ABSTRACT

In the past decades, fiber laser and amplifier systems have seen a rapid power increase due to the efficient heat dissipation and robust single-mode operation. The fiber lasers and amplifiers have become attractive sources for applications spanning from industry and defense to scientific research. In particular, the fiber lasers and amplifiers have penetrated for material processing industry including marking, cutting, welding and drilling. It had been known that the highest achievable output power in fiber laser and amplifier systems is largely limited by the nonlinear scatterings such as stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS). However, a new phenomenon under high power operation, the so-called transverse mode instability (TMI), was experimentally observed in a large mode area (LMA) ytterbium (Yb)-doped fiber amplifier in 2011. The TMI can occur much earlier than the SBS and SRS in average power scaling, hence becoming the first limitation in high-power fiber operations till now.

The TMI refers to the output beam degradation, caused by the power transfer from the fundamental mode (FM) to the higher-order mode (HOM), for input pump power above a certain threshold. The origin of TMI is attributed to the stimulated thermal Rayleigh scattering (STRS) that provokes a phase shift, induced by the thermal diffusion time across fiber core, between the irradiance grating and thermally induced refractive index grating. The interference between two populated modes produces the irradiance grating along the fiber, which has a period equal to the beating length between two modes. Then the thermally induced refractive index grating is generated by irradiance grating through a quantum defect (QD) in fiber core. The QD created by transition from pump to signal frequency is recognized as the main heat source to modify the refractive index. Recently, it was found that photodarkening (PD) leads additional heating and contributes to the thermal grating. Hence, PD suppressed fiber becomes more important for high power scaling. As the TMI has been discovered very recently, approaches to suppressing the TMI have been very limited. HOM suppression by fiber bending has been the most popular method to suppress the TMI. TMI suppression by pump modulation was reported, but it is not a preferred method as it could lead to damage of the system. Therefore, the motivation of this thesis is to address the TMI in a fiber level through investigation of fiber designs suitable for power scaling with high TMI suppression.

Firstly, I developed a four-dimensional (4D) (x,y,z,t) highly numerical model, with the fast Fourier transform (FFT) based beam propagation method (BPM), to simulate and investigate the TMI behaviors in an arbitrary fiber design. Secondly, I theoretically study the TMI in non-circular ytterbium-doped fibers to investigate the heat sink arrangement and TMI suppression. Thirdly, I investigated maximum achievable power in a PD fiber through parametric optimization. A PD fiber provides high pump absorption and high fabrication yield, which would benefit designing laser or amplifier configurations when the TMI is suppressed. Lastly, a TMI suppressed design is proposed based on annual core fibers. TMI effects are theoretically investigated in Yb-doped ring-core and multicore fibers. The annual core is found effective to reduce thermal loss, thus suppressing the TMI. The ring shaped near field beam can be converted to a Gaussian-like beam profile in a far-filed with up to 88% conversion efficiency.

The thesis contributes to thorough investigation of the TMI behavior in a fiber level, leading to new insights of fiber design aspects. The thesis concludes that power scaling in fiber lasers and amplifiers can be continuously progressive by investigating alternative fiber designs that could considerably suppress the TMI.