Recent advances in the thermodynamic description of beam cleaning in multimode fibers

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Transporting information over multimode fibers (MMF) faces two main challenges: high-bit-rate signal dispersion in the time domain and image corruption due to multimode interference in the spatial domain. The large dispersion of mode group velocities hampers their capacity to transport high-bit-rate signals, while different modal phase velocities cause multimode interference, leading to corrupted images. Additionally, the resulting speckled output intensity pattern is highly sensitive to external perturbations like stress or bending, causing mode power transfers via linear mode coupling. Due to these limitations, singlemode fibers (SMF) have become the preferred choice for most optical data communication and beam delivery applications. SMFs guide only one mode, eliminating modal dispersion and naturally preserving the input laser's Gaussian-like beam shape.

A few years back, an intriguing phenomenon called beam self-cleaning (BSC) has been observed in MMFs [1]. The Kerr effect can eliminate speckles and produce a stable, bell-shaped beam at the output of a few meters long graded-index (GRIN) MMF [2]. This effect occurs when the input laser power exceeds a certain threshold, which depends on the fiber length. Experimental observations show BSC of laser pulses with tens of kilowatts of peak power over a few meters of GRIN fiber. Interestingly, BSC can also be achieved by increasing the propagation distance along the GRIN fiber while keeping the input peak power constant, highlighting that the accumulated nonlinear phase shift determines BSC occurrence.

BSC significantly improves the beam spatial quality, reducing the M^2 values from around 10 to between 1 and 4. This improvement is crucial for various applications, as current SMF-based technologies are limited in pulse peak power and energy due to the small mode size and relatively low power damage threshold of SMFs. In contrast, MMFs can handle higher power due to their larger mode area, making them ideal for high-power laser technologies. Indeed, BSC has been demonstrated in high peak-power mode-locked MMF lasers [3,4] and applications like high-resolution nonlinear microscopy and endoscopy [5].

Despite numerous experimental demonstrations across various laser pulse durations and wavelengths, the exact physical mechanism behind BSC remains a topic of debate. Initial explanations like higher nonlinear losses for high-order modes (HOM) and loss of spatial coherence through nonlinear spectral broadening have been disproven. Instead, BSC appears to result from a specific mode power distribution, described by the Rayleigh-Jeans (RJ) law, indicating a thermodynamic approach to understanding BSC [6,7]. Indeed, a large part of the output beam energy remains in HOM, and the central bell-shaped beam's waist is wider than the fundamental mode. This has suggested that BSC is associated with a stable mode power distribution rather than continuous power flow from HOM to the fundamental mode. In this sense, the RJ law provides a framework for describing BSC as wave thermalization according to statistical mechanics principles.

Specifically, theoretical models, such as weak wave turbulence and classical wave condensation, predict that BSC results from the thermalization process in a GRIN fiber. This involves a mode power redistribution resembling 2D hydrodynamic turbulence, with energy flowing towards both the fundamental mode (inverse cascade) and HOM (direct cascade) at the expense of intermediate modes [8]. Experiments and numerical simulations support these theories, linking the microscopic state of multimode beams to macroscopic parameters like temperature and chemical potential, and predicting the equilibrium mode occupation probability distribution by the RJ law [9-11].

Thermodynamic approaches rely on conservation laws: specifically, the conservation of power and linear momentum (or Hamiltonian). Typical experimental conditions for observing BSC fulfill these laws, with linear losses being negligible and power levels far below the threshold for catastrophic self-focusing.

Nevertheless, BSC has also been observed under conditions different from those required by thermodynamics, e.g., in the presence of highly dissipative effects [12]. In addition, recent experiments have shown that BSC maintains the spatial coherence of the source [13,14] and occurs even in combination with supercontinuum generation [15]. Such results are outside the thermodynamic framework, which only considers spatially incoherent monochromatic waves. All this indicates that the BSC's robustness goes beyond what thermodynamic descriptions indicate.

This contribution aims to review the recent advances in the thermodynamic description of BSC, highlighting the experimental results that agree with theoretical predictions as well as those that extend BSC beyond its thermodynamic understanding.

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