Robust Multidimensional Solitary States in Hollow-Core Fibers for Ultrafast Light Source Applications

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We investigate the stability and energy transfer limits of multidimensional solitary states (MDSS) in Raman-active gas-filled hollow-core fibers. Combining theory, simulations, and experiments, we reveal that MDSS can coexist with instabilities while maintaining their structure. Our findings offer insights into multimode nonlinear dynamics, enabling advancements in ultrafast optics.

MDSS in gas-filled hollow-core fibers (HCFs) exhibit unique energy transfer dynamics governed by Raman scattering and intermodal nonlinear interactions [1]. Here, we investigate the stability of MDSS and the fundamental limits of energy transfer in Raman-active gas-filled HCFs. Specifically, we show that beyond a critical input energy, a secondary red-shifted Raman component emerges due to Raman gain in higher-order modes. Similar to other multimode systems, this instability originates from spatiotemporal modulation instabilities (STMI), which influence the system's attractor [2].

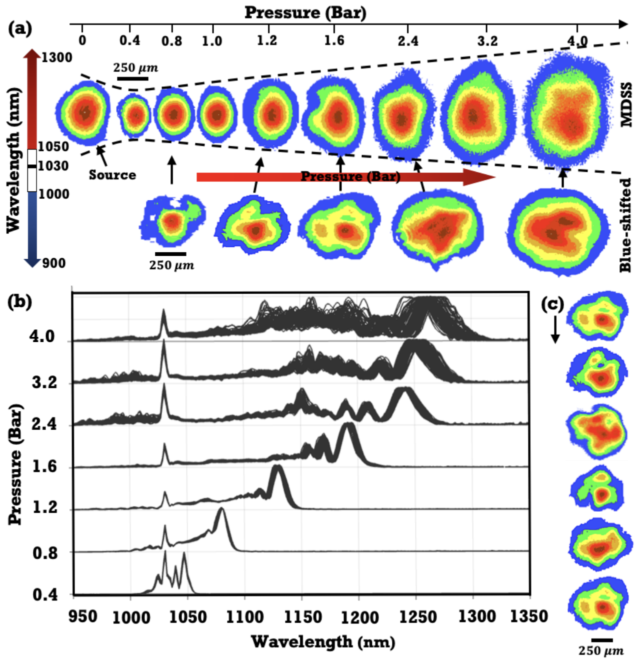

Figure 1: a) Beam profile of the MDSS and blue-shifted regions using a spectral short-pass and long-pass filters. b) Spectral broadening of the output beam by MDSS at different N_2O gas pressures with an input pulse energy of 500 μJ

To achieve this, we employ a Yb-based laser with a pulse duration of 700 fs and a central wavelength of 1030 nm. The laser is directed into a 2.5 m long HCF with a core diameter of 500 um, which is filled with N2O gas. Figure 1 presents the variation of spatial beam profiles in the red-shifted and blue-shifted regions (Fig. 1a) and the corresponding spectral features (Fig. 1b) as a function of increasing gas pressure, with input pulse energy of 0.5 mJ. Initially, as the gas pressure increases, a red-shifted beam is created. Its size is smaller than that of the input beam, and it maintains a symmetric shape. This suggests the presence of higher-order symmetric modes in this region, marking the formation of an attractor [2]. At the same time, the blue part of the spectrum is also observed. At first, the beam in blue part exhibits a symmetric shape but is significantly smaller than the fundamental beam, indicating strong self-focusing in this region. As the gas pressure increases further, the blue-shifted component begins to diverge, and the beam in this region becomes unstable. Simultaneously, MDSS in the red-shifted region starts to develop additional spatiotemporal structures around itself, leading to an increase in beam size and marking the onset of attractor instability. As seen from the spectral evolution, the entire spectrum exhibits increasing instability with higher gas pressure. Another intriguing observation is that as self-focusing strengthens in the blue part of the spectrum, a second red-shifted spectral component emerges, which becomes prominent at 2.4 bar. This effectively divides the red-shifted region into two parts, with the newly formed red-shifted component being significantly more unstable. This instability further disrupts the primary attractor. These observations provide clear evidence of the rich and complex physics underlying attractor formation. Using a combination of a theoretical model and multimode numerical simulations, we investigated these experimental results in greater detail to uncover the underlying physics behind our observations. Our results offer new insights into the interplay between stability and multimode nonlinear dynamics in structured light systems. By demonstrating that MDSS can maintain coherence even in the presence of spectral instabilities, we open new possibilities for their use in ultrafast optics, high-energy pulse propagation, and nonlinear multimode fiber systems.

References

[1] R Safaei, G Fan, O Kwon, K Légaré, P Lassonde, B E Schmidt, H Ibrahim and F Légaré, Nat. Photonics **14**, 733 (2020)

[2] L G Wright, Z Liu, D A Nolan, M-J Li, D N Christodoulides and F W Wise, Nat. Photonics **10**, 771 (2016)