benefits for low latency communications [60], lower-than-silica scattering losses in the visible [18], and as a structure for gas-filled fiber lasers and sensors [61, 62]. It is worth noting that long fibers are not the only potential applications of the molten core technology—the fiber geometry allows unique processing, and for some applications the device length may be short—either for a spliced in-line structure, or an array of parallel elements manufactured from an assembly of fibers [63].

2.2. 'Have no fear of perfection—you will never reach it'

With apologies to Salvador Dali for borrowing his quote, the design of optical fibers has, like light and fiber materials, taken an equally fascinating arc over the past 60 years. From the earliest days of graded index and step-index single and multimode fibers, the concept of perfection implied achieving the lowest loss, highest manufacturing speed and yield, and longest lengths with consistent dimensions. While the silica quality and chemical vapor deposition method for the fiber preform play critical roles in the performance of the fiber, so too does the fiber design, i.e. refractive index profile, and its influence on the properties of the guided modes.

Demands for higher performance and a wide variety of fundamental inquiries have led to a revolution in fiber designs, ranging from designs for dispersion management [64], bend insensitivity [65], photonic bandgap guidance [66], and transverse Anderson localization [67], to name just a few. Two observations are worthy of note in regard to the evolution in fiber design types.

First, fiber design considerations are intimately linked to the materials from which the fibers are made since the material's optical properties, thermodynamic or kinetic instabilities, and process compatibility all factor into what geometries can and cannot be made, at least in a scalable manner. However, with few exceptions, most fibers are silica based, unsurprisingly leveraging expertise and scale associated with telecommunication fibers. Departures from this material are less common, and wider applications of materials science often are ignored in the previously discussed triumvirate.

Second, the fiber design arc seems to have curved from the simple, e.g. solid core and clad, to complex, e.g. Kagomé hollow core fibers [68], and now back towards the simpler, e.g. structurally humbler but electromagnetically elegant anti-resonant fibers [69]. Indeed, in their simplicity lies their sophistication. However, this observed trend relates to radial or azimuthal symmetries, since many are longitudinally invariant. A complementary trend has been the evolution from the radially periodic but longitudinally constant photonic crystal fibers (PCFs) and microstructured optical fibers (MOFs), to radially and axially aperiodic or random but longitudinally constant fibers [51, 70] and thence to other symmetries, such as chiral fibers [71].

Figure 1 provides a generalized and by-no-means thorough, representation over time of how innovations associated with light, fibers, and materials have become coupled and, now, are essentially all working in unison.

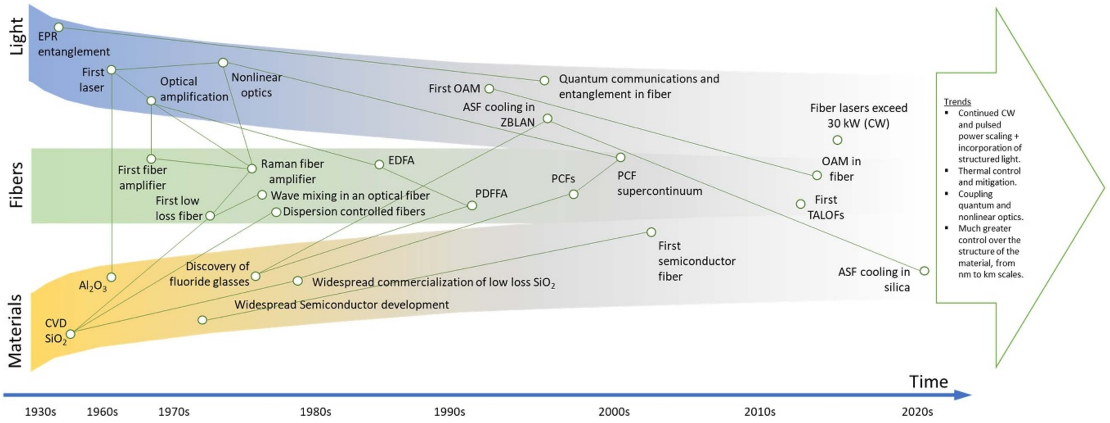

Figure 1. Representation of selected important innovations at the intersections of light, fibers, and materials that have and will continue to leverage each other for the development of future technologies.

3. Future possibilities

While it typically is not wise to predict the path of technology, the advances in modeling, processing and design of fibers are opening new doors. Practical applications are harder to anticipate but are likely to build from initial fundamental studies.

Telecomm fiber was a targeted goal, but even 50 years after the first low loss (<20 dB km^{-1}) optical fibers were realized [72, 73], the community is truly only scratching the surface of what seems possible at the interface of light, materials, and fiber design.

While unanticipated advances are likely to play a role in the more distant future, examining the combination of recent developments is a reasonable approach to seeing what may happen in the next 5–10 years. Advances in the following areas all seem possible.

- Synergies may be realized for vortex beams in multi-material and composite optical fibers where optical properties of the fiber can be controlled radially and axially. Advances in materials structuring of the cores may lead to fibers that directly generate or tailor vortex beams. Indeed, work is already underway unifying conventional fiber amplifiers with high power vortex beams [74] and, so, bringing new and more advanced materials to bear on these systems is a nature extension for future development.
- Given progress with low loss couplers between conventional silica fibers and silicon core fibers [75], opportunities exist for building optoelectronic circuits and control systems onto, e.g. side-polished optoelectronic fibers. In other words, novel *on-fiber optoelectronics* might result from the marriage of highly scalable semiconductor fab and fiber draw. Improved fiber coupling to planar silicon photonics is also likely.
- As a complement to on-fiber optoelectronics, *in-fiber optoelectronics* based on semiconductor core optical fibers is in the early stages, with advanced nonlinear and THz fiber photonics demonstrations [7, 76]. The reduction in transmission losses at longer wavelengths, due to the glass cladding, may possibly be achieved by developing (a) infrared (IR) glass claddings [77], (b) reducing the volume of silica proximate to the core [78, 79], or (c) creating a semiconductor core/clad structure within the glass capillary using radial laser annealing. Kudinova *et al* [80] provides a proof of concept where, for a SiGe core fiber, a lower index Si-rich inner cladding is created around a higher index Ge-rich central core.
- How high and low can one go? Now that a fuller cross-section of the periodic table is available as core phases or dopants in practical optical fibers (see, for example, table V in [81]), to what extent do these novel compositions permit nonlinearities that are orders of magnitude higher or lower than previously thought possible? Ultra-high nonlinearities can permit very low power (in-fiber) optoelectronics. Ultra-low nonlinearities, particularly as relates to stimulated Brillouin, Raman, and thermal Rayleigh scattering, presently limit power-scaling in high power laser systems. Novel, intrinsically low nonlinearity fiber materials offer a direct route to mitigate these limits while affording simple fiber designs and manufacturing [5, 81, 82].
- What about zero? While the preceding opportunity notes intrinsically low nonlinearity, a truly revolutionary opportunity is that of zero nonlinearity. This is achievable without exotic systems, such as metamaterials, by pairing conventional materials that exhibit positive- and negative-valued material properties that drive a given nonlinearity. For example, simple binary glasses can be designed that balance positive (transverse) photoelasticity, e.g. SiO_2, with negative (transverse) photoelasticity, e.g. BaO, to yield a zero (transverse) photoelastic glass fiber that would exhibit zero Brillouin scattering. By materially mitigating nonlinearities

at their spontaneous origin, nonlinear scattering effects would never have a chance to become stimulated and become parasitic [5, 81, 82].
- Can the diverse properties of light, the periodic table, and novel designs conspire to provide a slope-change in Keck's Law? [83].
- Fiber drawing may emerge as a materials processing method, useful, for example, as a step in the production of multicore detectors. Connections could be made to individual pixels using the glass, with the cores as detectors. As an example, GaSb has defied use in plateau geometries due to surface migration of the components. Glass segregation of the active elements would avoid this.

Without doubt, the future of optical fiber has been, is now, and will continue to be full of light [84].

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The Authors with to acknowledge thoughtful and insightful conversations from Professor Anna Peacock (University of Southampton), Dr Robert Rice (Northrop Grumman Corporation), and Professor Siddharth Ramachandran (Boston University). The authors also acknowledge with gratitude financial support from the J E Sirrine Foundation (J B), the Swedish Research Council (Grant 2016–04488) (U J G) and the Knut and Alice Wallenberg Foundation (Grant 2016.0104).

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