Towards the Perfect Optical Fiber

John Ballato[1,*] and Peter Dragic[2]

[1] *The Center for Optical Materials Science and Engineering Technologies (COMSET) and the Department of Materials Science and Engineering, Clemson University, Clemson, SC 29634 USA*
[2] *Department of Electrical and Computer Engineering University of Illinois at Urbana-Champaign, Urbana, IL 61801*

Optical fibers are being used in an ever more diverse array of applications today. Many of these modern applications are in high-power and, particularly, high power-per-unit-bandwidth systems where optical nonlinearities historically have not limited overall performance. Today, however, nominally weak effects, such as stimulated Brillouin scattering (SBS), are restricting continued scaling to higher optical powers. To address these limitations, the optical fiber industry has focused on fiber geometry-related solutions such as large mode area (LMA) designs. However, since all linear and nonlinear optical phenomena are fundamentally materials-based in origin, this paper identifies material solutions to present and future performance limitations in high power optical fiber-based systems.

Introduction

Light today, in all its high- and low-tech uses, enables a global economic impact of about $7.5 trillion (USD) annually [1]. The three largest, and growing, market sectors associated with light-based products are telecommunications, transportation, and biotechnologies [2]. Smaller by market size and value but critical technologies nonetheless are defense, security, and sensor systems, which drive technology development at "specialty" (high value and performance, low volume) levels.

Despite the importance of light to the many modern conveniences there has been decades-long erosion in the appreciation given to the materials as enablers of such technologies [3]. Prototypic systems that are being suggested as future solutions to present limitations are being driven by 'structural' (geometric) considerations as opposed to material ones. Perhaps the best examples of such design-based solutions are photonic crystal fibers (PCFs) where transversely periodic arrays of air holes run longitudinally down an optical fiber. PCF designs range from the fairly straight-forward to the highly intricate. Although PCFs can force light to behave quite differently from its conventional waveguiding nature, many phenomena, such as reduced nonlinearities, can be accomplished more simply through materials.

Accordingly, this paper seeks to further the recommendations of two works [3,4,5] by reviewing materials-related solutions to high energy optical fiber laser-based systems. Given that the lowest threshold nonlinearity that presently limits performance is stimulated Brillouin scattering (SBS), this phenomena will be used as the primary example. However, also to be discussed are higher order mode instabilities (HOMI). It is our hope, along with Refs. [3,4,5], that this work will help to reinvigorate the global materials community to rejoin the development of next generation optical fibers.

Results and Discussion

The intensity of light in many continuous wave (CW) and pulsed laser systems today is sufficient to induce optical nonlinearities. This results in a number of nonlinear and parametric photonic processes that are either practically employed or considered as parasitics to performance [6]. Such processes include Raman scattering (or stimulated Raman scattering, SRS), Brillouin scattering (or stimulated Brillouin scattering, SBS), Self-Phase Modulation (SPM), and Four-Wave Mixing (FWM).

Since these effects are light intensity-dependent, one conventional approach to their mitigation (or control) is to spatially spread the optical power out over a larger cross-sectional area thereby reducing the effective optical power-per-unit area. This approach has led to "large mode area" (LMA) fibers where the dimension of the central fiber core is expanded relative to more traditional designs. However, large core sizes tend to render such fibers electromagnetically 'few-moded.'

Several methods to overcome this obstacle have been proposed and implemented such as restricting the launch conditions of the light to only excite the fundamental optical mode (FOM) [7]. Unfortunately, coupling between allowed propagation modes is generated through fiber bends, packaging, and environmental conditions, all of which leads to the degradation in the beam's mode quality (or M^2). An early approach to overcoming the inevitable multimode nature of LMA fibers was the discovery that through careful bending of the fiber, higher order modes (HOMs) could be scattered from the core [8] leaving what is effectively single mode operation. It also is possible to design a microstructured fiber for 'endlessly single mode operation' [9], but their bend intolerance has largely confined these fibers to the rod-like (very large fibers that are, for all intents and purposes, rods) regime. In the restricted mode launch regime, it was found subsequently that excitation of a HOM in a few-moded fiber offered increased mode robustness and the benefit that the HOMs have larger mode areas than the FOM [10].

Other "effectively" single mode LMA fibers have also been developed with the general goal being to provide some form of differential loss to the HOMs relative to the FOM. Several recent fiber designs include the chirally-coupled core fiber [11], photonic bandgap Bragg fiber [12], solid photonic bandgap fibers [13], leakage channel fibers [14], and selectively-doped triple clad fibers [15]. While there is clearly no shortage of methods to improve beam quality from LMA fibers, such designs are quite complex in their geometries and while effectively single mode operation does result, there is a power threshold above which

single mode operation is unstable [16,17]. This 'higher order mode instability' (HOMI) results in a time varying output beam profile that negates many of the benefits of LMA fibers.

The authors (JB and PD) have been advocating for a different approach to mitigating and, in some cases, completely removing these parasitic effects from consideration based on the thoughtful choice of materials rather than on fiber design [3]. While several examples are provided below, it is necessary first to describe the interaction of light with the fiber material and how such nonlinear and/or parasitic phenomena arise. Only then can the materials-related solutions be more fully appreciated.

Materials Physics of Optical Phenomena

Nonlinear optical phenomena in optical fibers can be either useful or deleterious depending upon the application. For high power applications these processes typically are parasitic and create limitations to power scaling. Since nonlinearities are intensity-dependent, as noted, a larger mode diameter usually implies a higher threshold for these interactions. To some extent, nonlinear effects can be controlled with waveguide design. However often overlooked is the fact that these processes are defined mathematically as a combination of material properties. Accordingly, with careful materials selection, it is possible to tailor or design the composition to reduce the nonlinearities to acceptable levels for a given application.

The nonlinear process often considered first is stimulated Brillouin scattering (SBS), which is an interaction between hypersonic acoustic waves and the optical signal in a fiber. Brillouin scattering originates as a spontaneous process (spontaneous Brillouin scattering, SpBS) with optical back-scattering efficiently taking place based on acoustic waves that are Bragg-matched to the optical wave. The acoustic wave is a periodic longitudinal pressure, and therefore density (hence refractive index), variation. This spatially modulated density then corresponds to a spatially modulated refractive index which, via electrostriction, causes interference between the forward-propagating signal and back-scattered light which feeds the acoustic (pressure) wave. This 'positive feedback' process increases in efficiency with optical power after a 'threshold' is reached after which Brillouin scattering is in a stimulated state.

The Brillouin gain coefficient is given to be

$$g_B = 2\pi n^7 p_{12}^2 / c\lambda^2 \rho V_a \Delta\nu_B$$

([18], in units of m/W), where λ is the optical wavelength, n is the refractive index, p_{12} is a Pockels photoelastic constant, c is the speed of light, ρ is the mass density, V_a is the acoustic velocity, and $\Delta\nu_B$ is the Brillouin spectral width. Given the dependencies of these contributors to Brillouin gain on material parameters, beneficial materials from the perspective of reduced SBS are 1) a large acoustic velocity, 2) relatively low index, 3) relatively large mass density, 4) large Brillouin spectral width and 5) low p_{12}. These trends provide a clear guideline to materials selection for reduced Brillouin gain. In order to model the materials system, an additive approach based on the work of Schott and Winkelmann [19,20,21] can be utilized to calculate each of these terms for a multicomponent glass. For complete details, the reader is referred to Reference [22]. One especially important point is in regards to p_{12}, which can be either positive or negative and, therefore, a suitable combination of materials can yield a p_{12} that is very close to zero. As a result, there exists a possibility of a fiber with zero Brillouin gain.

Such negation of certain material coefficients in order to suppress or eliminate a given nonlinearity can also be applied to HOMI. The HOMI process is believed to be driven by the material's thermo-optic coefficient, dn/dT [16,17]. Accordingly, reduced HOMI LMA fibers would be ones made from materials with reduced thermo-optic coefficients.

Other nonlinearities, such as Self-Phase Modulation (SPM) and Four-Wave Mixing (FWM) result from the optical intensity dependence on refractive index [18]. SPM can be observed in pulsed operations and results from an intensity-induced time-varying refractive index. The effect of these processes is to broaden the optical spectrum, which may be undesirable in high peak power and multi-wavelength systems. Since the dependence of the refractive index is given by $n(I) = n_0 + n_2 I$, where n_0 is the linear refractive index, I is the optical intensity, and n_2 is the nonlinear refractive index, suppression of these parametric phenomena will require a minimization of n_2. Accordingly, a materials solution to these parasitic phenomena rely on developing optical fiber materials with reduced (if possible, zero) photoelasticity (p_{12}), nonlinear refractive index, and thermo-optic coefficients.

Though one composition that exhibits all of these effects would be ideal, it generally is not necessary since each phenomena possess different threshold conditions and is often application-specific.

Materials Solutions

In specific regard to SBS suppression, the main consequence of the discussion above is whether or not a material solution, rather than a geometric one, exists. In terms of glass modifiers to silica, from which all practical fibers are made, one desires compounds that increase the refractive index, density, acoustic velocity, and Brillouin line-width while reducing the photoelastic coefficient. Divalent species, such as alkaline earths compounds (MgO, CaO, SrO, and BaO) and selected trivalent ones, (Al_2O_3, Y_2O_3, and the lanthanide oxides) impart the desired features into silica. However, in each case, there are limited compositional ranges over which these multi-component glasses are stable. A classic example of this is the Al_2O_3-SiO_2 system, which exhibits a well-known immiscibility [23]. Accordingly, the amount of Al_2O_3 that can be homogeneously mixed into SiO_2 is about 12 weight percent. Unfortunately, other binary systems also suffer from similar limitations though the exact immiscibility range differs for each. These include the following systems: Y_2O_3-SiO_2 [24], MgO-SiO_2 [25], CaO-SiO_2, SrO-SiO_2 and BaO-SiO_2 [26], and ternary systems Y_2O_3-Al_2O_3-SiO_2 [27] and MgO-Al_2O_3-SiO_2 [25].

The molten core method offers a powerful and straight-forward route to the fabrication of optical fibers from materials that otherwise would be very difficult to form into conventional glass preforms and draw into fiber. As an example, for high Al_2O_3-content fibers, pure sapphire has been used [28]. Similarly for high Y_2O_3-Al_2O_3, BaO- and MgO-Al_2O_3-content fibers, YAG ($Y_3Al_5O_{12}$), BaO and spinel ($MgAl_2O_4$) yielded very interesting

fibers that could not otherwise be realized [29-31] since such compounds typically phase-separate when mixed with silica.

Specifically towards reduced Brillouin scattering, one particularly important opportunity that is enabled by the molten core process is the ability to realize glasses that possess zero, or near-zero photoelasticity. As noted, Brillouin gain is dependent on the p_{12} photoelastic coefficient. While silica glass possesses a positive p_{12} value many of the materials noted above possess a negative p_{12} value. Given the proper compositions, a glass that can balance the positive and negative photoelastic contributions could be synthesized that yielded very low Brillouin scattering. The previously noted sapphire- (Al_2O_3) derived aluminosilicate fiber did just this: the alumina possessed a slightly negative p_{12} value (-0.03) which, when "mixed" homogeneously with silica (p_{12} = 0.271) from the (silica) cladding dissolution, resulted in a core that exhibited an SBS gain reduced by nearly 20 dB over conventional optical fiber compositions [28].

Optical Fibers with Reduced Higher Order Mode Instabilities (HOMI)

As noted above, a dynamic randomization of mode distribution is observed exists in active LMA fibers that is known as "higher order mode instability" (HOMI). HOMI is believed to result from a thermally-induced refractive index grating and since the process is believed to be driven by the thermo-optic coefficient (dn/dT) it is reasonable to consider reducing HOMI through choice of core material. Simply stated, if dn/dT = 0, then such modal instabilities should be improved, if not completely removed. Much like the aforementioned work on intrinsically-reduced-Brillouin-gain, combining materials with thermo-optic coefficients of opposite sign could potentially give rise to significant reductions in thermo-optic coefficients. SiO_2, GeO_2, and Al_2O_3 all exhibit positive dn/dT values while P_2O_5 and B_2O_3 has negative ones [32]. As an example, the thermo-optic coefficient for a borosilicate glass does possess a composition where dn/dT = 0.

Experimental Section

Specific optical fibers whose properties are described here have been reported on individually and the reader is referred to the following References: YAG-derived fibers [29], sapphire-derived fiber [28], spinel-derived fiber [31], baria-derived fiber [30], ytterbia-derived fiber [33], and lanthana-derived fiber [34].

Optical fibers are conventionally prepared using one of a series of chemical vapor deposition methods [35-37]. In such cases, the core and clad glass compositions exhibit reasonably similar thermal and thermomechanical properties such that they can be co-drawn into a fiber. This compatibility tends to imply that the core/clad compositions are not overly different. Based on the original molten core work [38], the approach has been further expanded to which the reader is referred to References [3] and [39], which provide a more detailed review of the method and material.

Conclusions

Provided here was a brief review of the next generation optical fibers that meet selected needs of present and future high energy laser systems through a materials, rather than intricate design approach. Though most of the focus here has been placed on all-glass optical fibers derived from crystalline precursors using the cost effective molten core approach, the more general message is that materials clearly offer solutions that plague the optical fiber industry.

Notes and References

**Corresponding author E-mail: jballat@clemson.edu*

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