Spatio-temporal Mode Characterization of Disordered Weakly Nonlinear Graded-index Multimode Fibers

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In the transmission of relatively low power telecom signals, the performance of space-division multiplexed (SDM) transmission systems employing multimode graded-index fiber (GIF) is mostly affected by linear random mode-coupling (RMC) [1, 2]. The study and characterization of power exchanges among the propagating modes, owing to fiber imperfections and bending [3, 4], is of utmost importance in SDM systems, because it involves an appropriate optimization of modal multiplexing and de-multiplexing techniques. Here we propose a 3D modal reconstruction method, using as input condition spatio-temporal bullets $E_p(x,y,0,t) = A_p(0,t)F_p(\mathrm{x,y})$, describing individual modes, while accounting for laser linewidth and pulse temporal shape. The input 3D bullets are propagated by using a coupled-mode GNLSE [5]. RMC is accounted by adding a random phase between modes at input, and weighting the output modal power by power fractions $|c_i|^2$ provided by the experiments; hence, the total output bullet field is given by $E_{tot} = \sum_{i=1}^{M} c_i E_i(x,y,z,t)$. By integrating $|E_{tot}|^2$ vs. time, the output near-field is obtained; whereas integration vs. *(x,y)* yields the instantaneous power profile.

Experiments were carried out to find out whether linear RMC and weak nonlinearity lead to a well-defined output mode distribution. In the experimental setup, 1.4 ps unchirped pulses at 1550 nm wavelength and 100 kHz repetition rate were launched with circular polarization on different spans of OM4 graded-index fiber. Input beam profile was not Gaussian, in order to stimulate higher order modes at the input.

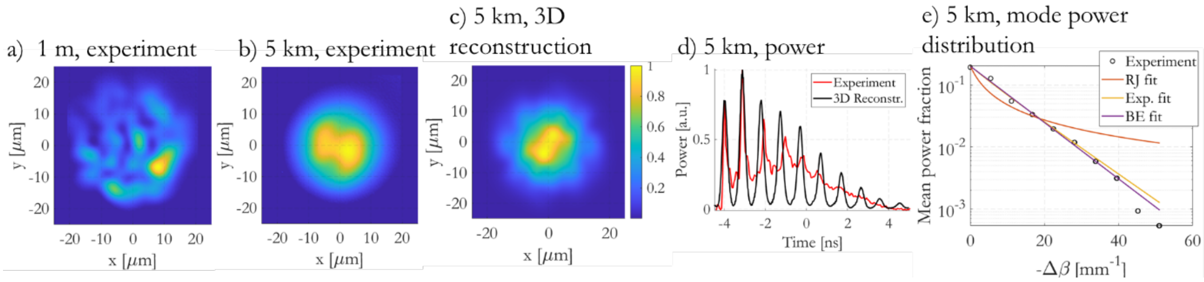

Fig. 1 Experimental near-field at a) 1 m and b) 5 km. c): 3D reconstruction of the near-field at 5 km. e) measured and reconstructed instantaneous power at 5 km. e): Experimental mean modal power with Bose-Einstein (BE), Rayleigh-Jeans (RJ) and exponential fits.

Figs.1a, b, c show the measured near-field after 1 m and 5 km of GIF, and the 3D reconstruction at 5 km, respectively. Fig. 1.d provides the measured and reconstructed power; fiber chromatic dispersion broadens the pulse to 285 ps after 5 km of propagation, whereas modal dispersion separates the mode groups up to 9 ns after 5 km. The total pulse energy in the fiber is 12 pJ, which produces a total nonlinear phase shift of 0.6 rad over an effective length of 140 m, so that the propagation regime can be considered as pseudo-linear [ref??]. The speckled pattern observed at 1 m evolves into a smoother beam after 5 km of fiber; this pattern corresponds to the mean modal power fraction of Fig. 1e, measured from Fig. 1d vs. the differential propagation constant of the modes. The mode power fraction is properly fitted by a Bose-Einstein distribution, which can be associated with reaching a thermalized state [6].

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