Linearly polarized monolithic high power LMA-fiber lasers

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Large mode area (LMA) fibers enabled a rapid increase of continuous-wave (CW) single-transverse-mode fiber laser powers [1, 2], which currently are above 1-kW [3, 4]. However, high power LMA fiber lasers with linearly-polarized output are at much lower powers of ~0.6-kW [5], the main limitation being the need for additional external-cavity bulk polarizing components. Need for such components is also prohibiting an all-fiber design of an LMA PM system, which is a critical technological limitation. We report our progress in providing a solution to this problem by developing monolithic linearly polarized CW LMA fiber lasers, with output powers exceeding 400-W in a single transverse-mode and spectrally stabilized narrow-linewidth output beam. This approach is unique in that, unlike other demonstrated high-power PM fiber laser designs, it does not use any external bulk polarizing components or highly-specialized single-polarization fibers. Additionally, we also demonstrate narrow-linewidth spectrally-stabilized high power operation by using a fiber Bragg grating (FBG) in a LMA fiber spliced to the PM cavity. This simple and robust all-fiber design is particularly attractive for further fiber power scaling to >10-kW using multiple-beam combining techniques [6]. It also facilitates use of high power fiber lasers in a broad variety of other applications where single polarization output is critical, such as nonlinear wavelength conversion using SHG or OPO [7].

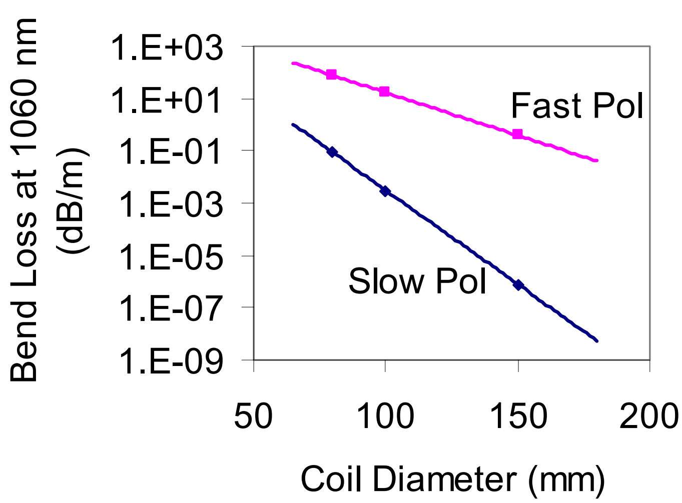
Our approach is based on using coiling-induced mode filtering in low-NA high-birefringence (HiBi) LMA fibers to achieve both single transverse mode and linear polarization output. Due to stress-induced high birefringence in PM fibers, linearly polarized light waves propagating in these fibers have different refractive indices depending on the polarization orientation: light polarized along the "slow axis experiences higher refractive index than the light polarized along the "fast" axis. This leads to different modal loss for the two different polarizations, similarly to the difference in the loss between different order modes. From practical perspective, combination of low-NA and HiBi are crucial for achieving significant polarization-mode (as well as higher-order mode) loss differentiation for realistic coiling conditions (coiling radius and coiling tolerances). This is illustrated in Fig. 1, where the calculated bending loss for "fast" and "slow" polarizations for 20-µm 0.06 NA HiBi LMA fiber are plotted as a function of the coiling radius.

Fig. 2 shows the setup of the fiber laser. An Yb-doped Panda-type HiBi LMA double-clad fiber is used as the gain medium in the system. The fiber has 20µm core and 400µm octagon-shaped pump cladding with 0.06 NA and 0.45 NA for the core and the cladding, respectively. The fiber length of 33-m has been selected to optimize pump absorption at 940nm. One end of the Yb-doped fiber was straight cleaved and the other end was spliced with a high reflectivity (R>99%) fiber Bragg grating at 1085nm imprinted into identical 20-µm core and 0.06 NA LMA fiber. The splicing procedure has been carefully developed to produce negligible loss and intermodal scattering at the splice, thus preserving single-transverse mode quality of the laser output. The laser cavity was formed by a straight cleaved end (3.5% Fresnel reflection) and the high-reflectivity FBG. The free fiber end on the grating side was angle cleaved with ~11∘ to eliminate end reflections. The Yb-doped fiber was coiled with 7.5cm diameter, which according to Fig. 1 allows achieving sufficient loss-discrimination between two linearly polarized HiBi fiber LP_{01} mode eigen-polarizations, thus allowing only one polarization in a single transverse mode at the output. Three fiber-coupled pump modules operating at 915nm, 940nm and 976nm wavelengths were wavelength-multiplexed and coupled from the straight-cleaved end. One more pump module operating at 915nm was coupled from the angle cleaved end with a FBG. All four pump modules provided a maximum of 610W of pump power coupled into the fiber. To eliminate thermal effects in the fiber it was carefully heat-sunk.

Fig. 3 shows output power of the laser. With the total 610W of coupled pump power, we generated 405W of the laser output power with the slope efficiency of 65.9%. Minor slope-efficiency reduction compared to an uncoiled fiber (70.9%) indicates a minor effect of the coiling-induced extra loss of the "slow" LP_{01} mode. Up to 30W of extra pump loss (5% of the coupled maximum pump power) has been also observed due to the tight coiling. Figure 4 shows a polarization extinction ratio (PER) of the laser output measured at different laser powers. ~18-dB polarization extinction ratio has been obtained almost independently of the laser power. Measured M^2 value of the output beam is < 1.1.

Lasing wavelength at 1085.2nm and laser spectral bandwidth has been defined by the reflection spectrum of a fiber Bragg grating at one end of the laser cavity. Although grating bandwidth was equal to the laser bandwidth of 0.5-nm, but at high output powers we observed broadening of the laser spectral width: for 184-W output spectral width was 1.22-nm and for 405-W output it increased to 1.95-nm. No stimulated Raman scattering occurred in the laser even at the highest achieved output powers. Stimulated Brillouin scattering was also suppressed due to the broad spectral width of the signal.

In summary, we have developed a single-polarization high-power 20-µm core fiber laser design which does not use external bulk polarizing components. Power scalability of such LMA fiber laser to >400-W have been demonstrated, which has been pump-power limited and, according to our estimates, could be further increased to >2-kW [2] without encountering SBS or SRS effects. Note also that this power is the highest ever reported for narrow-linewidth PM fiber output. Observed polarization extinction ratio of ~18-dB does not degrade even at the highest observed laser output powers. This fiber laser design can be implemented as an all-fiber laser cavity, as has been demonstrated by the use of in-cavity fiber-Bragg grating reflector. Indeed, these fiber gratings were fabricated in the 20-µm core fiber and were spliced to the LMA Yb-doped fiber without observable penalty on output beam quality and polarization extinction ratio. Such monolithic PM and narrow-linewidth design is particularly valuable for future fiber laser power scaling using both coherent and spectral beam combining techniques, and the whole class of other applications – for example, high power nonlinear wavelength conversion.



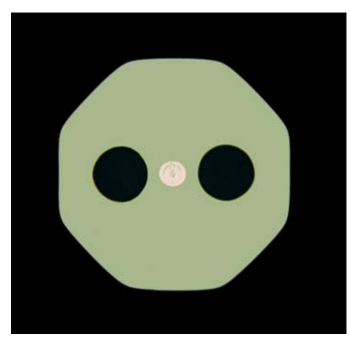


Figure 1. Theoretical simulation of bending loss in 20µm core, 400µm cladding PM fiber with 0.06 core NA and $3x10^{-4}$ birefringence. A picture of fiber cross-section is also shown.

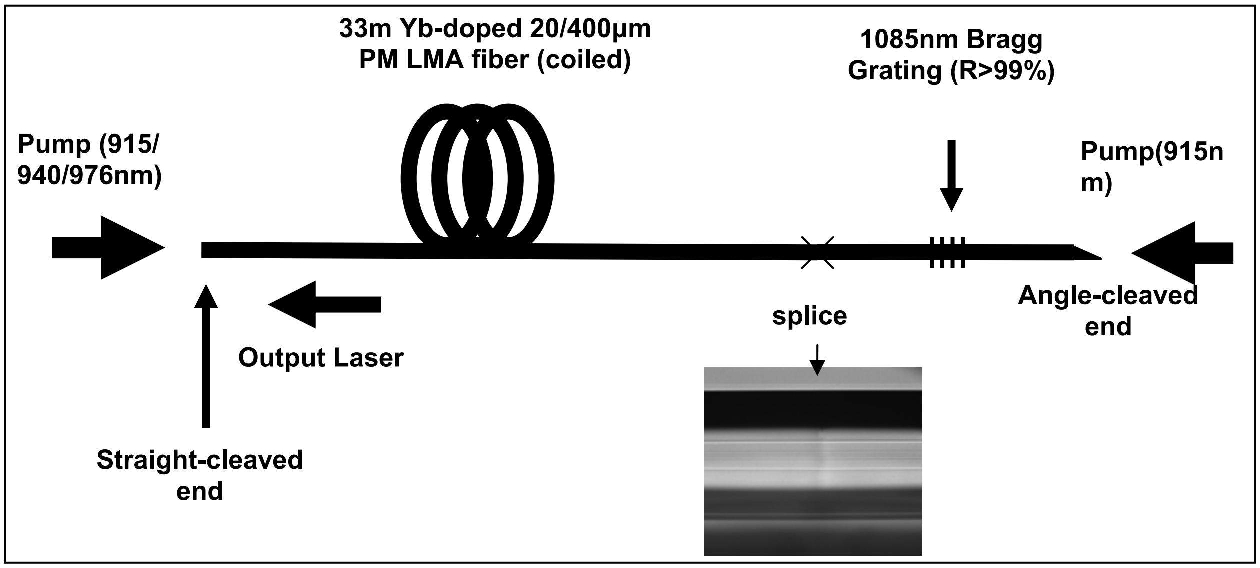


Figure 2. Experimental Setup.

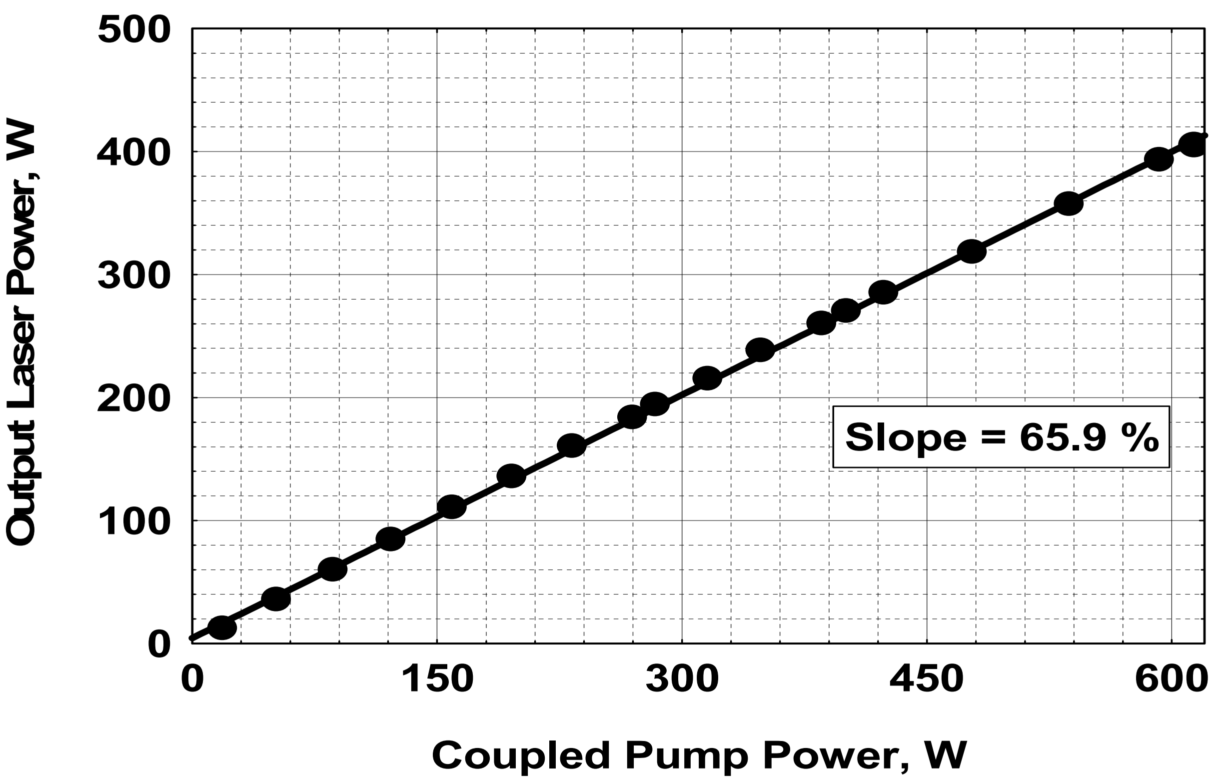


Figure 3. Measured PM laser power.

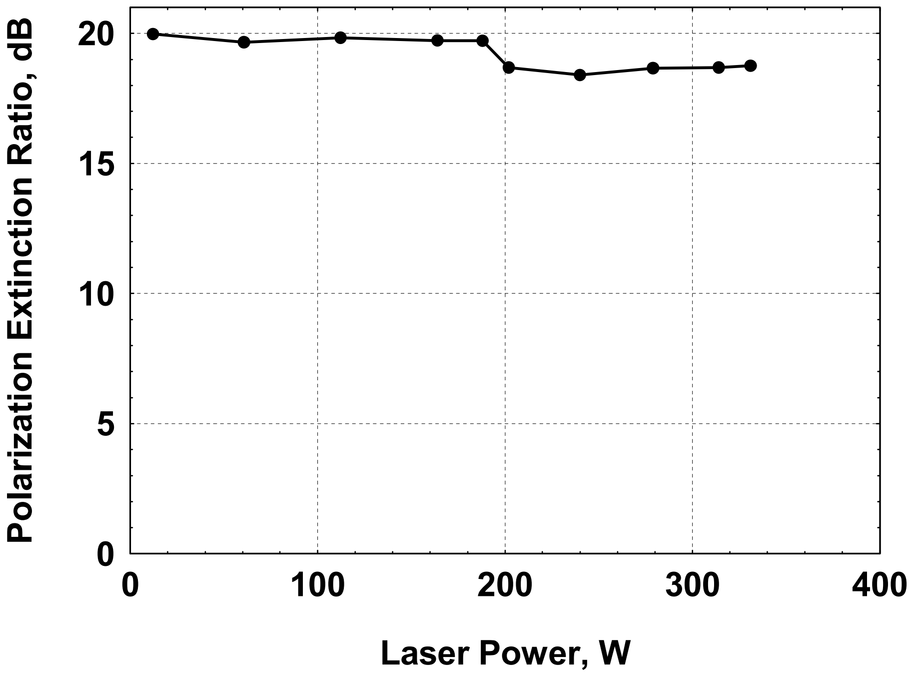


Figure 4. Measured polarization extinction ratio (PER) at different PM laser output powers.

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