Abstract

Recent years have witnessed an exponential growth in high-power fiber lasers for industrial applications. Most of the commercial fiber lasers are based on ytterbium (Yb)-doped system that provide lasing window from 1.0-1.1 μm. The power scaling in high-power fiber lasers are limited by the nonlinear and thermal effects. Large mode-area (LMA) fibers have emerged as a promising tool to reduce detrimental nonlinear effects, while satisfying stringent requirements of single-mode (SM) operation to ensure high beam quality. In practical environments, LMA fibers are bent to make the compact fiber lasers systems that lead to the severe reduction in the mode-area and beam quality of LMA fibers. To overcome mode-area shrinking and degraded beam quality, researchers have looked into modifying fiber designs in several ways.

Leakage-channel fibers (LCFs), a variant of photonic crystal fibers have been reported as an alternative solution to realize LMA. First, a simple all-solid LMA LCF with asymmetric cladding has been proposed to achieve effectively single-mode (ESM) operation. The modal properties of the proposed design have been investigated and results have confirmed that the proposed fiber exhibits low bending loss (BL) of the fundamental mode (FM) and very high differential loss ratio between the higher-order modes (HOM) and the FM at the allowable bending radii of 5-15 cm. The LMA LCF exhibits an effective mode-area of ~1970 μm^2 at 1064 nm in straight case which reduces heavily on bending in 5 cm radius. The effective mode-area is enhanced by incorporating a microsized low-index capillary in the centre as confirmed through numerical simulations.

We have further explored possible and feasible fiber designs to overcome the limitation of large mode-area at commercial packaging radius of 7.5 cm. It has been worked out to make use of pre-bend compensated refractive index profile fiber designs to counteract the mode-area reduction while bending and maintaining the single-mode operation. We have successfully achieved bent hybrid LCF (HLCF) designs to attain ESM operation and low BL. The HLCF designs consist of high-index rings surrounding the low-index fluorine-doped silica rods to compensate the bend induced distortion. The optimized hybrid LCF exhibits a mode-area of ~1406 μm^2, good beam quality factor, M^2 of ~1.2 and ESM operation at the bending radius of 7.5cm.

We have also studied the effects of thermally induced refractive index change on the mode-area of bend-compensated LMA modified HLCF (M-HLCF) and double-clad M-HLCF in various heat load conditions. Numerical simulations reveal that the effective mode-area of M-HLCF, which is ~1433 μm^2 at the room temperature, reduces marginally to ~1387 μm^2 when the temperature distribution rises to ~125°C while maintaining the SM operation. The double-clad M-HLCF exhibits a mode-area of ~ 1000 μm^2 for all the heat load density variations up to maximum of 12×10^9 W/m^3, corresponding to 250°C temperature at the center of the fiber core region. Finally, the lasing characteristics of a newly designed Yb-doped double-clad M-HLCF (YDMHLCF) have been numerically investigated for strongly pumped conditions. The doped-region size is optimally found through simulations, equivalent to the size of core diameter in order to achieve maximum conversion efficiency for the bend and straight cases. It is found that a 2 m long YDMHLCF exhibits constant slope efficiency of ~78% for the straight case and practical bending radius of 7.5 cm when pumped with a 975 nm laser diode.

Keywords: Fiber lasers, Large mode-area, Photonic crystal fiber, Leakage-channel fiber