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Editorial

The Materials Science of Optical Nonlinearities and their Impact on Future Optical Fiber Lasers

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Editorial

Optical fibers are hair-thin strands of ultra-pure glass that carry all voice and data communications around the world. The light on which information is encoded is confined to a central core whose diameter is on the order of 10 μm. At sufficiently high optical powers, the intensity of light (power/area) can exceed the intensity of the Sun's surface which leads to a variety of light-matter interactions. These optical nonlinearities are often undesirable and parasitic to system performance.

Of particular practical consequence in modern optical fiber-based lasers are stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), nonlinear refractive index (n_2)-related wave-mixing phenomena, and transverse mode instability (TMI).

Brillouin scattering is a coupling between the glass' acoustic phonons and the light. Above a threshold power level, the spontaneous effect becomes stimulated. In its stimulated form, this scattering acts as a highly efficient (back) reflector to the light that can severely damage the optical system and limits the power per unit bandwidth that can be coupled into, or produced from, an optical fiber.

Raman scattering is also an acousto-optic interaction but involving the creation (Stokes') or annihilation (anti-Stokes') of the glass' optical phonons and the light. Such phenomena can be problematic when wavelength control is mandatory.

The nonlinear component of the refractive index (n_2) drives wave-mixing phenomena above a critical threshold power. In such cases, the refractive index is spatially and temporally modulated and results in spectral broadening of the optical signal.

Transverse mode instability, which arises from stimulated thermal Rayleigh scattering (STRS), is a thermally driven mode-hopping associated with dynamic spatial heat fluctuations in a fiber. An index grating is formed that phase-matches incident and scattered light modes in an optical fiber that is lasing or amplifying above a given threshold power.

In order to reduce the impact of these nonlinearities, the global optical fiber and fiber laser community has largely focused on redesigning fibers in such a way as to spread out the distribution of light over a larger cross-sectional area; so-called "Large Mode Area" (LMA) fibers. However, as optical power levels continue to rise, the requisite mode areas have increased to a point where fiber geometries are especially complex which makes them expensive and low-yield. More importantly, such geometric approaches do not actually address the fundamental origins of the nonlinearities.

As noted, optical nonlinearities fundamentally arise through the interaction of the light with the material through which it is propagating. Accordingly, tailoring of the glass composition and structure to influence its interaction with light is the most direct approach – a materials approach – to mitigating parasitic effects.

Materially, Brillouin scattering is proportional to $n^8p_{12}{}^2k_s$, where n is the refractive index, p_{12} is the transverse photoelastic (Pockels) coefficient, and K_S is the adiabatic compressibility, respectively, of the material through which the light propagates. The more powerful approach is to target the p_{12} photoelasticity since it is the only relevant property that can take on a value of zero, which would lead to the complete eradication of Brillouin scattering. This conceptually can be achieved through a composition that contains both a positive p_{12} material, such as SiO_2, and a negative p_{12} component, such as SrO, BaO, or Al_2O_3.

Raman scattering is materially proportional to the glass' molar volume and the square of the bond compressibility parameter. Raman scattering, in both spontaneous and stimulated forms, is reduced for glasses that possess a low molar volume and small bond compressibility parameter. Suppression of wave-mixing nonlinearities materially requires a reduction of n_2. In practice, because of the intrinsically low nonlinear index of silica, further reductions in n_2 typically rely on fluorine and phosphorus doping, which either lowers the polarizability (fluorine) or promotes greater covalency (phosphorus) there by reducing polarizability.

Materially, mode instabilities are driven by the quotient of TOC/($\rho \times C_p$), where TOC is the thermo-optic coefficient, ρ the density, and C_p the specific heat. Of these, the TOC offers the greater compositional tailorability and, like Brillouin scattering, has the potential to take on a zero value when materials with positive (e.g., SiO_2) and negative (e.g., BaF_2, SrF_2) values are employed.

In order to realize these intrinsically low nonlinearity glasses, advancements in optical fiber processing is required. This is because conventional vapor deposition methods are limited in both the range of constituents as well as their level of doping into the silica host. To access a larger compositional space, the molten core method was developed and has become the global approach of choice to novel fiber compositions. In this molten core method, a precursor phase is sleeved inside a glass capillary tube and drawn directly into fiber. The precursor phase is the source for the fiber's core composition and is selected such that it melts at the fiber draw temperature. As the fiber

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is drawn, the molten core is quenched rapidly as the fiber cools, which kinetically traps a glassy core state that is composed of the precursor components along with some silica from the cladding that dissolves in during the draw.

Summarized here were the basics of a materials approach to mitigating performance-limiting effects in modern optical fibers. Through judicious selection of glass composition, such optical nonlinearities cannot only be reduced but may even be wholly negated. This would not only obviate existing limitations but open up entirely new light-based defense, security, medical, and manufacturing opportunities. For greater details on the materials science of optical nonlinearities and this unified materials approach to their mitigation, the Reader is referred to [1-4].

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