First Demonstration of Beyond Kilowatt-Level Single-Frequency Fiber Amplifiers

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High-power single-frequency laser with diffraction-limited spot is the optimal light source for gravitational wave detection (GWD), remote communication, and other frontier scientific applications. Fiber laser systems, renowned for their structural flexibility, ease of maintenance, and straightforward system cleanliness, offer a promising pathway to achieving high-power single-frequency lasers. When coupled with advanced beam quality and noise control strategies, fiber laser systems are poised to deliver a reliable and high-performance light source for these demanding applications. The Laser Zentrum Hannover, which currently supplies the laser source for LIGO, has emphasized that kilowatt-class, ultra-low-noise single-frequency fiber lasers are pivotal for next-generation gravitational wave detection systems. This sentiment was further underscored in a 2019 Nature in focus news article, which outlined a major upgrade plan for LIGO aimed at significantly enhancing its detection capabilities. One of the key elements in this plan is the power enhancement of single-frequency fiber lasers. However, after nearly two decades of development, the output power of all-fiber single-frequency lasers with near-diffraction-limited beam quality still remains at 400 W level due to the inner contradictions in the comprehensive suppression of the stimulated Brillouin scattering (SBS) and the transverse mode instability (TMI) effects.

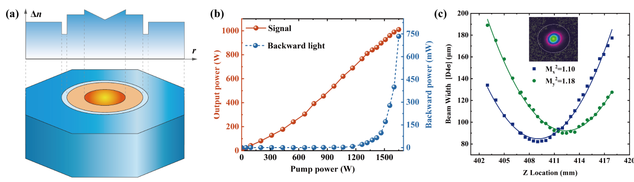

Figure 1: (a) Refractive indexFig; (b) Power curve; (c) Beam quality

In this paper, we will demonstrate our innovative design and breakthrough results in the field of single-frequency fiber lasers. The main highlights of the work include three aspects: (i) Elaborate on the design considerations ranging from theoretical calculations of SBS and TMI thresholds, to the selection of equivalent NA, and further to the refractive index distribution and ultimately propose the design of the bat-type refractive index distribution fiber. (ii) Break through the technical challenges of key components and develop an active fiber capable of supporting kilowatt single-frequency laser amplification (iii) Construct a high-power verification system and realize internationally leading technical specifications with power >1 kW, M^2 <1.2. Detais can be seen in Figure 1.

In conclusion, the bat-type refractive index distribution design demonstrates exceptional performance in single-frequency fiber laser power amplification. And the bat-type refractive index distribution design also exhibits excellent compatibility with existing fiber structures, ensures seamless integration into current laser systems, paving the way for cost-effective mass production. Additionally, this refractive index distribution offers a novel approach to comprehensively suppressing nonlinear effects and transverse mode instability (TMI), making it highly promising for broader applications in fields such as broadband laser amplification and ultrafast laser systems.