Hydrodynamic 2D turbulence and beam self-cleaning in multimode optical fibers

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Spatiotemporal light beam dynamics in multimode optical fibers (MMFs) has emerged in recent years as fertile research domain in nonlinear optics. Intriguing spatiotemporal wave propagation phenomena such as multimode optical solitons and parametric instabilities leading to ultra-wideband sideband series, although predicted quite a long time ago, have only been experimentally observed in MMFs in the last few years.

It is well known that linear wave propagation in MMFs is affected by random mode coupling, which leads to highly irregular speckled intensity patterns at the fiber output, even when the fiber is excited with a high quality, diffraction limited input beam. Recent experiments have surprisingly discovered that the intensity dependent contribution to the refractive index, or Kerr effect, has the capacity to counteract such random mode coupling in a graded index (GRIN) MMF, leading to the formation of a highly robust nonlinear beam. The self-cleaned beam at the fiber output has a size that is close to the fundamental mode of the MMF, and sits on a background of higher-order modes (HOMs). Typically, spatial self-cleaning is observed in several meters of GRIN MMF at threshold power levels of the order of few kWs, orders of magnitude lower than the value for catastrophic self-focusing. Moreover, self-cleaning is most easily observed in a quasi-continuous wave (CW) propagation regime (i.e., by using sub-nanosecond pulses), so that dispersive effects can be neglected. In such regime, nonlinear mode coupling is the sole mechanism responsible for the self-cleaning of the transverse spatial beam profile at the fiber output. So far, although different tentative explanations have been provided, the physical mechanism leading to Kerr beam cleaning remains an open issue.

Our theoretical study and experiments indicate that Kerr beam self-cleaning results from parametric mode mixing instabilities, that generate a number of nonlinearly interacting modes with randomized phases – optical wave turbulence, followed by a direct and inverse cascade towards high mode numbers and condensation into the fundamental mode, respectively. This optical self-organization effect is analogue to wave condensation that is well-known in hydrodynamic 2D turbulence.

We experimentally demonstrate that beam self-cleaning in multimode optical fibers is a process that conserves the average mode number, in spite of the dramatic nonlinear change and self-organization into the fundamental mode of the output intensity pattern. The process of energy flow into the fundamental and HOMs at the expense of modes with intermediate wave numbers originates from a parametric instability. These results provide yet another demonstration of the parallelisms between hydrodynamic and optical turbulence, and of the universality of mechanisms for spatial pattern generation in different physical settings.

REFERENCES

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