Walk-off Solitons and Single-mode Spatiotemporal Attractor in Multimode Fibers

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Abstract: Optical solitons in multimode fibers exhibit complex dynamics which have no counterpart in the singlemode case. Experiments and simulations reveal the emergence of new phenomena such as walk-off solitons, dynamical attractors and mode transformation collisions.

1. Introduction

The propagation of optical soliton in multimode (MM) fibers has been theoretically predicted since a long time [1]. MM fiber solitons are a relatively accessible example of otherwise elusive objects such as spatiotemporal solitons or light bullets [2], where dispersion and diffraction are simultaneously balanced by nonlinearity and linear waveguiding. Since some early experiments reported Raman soliton generation in MM graded-index (GRIN) fibers [3], the field of MM fiber solitons has remained largely unexplored, especially when compared with their extensively investigated singlemode counterparts. Motivated by the potential use of MM fibers in spatial-division-multiplexing communications [4] and fiber lasers [5], experimental studies on MM fiber solitons have gained an increasingly renewed research attention over the past ten years [6–9].

In this presentation, we overview our recent extensive experimental and theoretical studies of MM soliton propagation dynamics in optical fibers. These have permitted us to unveil several novel physical effects.

2. High-energy soliton fission

A first interesting aspect of MM solitons is to see what happens when their pulse peak power approaches the critical value for self-focusing. As well known, in bulk purely Kerr media, self-focusing prevents stable light bullets to propagate, owing to self-similar optical wave collapse. On the other hand, the guiding index profile of MM fibers acts as a stabilizing potential for light, which enables stable spatiotemporal beam propagation. To clarify this aspect, we studied the process of high-energy (i.e., for peak powers in the MW range, approaching the collapse value) femtosecond soliton fission in GRIN MM fibers. This has permitted us to reveal a novel nonlinear propagation regime, where solitons produced by the fission have a nearly constant Raman wavelength shift, and same pulse width over a wide range of soliton energies [10]. This regime is characterized by the presence of strong nonlinear absorption, which clamps the transmitted energy at the fiber output. As a result, the Raman soliton self-frequency shift (SSFS) is suppressed. Moreover, a significant side-scattering of photo-luminescence is observed over the first few centimeters of fiber, owing to multiphoton absorption by intrinsic defects of the fiber core material [11].

3. Walk-off solitons

For peak powers below the threshold for nonlinear losses to occur, we studied in detail the physical mechanism leading to femtosecond MM solitons. Differently from singlemode fiber solitons, where a balance occurs between chromatic dispersion and self-phase modulation, in MM fibers nonlinearity must also balance modal dispersion. This means that a singlemode soliton can have an arbitrary temporal duration, provided that its peak power or energy is properly adjusted. In contrast, MM solitons in an MMF only form when the modal walk-off distance equals both nonlinear and chromatic dispersion lengths. Therefore, we may term such objects as "walk-off" MM solitons: they have a pulsewidth and energy, which are independent of the input pulse duration, and only depend on the fiber dispersive parameters [12].

4. Spatiotemporal attractor

Experiments and simulations have jointly shown that MM walk-off solitons are ultimately unstable objects which irreversibly evolve, in the range of hundreds of nonlinearity lengths, into stable singlemode solitons carried by the fundamental mode of the fiber [13]. This soliton acts as a dynamical attractor of the MM fiber, for up to the record value (for MM fibers) of 5600 chromatic dispersion distances. This finding invalidates the use of variational approaches, which intrinsically require the indefinite maintenance of the initial multimode profile of a MM soliton.

5. Multimode solitons in step-index fibers

We have also studied the conditions for the generation and propagation stability of MM walk-off solitons in step-index fibers, by comparing their properties with those of MM solitons in GRIN fibers. Again we found that, after a certain propagation distance, the MM soliton energy is gradually captured by a stable singlemode soliton, carried by the fundamental mode of the fiber [14].

6. Multimode soliton transformation by collisions

As a last topic, we investigated the process of the collision of two different MM solitons, that result from the Raman-induced fission of an initial intense femtosecond pulse in a GRIN fiber. Remarkably, we found that the SSFS of the trailing MM soliton may be reduced as the input pulse energy grows larger, so that it accelerates until it collides with the second leading MM soliton. This collision leads to both energy transfer among the MM solitons and, unexpectedly, to a significant internal redistribution of their modal composition [15].

Conclusions

To conclude, our studied have revealed several aspects of the complex but fascinating new world of MM solitons, and will have an impact in emerging technologies such as MM communications, lasers and imaging.

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References

1. A. Hasegawa, "Self-confinement of multimode optical pulse in a glass fiber," Opt. Lett. **5**, 416–417 (1980).
2. Y. Silberberg, "Collapse of optical pulses," Opt. Lett. **15**, 1282–1284 (1990).
3. A. B. Grudinin, E. Dianov, D. Korbkin, M. P. A, and D. Khaidarov, "Nonlinear mode coupling in multimode optical fibers; excitation of femtosecond-range stimulated-Raman-scattering solitons," J. Exp. Theor. Phys. Lett **47**, 356–359 (1988).
4. A. Mecozzi, C. Antonelli, and M. Shtaif, "Coupled Manakov equations in multimode fibers with strongly coupled groups of modes," Opt. Express **20**, 23436–23441 (2012).
5. L. G. Wright, D. N. Christodoulides, and F. W. Wise, "Spatiotemporal mode-locking in multimode fiber lasers," Science **358**, 94–97 (2017).
6. W. H. Renninger and F. W. Wise, "Optical solitons in graded-index multimode fibres," Nat. Commun. **4**, 1719 (2013).
7. L. G. Wright, W. H. Renninger, D. N. Christodoulides, and F. W. Wise, "Spatiotemporal dynamics of multimode optical solitons," Opt. Express **23**, 3492–3506 (2015).
8. L. G. Wright, D. N. Christodoulides, and F. W. Wise, "Controllable spatiotemporal nonlinear effects in multimode fibres," Nat. Photonics **9**, 306–310 (2015).
9. L. G. Wright, S. Wabnitz, D. N. Christodoulides, and F. W. Wise, "Ultrabroadband dispersive radiation by spatiotemporal oscillation of multimode waves," Phys. Rev. Lett. **115**, 223902 (2015).
10. M. Zitelli, F. Mangini, M. Ferraro, A. Niang, D. Kharenko, and S. Wabnitz, "High-energy soliton fission dynamics in multimode GRIN fiber," Opt. Express **28**, 20473–20488 (2020).
11. M. Ferraro, F. Mangini, M. Zitelli, A. Tonello, A. D. Luca, V. Couderc, and S. Wabnitz, "Femtosecond nonlinear losses in multimode optical fibers," Photon. Res. **9**, 2443–2453 (2021).
12. M. Zitelli, F. Mangini, M. Ferraro, O. Sidelnikov, and S. Wabnitz, "Conditions for walk-off soliton generation in a multimode fiber," Commun. Phys. **4**, 1–6 (2021).
13. M. Zitelli, M. Ferraro, F. Mangini, and S. Wabnitz, "Single-mode spatiotemporal soliton attractor in multimode GRIN fibers," Photonics Res. **9**, 741–748 (2021).
14. M. Zitelli, Y. Sun, M. Ferraro, F. Mangini, O. Sidelnikov, V. Couderc, and S. Wabnitz, "Multimode solitons in step-index fibers," Opt. Express **30**, 6300–6310 (2022).
15. Y. Sun, M. Zitelli, M. Ferraro, F. Mangini, P. Parra-Rivas, and S. Wabnitz, "Multimode soliton collisions in graded-index optical fibers," arXiv preprint arXiv:2202.09843 (2022).