Amplification of Structured Light in Optical Fibers

Kazi Abedin
LGS Labs, CACI International. 15 Vreeland Road, Florham Park, New Jersey 07932.
kazi.abedin@caci.com

Abstract: In this talk, the potential of optical fiber in amplifying structured light will be presented. To this end, several multimode fibers with index profile tailored to guide mode with different structures, such as super-Gaussian, Sinc, Bessel will be shown.

Cladding pumping technique, since its first demonstration of amplifying coherent radiation in the 1μm wavelength range using neodymium doped fiber [1], has found application in almost every high-power fiber amplifier. In this approach, pump radiation from multimode laser diodes is applied through the cladding of the gain fiber to create a uniform population inversion in the rare-earth doped core region that is embedded in the cladding. Initially demonstrated for amplification of signal guided in a single mode, this pumping scheme has been extended to configurations that contain multiple modes as well as plurality of waveguiding cores, aiming to enable such fields as space division multiplexed optical communications and industrial material processing [2-4].

The ability of cladding pumping to excite a wider doped region opens the possibility of amplifying structured light in optical fiber. Structured light refers to a broad class of beams that manifest abrupt changes in amplitude, phase and/or polarization within the beam envelope. Some examples include polarization vortex beam, orbital angular momentum beam, rectangular shaped beam, Bessel beam, Necklace beam [5-9]. Currently, intense research efforts across the globe have been underway towards a facile generation of various types of structured beams, employing either or both bulk and fiber optics. Such beams are tailored for use in a myriad of applications including fiber-optic or free-space communications, high-resolution microscopy, quantum entanglement, machining, to name a few.

To efficiently amplify the structured light in an optical fiber, there are two critical and necessary requirements. Firstly, the fiber must be able to support low-loss guidance of the desired beam. And, secondly, the fiber must allow the launching of the structured light with a proper phase and amplitude distribution to ensure a high overlap integral with the guided mode(s). Additionally, to amplify with a high signal to noise ratio at the fiber output, the signal intensity at the input of the amplifier needs to be high enough to be able to compete against the quantum noise arising from the large number of modes supported by large diameter core (=V-number^2/2). Recently, selective amplification of a higher order linearly polarized mode, $LP_{0,10}$ was successfully demonstrated in a cladding pumped ytterbium-doped fiber amplifier [10,11]. The $LP_{0,N}$ mode, which resembles a truncated Bessel-like beam, could also be converted back to a Gaussian-shaped beam using an axicon lens and diffractive optical element. The experimental results, agreeing well with the theoretical predictions, suggested that the amplifier preserved the amplitude and transverse phase distribution of the structured light during amplification in the gain fiber.

It is also highly intriguing to study and evaluate what other forms of structured light one could possibly amplify in optical fibers. Recently, fibers with more intricate index profiles were developed to guide the Airy beam [12]. Airy beam has unique characteristics of being non-diffracting, self-accelerating and self-healing in properties. This beam in the far-filed becomes flat-top circular beam. The novel fiber was designed using inverse waveguide solving technique from the electric field profile, and the fabricated fiber successfully supported airy beam up to 4rd lobe. This powerful method can be effectively used to realize other fibers that could generate, directly at the fiber output, beams which resemble flat-top, Sinc, or other shapes of electric field distribution, as shown in Fig. 1.

The structured mode output from fiber can be further tailored with the help of bulk optic components, such as birefringent plates, spiral phase plates, segmented phase plate and meta-surfaces, that are useful for modifying the polarization and phase (dynamic or geometric) of optical beams. This can enable the generation of high-power structured beams of unique intensity, polarization and phase distributions, covering the entire higher-order Poincaré sphere [4, 8] to address the needs of different applications. In this talk, we will discuss the prospects of cladding pumped fiber amplifier for guiding and amplifying structured light, and will highlight related technologies that will be crucial for the successful implementation of such amplifiers and their adoption at a wider scale.

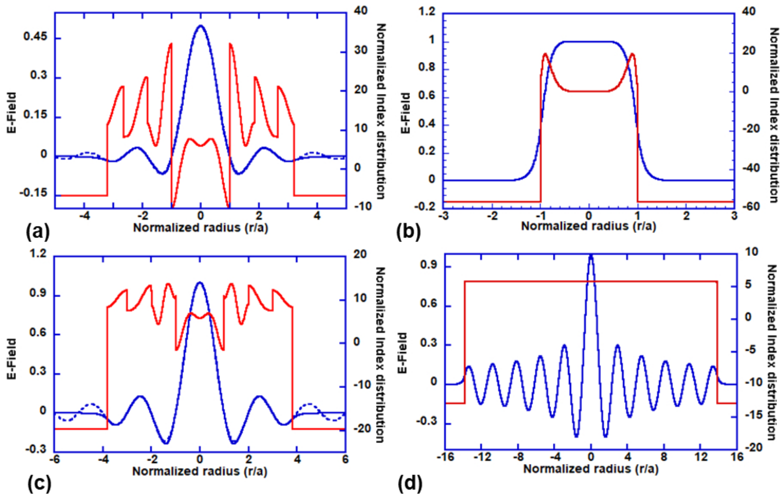

Figure 1. Fibers designed to support the optical field distribution of various structures. Blue lines (dashed: ideal, solid: truncated) show the field profile and red lines are the corresponding normalized refractive index distribution. a) Airy mode $\psi=J_1(C.r/a)/(C.r/a)$, with C=3.831, as reported in Ref [12], b) Super-Gaussian beam $\psi=\exp[-(r/a)^N]$, N=8, c) Sinc beam, $\psi=\sin(\pi r/a)/(\pi r/a)$, and d) Bessel beam $\psi=J_o(C.r/a)$ with C=2.4048 (first zero of the Bessel function J_o). Normalized index distribution is defined $\nu(r/a) = a^2k^2(n^2\text{-}n_{eff}^2)$.

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