Novel Technologies for High Precision Characterization of Fibers

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Abstract: Optical fiber gain profiling, spectrogram modal analysis, and interferometric refractive index and residual stress measurement are reviewed. These novel characterization technologies are important for designing, assembling and optimizing fiber-based lasers and amplifiers.
OCIS codes: (060.2280) Fiber design and fabrication; (120.3180) Interferometry; (060.2270) Fiber characterization

1. Introduction

Optical fibers have long been used for telecommunications, sensing, and medicine, and are now making inroads as high-power optical amplifiers and laser sources. The design, assembly, and performance of fiber-based systems have recently benefitted from the availability of highly precise, wavelength-agile refractive index [1-5], and residual stress measurement technology [6,7], spatial gain profiling [8,9], and spectrogram modal analysis [10,11]. These technologies are enabled by inexpensive computing power and have been inspired by medical diagnostics. The fiber index profiling, residual stress measurement, and gain profiling technologies are unusual in that they interrogate the fiber transversely through its side, rather than along its length, and therefore they can be used to map out variations that occur over very short (micron-scale) axial distances.

2. Refractive Index Measurement of Optical Fibers

Transverse interferometry is a powerful platform for measuring the refractive index profile of optical fibers since it requires no cleave and therefore can be used to map out a changing refractive index profile that varies along the fiber's length, for example at a fusion splice, grating, or physical taper. Measurements can be performed at wavelengths varying from the ultraviolet- to the infrared, encompassing the operating bands of most optical fibers. Refractive index measurement accuracy and precision can better than ±0.0001 with spatial resolution finer than 1 μm. When the fiber is not azimuthally symmetric, interferograms acquired at a multiplicity of rotational angles can be combined with innovative tomographic algorithms that now permit remarkable two-dimensional cross-sectional measurements of multicore and microstructured optical fibers [12-14]. Three-dimensional measurements of other types of complex structures, such as waveguides inscribed inside fibers by femtosecond lasers, have also been demonstrated [9].

3. Residual Stress Measurement

With the aid of the stress-optic relations, refractive index data acquired by transverse interferometry at distinct polarizations can be used to determine the residual axial elastic stress along the fiber axis. While the generalized stress state is a tensor quantity characterized by as many as six independent quantities at each location, all fiber stress measurement techniques can only directly measure the normal stress component in the axial direction. Therefore reconstruction of the full multi-component stress tensor requires numerical models based on direct axial stress measurements [15]. Nevertheless, the axial stress is itself useful for understanding thermal stress in highly doped fibers or polarization-maintaining (PM) fibers as well as mechanical stress induced by fiber draw conditions [6,7].

4. Gain profiling

Recent breakthroughs in the performance of high-power fiber lasers and amplifiers have led to new applications and rapid commercial growth. The spatial distribution of gain in fibers used in these systems can be precisely characterized by pumping them in a spatially homogeneous manner and transversely measuring the inhomogeneities of their spontaneous emission [6-9]. These measurements are particularly useful for detecting asymmetries in the gain efficiency (either due to dopant or host glass variations) or for establishing the spatial distribution of gain in a core/pedestal fiber design. While most high-power fibers are comprised of Yb-doped silica, other material systems and dopants are also amenable to such characterization providing appropriate pump wavelengths and detector arrays are employed.

5. Fiber Modal Content

Communications fibers were historically either rigorously single-moded or multimoded. Recently, optical fibers that operate between these extremes by guiding a few modes (typically 2-10) have been used for mode-division-multiplexing (MDM) or for high-power generation or transmission. Examples include core/pedestal fiber designs or enlarged fundamental mode area (large-mode area, LMA) design. Conversion of energy between guided modes, so-called *mode-coupling*, can happen at either discrete locations, such as a fusion splice, or over a distributed length of fiber, for example, due to coiling. Mode coupling frequently occurs from the fundamental to undesirable higher-order modes, thereby degrading beam quality and may contribute to important power constraints such as modal instability, so characterization and mitigation of mode coupling is critically important. Alternative techniques for characterizing beam quality, such as M^2, cannot identify or quantify relative mode power, and certainly cannot elucidate their origin. More recently developed approaches, such as S^2 [16] can identify modes, quantify their relative power, and elucidate their origin, but do not clearly distinguish between distributed mode coupling and discrete mode coupling in the presence of strong intermodal dispersion. Recently developed spectrogram technology [10,11] analyzes the signal emitted at the end of a fiber with staggered spectral windows that clearly distinguish between these types of mode coupling, thereby enabling more effective suppression of such mode coupling. Although spectrogram technology interrogates the fiber along its length, it can still provide meter scale resolution based on the time delay observed at the fiber output. Assessing the identity, strength, and origination of higher-order mode energy is useful for improving the design, assembly, and performance of fibers and components (i.e. mode converters, pump combiners) used in few-mode fiber systems.

6. References

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