Bose-Einstein Condensation in Multimode Fibers

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Multimode nonlinear optics in fibers has increasingly attracted attention in the past few years, in particular after the intriguing observation of beam self-cleaning in multimode fibers [1]. To this end, an initially noisy speckle input beam was shown to convert into a much cleaner beam profile upon nonlinear propagation within the multimode fiber, resulting in a significantly enhanced fundamental mode contents. So far, these experiments have been conducted in fibers that do not exhibit any dissipative mechanisms apart from scattering losses, and beam self-cleaning action often appeared rather limited near 50% fundamental contents. Here we show that dissipative cores can greatly improve beam self-cleaning beyond 90%, restoring nearly perfectly coherent beam profiles.

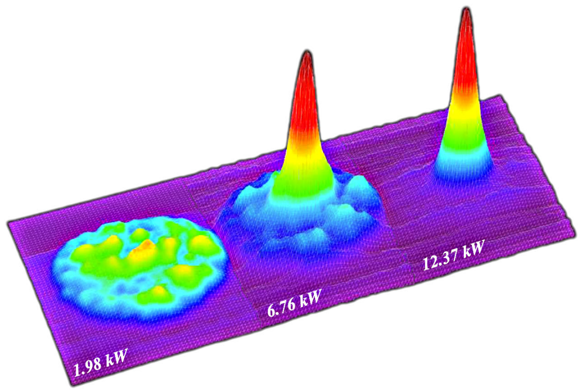

Figure 1: Near-field beam profiles measured with increasing launched peak power. At low powers an incoherent speckle pattern is observed due to the interference of multiple modes with different propagation constants. At elevated powers, the profile transforms into a spatial Townes soliton. A similar transition was observed in Bose-Einstein condensation [2]

Launching pulses from a mode-locked fiber laser with up to 20 kW of peak power into a multimode fiber, we observe a transition from incoherent low-power speckle beam profiles to near coherent nearly perfectly single-mode profiles above 10 kW peak power (Fig. 1). Quite surprisingly, the profiles do not condense in the fundamental mode of the step-index fiber, but in a Townes soliton with extended wings and near-perfect agreement down to about 5% of the peak intensity at beam center. The analogy of the observed phase transition to the Bose-Einstein condensation in dilute gases becomes clearer from understanding that both systems are ruled by the identical equation. Fiber modes are eigenvalue solutions of the transverse Helmholtz equation, which turns into the Gross-Pitaevskii equation by adding a nonlinear term to account for self-focusing action. The very same equation has been used to theoretically explain the formation of two-dimensional Townes solitons in Bose-Einstein condensation [2]. Further analyzing the condensation process within the framework of optical thermodynamics, we observe a threshold-like abrupt change of the chemical potential at about 8 kW peak power, indicative of a phase transition.

References

[1] K Krupa, A Tonello, B M Shalaby, M Fabert, A Barthélémy, G Millot, S Wabnitz and V Couderc, Nat. Photonics **11**, 237 (2017)

[2] M Anderson, J Ensher, M Matthews, C Wieman and E Cornell, Science **269**, 198 (1995)