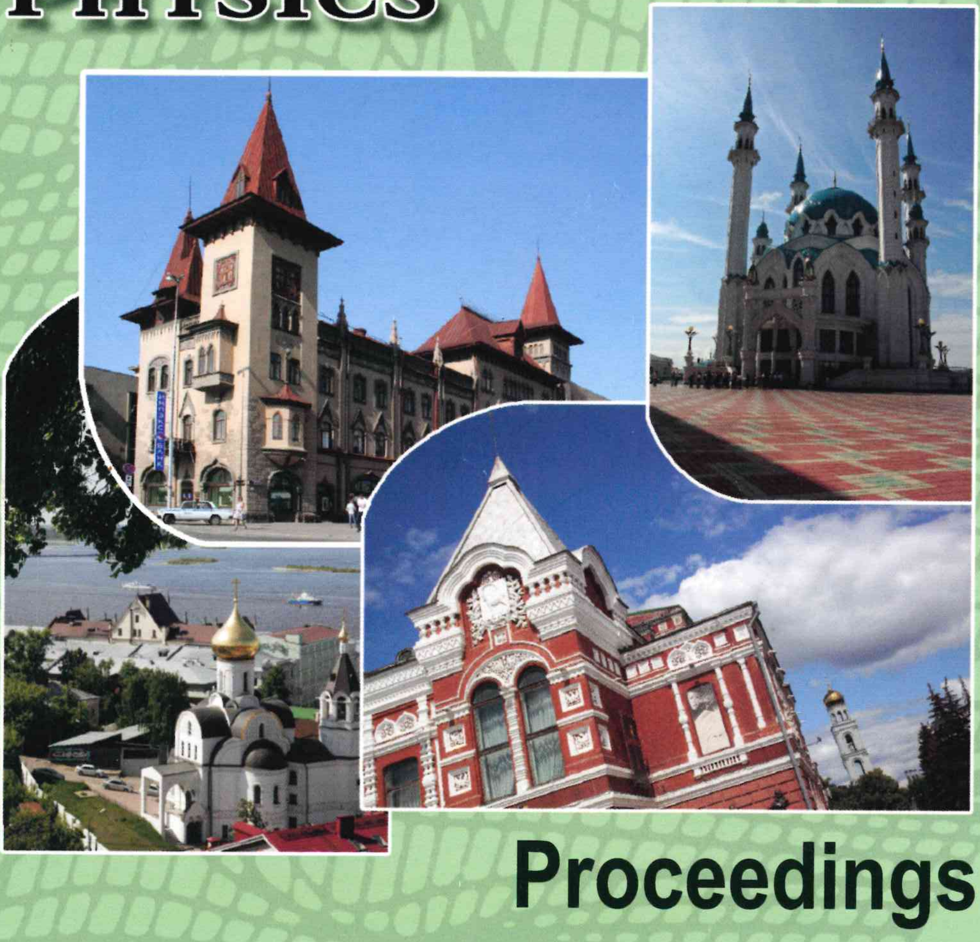
VII INTERNATIONAL CONFERENCE

FRONTIERS OF NONLINEAR PHYSICS



Proceedings

Nizhny Novgorod — Saratov — Nizhny Novgorod, Russia
June 28 — July 4, 2019

Hydrodynamic transverse condensation in multimode optical fibers

S. Wabnitz[1], **E.V. Podivilov**[1,2], **D.S. Kharenko**[1,2], **V.A. Gonta**[1], **K. Krupa**[3],
O.S. Sidelnikov[1,4], **S. Turitsyn**[1,5], **M.P. Fedoruk**[1,4], **S.A. Babin**[2]

[1]Novosibirsk State University, Novosibirsk 630090, Russia, stefan.wabnitz@uniroma1.it
[2]Institute of Automation and Electrometry SB RAS, 1 ac. Koptyug ave., Novosibirsk 630090, Russia
[3]Université Bourgogne Franche-Comté, ICB UMR CNRS 6303, 9 Avenue A. Savary, 21078 Dijon, France
[4]Institute of Computational Technologies SB RAS, Novosibirsk 630090, Russia
[5]Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK
[6]Dipartimento di Ingegneria dell'Informazione, Elettronica e Telecomunicazioni, Sapienza Università di Roma,
Via Eudossiana 18, 00184 Roma, Italy

Spatiotemporal light beam dynamics in multimode optical fibers (MMFs) has emerged as a fertile domain of scientific research in nonlinear optics and physics [1]. Intriguing spatiotemporal wave propagation phenomena such as multimode optical solitons [2], and parametric instabilities leading to ultra-wideband sideband series [3] have only been experimentally observed in MMFs over the last few years.

Among these, we are interested to study here the phenomenon of spatial self-condensation or self-cleaning of multimode light beams in MMFs. It is well known that linear beam 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 [4]. The self-cleaned beam at the fiber output has a bell-shape, with a diameter that is close to that of the fundamental mode of the MMF, while sitting on a low-power 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, which is 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 or degenerate four-wave mixing in a random medium is the mechanism responsible for the self-cleaning of the transverse spatial beam profile at the fiber output.

So far, although different tentative explanations have been put forward, the physical mechanism leading to Kerr beam cleaning remains largely an open issue.

Our theoretical study and associated experiments indicate that Kerr beam self-cleaning results from a parametric mode mixing instability. This instability generates a number of nonlinearly interacting modes with randomized phases, or optical wave turbulence, followed by a simultaneous flow of energy out of modes with intermediate mode numbers, accompanied by a direct and inverse cascade towards high mode numbers on the one hand, and condensation into the fundamental mode, on the other hand. This optical self-organization effect is analogue to the wave condensation that is well-known in hydrodynamic 2D turbulence [5].

In Fig. 1 we show the results of a nonlinear coupled mode simulation, where 153 modes were initially excited at the fiber input by a circularly symmetric Gaussian laser beam. We included in the simulation the presence of linear random mode coupling between nearly degenerate modes with the same radial number and different azimuthal number. As can be seen, the simulation correctly captures the random intensity speckles observed at low powers after 10m of propagation, and the condensation of light into a bright bell-shaped spot at high powers (here the input peak power is 3 kW).

Now, if we write the mode intensities f_n as

$$f_n = \sum_{p,m} |B_{p,m}|^2 \delta(n - 2p - |m|),$$

where *p,m* are the radial and azimuthal mode numbers, respectively, one may observe that, upon propagation, two fundamental are conserved. Namely, the energy

$$\sum_{n=0}^{\infty} f_n = 1,$$

and the average mode number

$$\sum_{n=0}^{\infty} n f_n = \bar{n} = const,$$

or helicity, respectively. Fig. 2 shows the numerically computed redistribution of the energy among different mode numbers, as the input power is increased. As can be seen, energy flows out of the intermediate mode numbers, and into the fundamental mode with $n = 0$, as well as into HOMs.

At the same time, the numerical simulations confirm the conservation of the helicity as the input power is increased above the self-cleaning threshold.

As illustrated in Fig. 3, we experimentally demonstrated the predicted conservation of the average mode number, in spite of the dramatic nonlinear change and self-organization into the fundamental mode of the output intensity pattern (see Fig. 4).

In our experiments, we launched into a 10-m-long GRIN MMF laser pulses from a Q-switched micro-chip Nd:YAG laser, with a duration of 0.6 ns at the wavelength of 1064 nm. Using a 62.5 μm core GRIN fiber, in combination with a beam expander that allowed us for a continuous change of the input beam radius from 15 to 32 μm. We found that the observation of the self-cleaning effect strongly depends on the beam size at the fiber input. For an input transverse beam size which is much larger than the diameter of the fundamental mode of the GRIN MMF leads to huge coupling losses, as too many HOMs are excited. On the other hand, when the input beam size is small enough, one excites a beam close to the fundamental mode of the fiber (of ~10 μm radius). Under such conditions, the output beam maintains a good quality, almost independently of power. The most interesting case corresponds to an intermediate beam size, for example, a 17 μm beam radius) which is close to the condition for optimal coupling into the MMF. The corresponding input beam still remains substantially larger than the fundamental mode (see Fig.4).

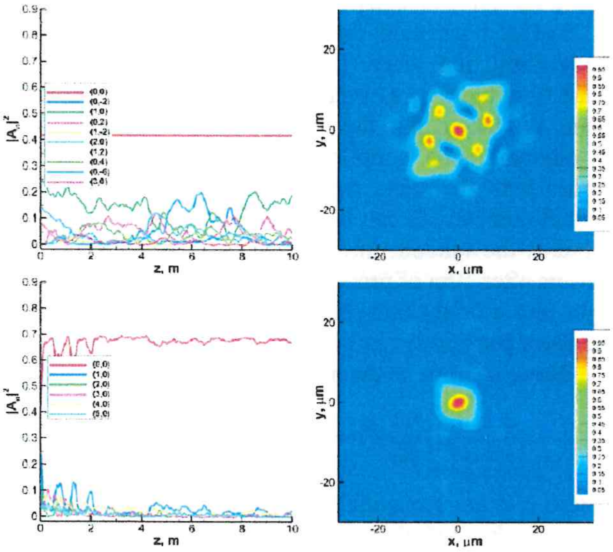


Fig. 1. Mode amplitudes evolution long the fiber coordinate, z (left column) and output transverse intensity pattern (right column) at low powers (top row) and at high powers (bottom row)

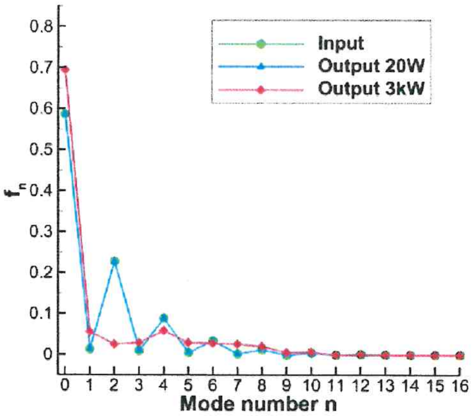


Fig. 2. Redistribution of output modal intensity fraction vs. mode number as the input power is increased

As shown in Fig.4, the speckled structure observed at low powers transforms, at powers >1 kW, into a bright spot that is totally insensitive to fiber deformations, and changes of the input beam polarization state.

In conclusion, the spatial self-organization of light in multimode fibers enables robust effective propagation of spatially bell-shaped beams in spite of the high number of permitted guided modes. The physical mechanism for spatial self-cleaning is nonlinear mode coupling. Energy transfer into the fundamental mode (and into higher order modes) is activated by a parametric instability. Conservation laws make self-cleaning analogous to condensation in 2D hydrodynamic turbulence (optical hurricane).

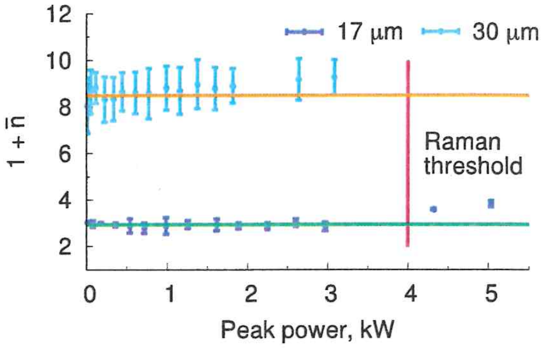


Fig. 3. Experimental confirmation of the conservation with power of the average mode number (below the Raman threshold), for input beams with different radius

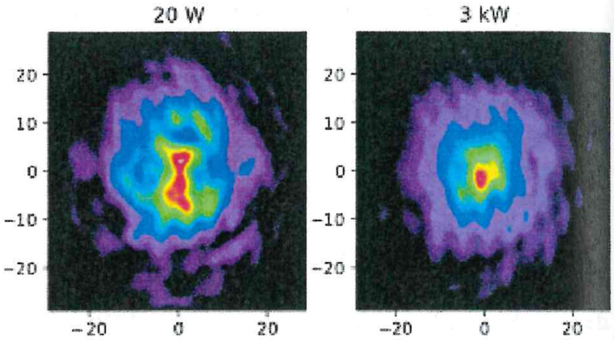


Fig. 4. Experimental output intensity pattern at low and high powers, corresponding to the green line case in Fig.3 (17 μm input beam radius).

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.

Acknowledgements. This work was supported by the Russian Ministry of Science and Education (Grant 14.Y26.31.0017), and the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant No. 740355).

References

1. L. G. Wright, D. N. Christodoulides, and F. W. Wise, *Nat. Photonics*, 1 (2015).
2. W. H. Renninger and F. W. Wise, *Nat. Communic*. 4, 1719 (2012).
3. K. Krupa, A. Tonello, A. Barthélémy, V. Couderc, B. M. Shalaby, A. Bendahmane, G. Millot, and S. Wabnitz, *Phys. Rev. Lett.* 116, 183901 (2016).
4. K. Krupa, A. Tonello, B. M. Shalaby, M. Fabert, A. Barthélémy, G. Millot, S. Wabnitz, and V. Couderc, *Nat. Photon.* 11, 234 (2017).
5. R. H. Kraichnan, *Phys. Fluids* 10, 1417 (1967).
6. E. V. Podivilov, D. S. Kharenko, V. A. Gonta, K. Krupa, O. S. Sidelnikov, S. Turitsyn, M. P. Fedoruk, S. A. Babin, and S. Wabnitz, *Phys. Rev. Lett.*, 122, 103902 (2019).