Replica symmetry breaking in 1D Rayleigh scattering system

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Recently, the emergence of a novel light source, known as random fiber laser (RFL), has captured significant interest[1]. RFL diverge from traditional laser by eschewing the standard resonant cavity, instead harnessing the stochastic Rayleigh scattering within the fiber for feedback. It is characterized by simple structure, high efficiency, good stability and flexible regulation[2], and has shown a wide range of application prospects in the field of communication, sensing and high-power laser[3][4][5]. It is also being considered as potential seed sources for future laser-driven inertial confinement fusion (ICF) systems[6]. The distinctive feedback mechanisms and abundant nonlinear effect inherent in RFL have also established it as a vital platform for delving into the intricacies of complex systems. Our team's research delves into the phase transition mechanisms of RFL, aiming to uncover their intrinsic workings to enable multifaceted manipulation of their emission properties. This endeavor is designed to enhance their performance within high-power laser systems.

RFL, with their distinctive feedback and gain mechanisms, display complex dynamics akin to those in spin glass systems rich in spin molecules, serving as an essential element in the profound investigation of spin glass theories. With the help of phase-sensitive optical time-domain reflectometer (Φ-OTDR) with proprietary technologies, we accurately measured the phase fluctuations of Rayleigh scattering in fibers, and proposed a Rayleigh-scattering-phase-variation model, which theoretically predicted the boundary parameter of photonic phase transition in the RFL[7]. Subsequently, the ubiquitous mechanism of the photonic phase transition is revealed: the photonic phase variation in RFL with Rayleigh scattering mechanism keeps an analogy to the role of temperature and disorder in the interactions between spins in the magnetic spin glass phase. We also theoretically predict and experimentally observe a unique phase transition phenomenon-mode asymmetry, which expands the current understanding of photonic phase transitions, providing a fresh perspective on the intrinsic mechanisms of complex systems. Furthermore, our research identified that the correlation of RFL is predominantly governed by the stochastic spikes scattered throughout the spectrum, which is pivotal for guiding the design, manipulation, and utilization of these lasers.

Given the significance of the time-domain intensity statistics of RFL for the reliability of high-power laser devices, our team innovatively crafted a 1053nm narrow-linewidth RFL and explored its time-domain intensity statistics through both experimental and theoretical research under full bandwidth conditions[8]. It is found that the time-domain intensity statistics characteristics of the RFL is related to the pump power, observing position and the fiber dispersion. Additionally, the time-domain intensity statistics of RFL exhibit an inward deviation from the exponential distribution, signifying interdependencies among various frequency components within the spectrum. Building on this research, we experimentally explored the connection between the dispersion and the time-domain intensity characteristics of the RFL. The results show that the dispersion accumulation will make the time-domain characteristics closer to the exponential distribution; on the contrary, the dispersion compensation leads to a more stable time-domain output. Leveraging these findings, we can tailor the time-domain output of random fiber lasers, with specific intensity amplitudes, to fulfill specialized application requirements.

Building upon our foundational theoretical research on RFL, we have conducted preliminary exploration of its potential application in ICF laser devices[9]. RFL, characterized by its instantaneous broadband and multidimensional tunability, demonstrate the potential to serve as seed sources in ICF laser devices. In alignment with the gain spectrum characteristics of neodymium glass amplifiers within ICF laser devices, our team has developed a two-level Nonlinear Schrödinger Equation (NLSE) model for the design of RFL seed sources. Following this, we introduced a precision spectral control scheme with matched the amplifier gain spectrum, successfully demonstrating the generation of nanosecond random laser pulses with a 2.5nm bandwidth and an energy output of 28mJ in our experiments. This study robustly illustrates the favorable prospects for the application of RFL in ICF laser devices.

In conclusion, our team's profound investigation into the phase transition of RFL has laid a theoretical groundwork for the precise and multidimensional manipulation of its output characteristics. This advancement paves the way for the enhanced application potential of RFL across various domains.

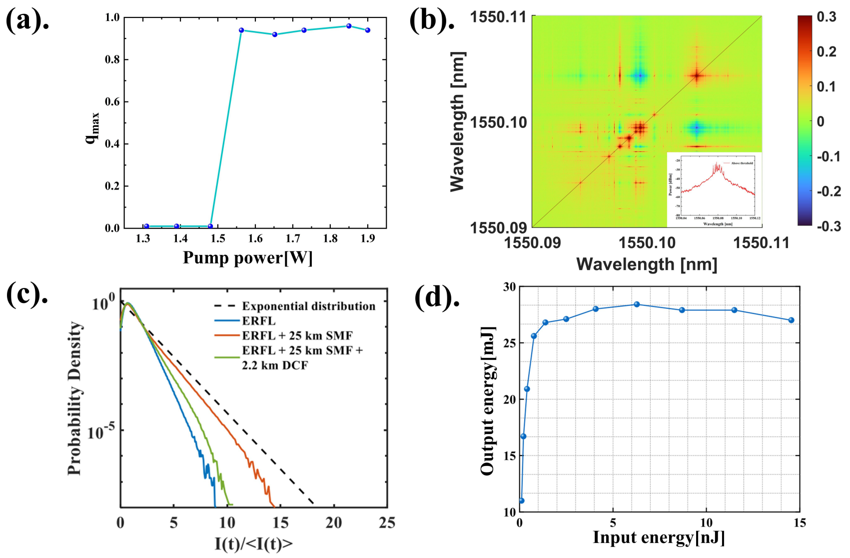

Fig. 1. (a). Phase transition in RFL; (b). Correlations between different modes of RFL, inset: corresponding spectrum; (c). Time-domain intensity of the RFL with different dispersion; (d). Energy curve of regenerative amplification in the ICF combined with RFL.

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