Nonlinear Multimode Fiber Optics

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Abstract: We overview recent advances in the nonlinear optics of multimode optical fibers, including ultrabroadband sideband and supercontinuum generation, Kerr and Raman beam cleanup, modal modulation instabilities, four wave mixing, and second harmonic beam cleaning.

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Since the observation of multimode optical solitons in a graded index (GRIN) multimode fiber (MMF) by Renninger and Wise in 2012 [1], there has been a resurgence of research activities involving optical pulse propagation and frequency conversion dynamics in MMFs. The peculiar property of these waveguides is the coupling among the temporal and spatial degrees of freedom of propagating beams, which can be controlled by properly adjusting the input conditions [2]. A spectacular manifestation of the spatiotemporal coupling process is the generation of ultrawideband sideband series resulting from the parametric resonance of oscillating multimode solitons [2,3] or continuous waves [4,5] in the anomalous or normal dispersion regime, respectively.

The Kerr effect leads to a self-cleaning of the transverse irregular intensity distribution resulting from the interference of multimode beams towards a well-defined and environmentally robust bell shaped beam [6,7]. The mode mixing leading to the spatial cleanup effect is associated with a complex temporal reshaping of the output multimode pulse profiles [8]. Although the Kerr beam cleaning is observed before a substantial self-phase modulation induced spectral broadening of the input pulses occurs, it can be preserved also in the presence of supercontinuum generation, whereby the multimode beam is carried by a bell-shaped spatial beam profile across its whole wavelength range [9,10]. Quite remarkably, Kerr beam cleaning is also obtained in a quasi-step index ytterbium doped MMF, both in the absence and in the presence of a pump laser. However the active configuration leads to substantially reduced input and path-average power thresholds [11]. Kerr beam cleaning has been exploited to obtain a spatial singlemode output and frequency conversion from a composite laser cavity including an ytterbium doped MMF [12], which may lead to the power scaling of mode-locked MMF lasers [13].

Another mechanism for achieving frequency conversion in MMF is modal four-wave mixing FWM [14]. Far detuned frequency translation has been demonstrated based on cascaded intermodal FWM in a few-mode GRIN MMF in a spontaneous [15] and seeded [16] configuration, respectively. Inter-modal modulation instability was exploited to achieve power-dependent frequency shifts from spontaneous sideband generation in a GRIN MMF [17]. Recent works have investigated the interplay of Kerr and Raman beam cleanup and supercontinuum generation in a specially conceived air-silica microstructure MMF [18]. Optical poling is known to induce a permanent second-order response in optical fibers: this effect has been exploited to demonstrate harmonic sideband generation and mutual cleaning of both fundamental and second-harmonic converted beams in GRIN MMFs [19,20].

In conclusion, nonlinear mode coupling in MMFs may be exploited for a novel generation of fiber optics devices that will enable the controllable generation and manipulation of high energy optical beams for a variety of applications, ranging from mode-locked and supercontinuum laser sources, stable beam delivery in the workplace for industrial cutting and welding, and biomedical imaging.

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