

# Integrated Tm: fiber MOPA with polarized output and narrow linewidth with 100 W average power

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**Abstract:** We report on a Tm: fiber master oscillator power amplifier (MOPA) system producing 109 W CW output power, with >15 dB polarization extinction ratio, sub-nm spectral linewidth, and  $M^2 < 1.25$ . The system consists of polarization maintaining (PM) fiber and PM-fiber components including tapered fiber bundle pump combiners, a single-mode to large mode area mode field adapter, and a fiber-coupled isolator. The laser components ultimately determine the system architecture and the limits of laser performance, particularly considering the immature and rapidly developing state of fiber components in the 2  $\mu\text{m}$  wavelength regime.

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## 1. Introduction

Thulium fiber lasers have recently emerged as sources providing diffraction-limited output in the 2  $\mu\text{m}$  wavelength range. Although not capable of surpassing ytterbium fiber lasers in terms of raw power or efficiency, Tm: fiber lasers have exceeded the 1 kW average power level [1] and many commercial Tm: fiber lasers have been introduced in recent years with CW [2,3], single-frequency [3], and short/ultrashort pulse output [4]. Furthermore, the overlap of the thulium emission band with a band of low atmospheric attenuation from 2030 – 2050 nm [5] makes it useful for long-range atmospheric propagation and "eye safe" applications [6,7].

Despite these recent achievements, the development of integrated high-power Tm: fiber lasers offering quasi diffraction-limited beam quality and polarized output has been limited by the relative immaturity of appropriate fiber components. In this article, we report on a Tm: fiber master oscillator power amplifier (MOPA) system producing 109 W CW output power, with >15 dB polarization extinction ratio (PER), sub-nanometer spectral linewidth,  $M^2$  and <1.25.

Similar to recent high power Tm: fiber laser systems [1, 8–11], our system utilizes a MOPA architecture (Fig. 1) with an oscillator based upon polarization maintaining (PM) single-mode fiber and a power amplifier based on PM large mode area (LMA) step-index fiber. As in [1], we have integrated the system by splicing the pump diode delivery fibers to tapered fiber bundle (TFB) pump combiners and splicing the oscillator to the amplifier through a mode field adapter (MFA). We have also incorporated wavelength and polarization control in the oscillator, and we utilize a fiber-coupled optical isolator between the oscillator and amplifier.

## 2. Laser design and performance

### 2.1 Oscillator

In the oscillator, we make use of a guided-mode resonance filter (GMRF) to provide wavelength stabilization. These devices consist of a sub-wavelength grating (SWG), fabricated on top of a planar waveguide layer. The refractive index contrast between the wave-guiding layer and the grating layer are engineered to determine the resonance peak wavelength and linewidth. This most recent GMRF design has been improved relative to our previous work [12]. The structure now includes a 50% duty-cycle linear SWG structure, with a 1400 nm period, producing a polarization sensitive resonance. The linear grating is etched to a depth of 200 nm, on the cover layer of the planar waveguide, which is PECVD deposited silica. The planar waveguide main layer is 860 nm thick silicon nitride deposited by plasma-enhanced chemical vapor deposition (PECVD). In addition, the GMRF guiding layer includes an anti-resonant reflecting optical waveguide (ARROW) concept [13] for the lower structure (on the substrate side), as shown in the inset of Fig. 2(a). This consists of a silica/silicon nitride layer pair, 125 nm and 70 nm thick respectively. The addition of the ARROW layers allow for a symmetric spectral response around the resonance (Fig. 2), as well as a narrower linewidth. The substrate of the device is fused silica, with an added backside anti-reflection, (AR) V-coating, centered at 2000 nm. The reflectivity of the AR V-coat was measured to be less than 0.5% from 1950 nm to 2100 nm. Reflectivity simulations were performed using a rigorous coupled-wave analysis (RCWA), which projects the resonance line to be 2034 nm, with a linewidth of 1.1 nm as highlighted in Fig. 2(a).

Although the use of GMRFs requires free-space collimation and feedback, it provides a simple and flexible way to change the wavelength of the oscillator, as it is possible to

fabricate many GMRFs with specifically engineered structural variations in order to precisely select the resonant wavelength. As part of this work, we have utilized several GMRFs with resonances at wavelength between 2035 – 2045 nm. The other components in the free-space portion of the oscillator cavity include an Infrasil 26 mm focal length collimating lens and a half wave plate (Fig. 1). The intracavity fiber facet is angle-cleaved in order to prevent parasitic feedback from Fresnel reflection. Similar performance could be achieved in an all-fiber configuration using an in-line polarizer and fiber Bragg grating, but for this work we needed the ability to discretely change the wavelength of the oscillator without breaking and re-splicing fiber.

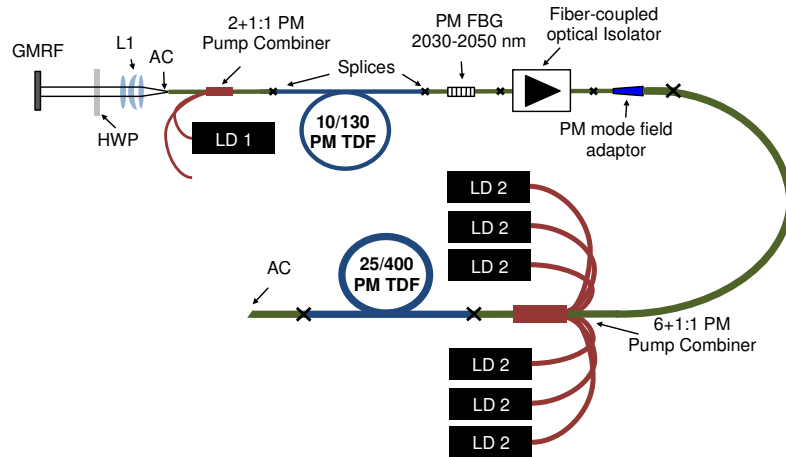


Fig. 1. MOPA laser schematic where: HWP is half-wave plate, L1 is a 26 mm focal length Infrasil triplet, AC is angle-cleaved fiber facet, LD1 is a 35 W 793 nm diode with 105  $\mu\text{m}$  diameter delivery fiber, LD2 are each 70 W 793 nm diodes with 200  $\mu\text{m}$  diameter delivery fibers.

The active oscillator fiber is a 4.5-m long section of polarization maintaining (PM) single-mode Tm-doped silica fiber with 10  $\mu\text{m}$  diameter/0.16 NA core and 130  $\mu\text{m}$  diameter/0.46 NA cladding manufactured by Nufern, and it is wrapped around a water-cooled mandrel at 13° C for thermal management. The oscillator is pumped with a DILAS Diodenlaser GmbH diode providing 35 W at 793 nm delivered via a 105/125  $\mu\text{m}$  diameter multimode delivery fiber. The diode delivery fiber is spliced to one input arm of a 2 + 1:1 TFB pump combiner manufactured by ITF Labs, in which the pass through signal fiber is matched to the PM 10/130 active fiber. As shown in Fig. 1, one end of the signal fiber of the 2 + 1:1 combiner is the fiber end in the free-space cavity portion while the other end is spliced to the active fiber. The opposite end of the active fiber is spliced to a chirped fiber Bragg grating (CFBG) from TeraXion written into a passive section of PM 10/130 fiber, which provides 20% reflectivity from 2030 – 2050 nm and serves as the oscillator output coupler.

We chose to use a CFBG to facilitate greater wavelength flexibility, as this architecture allows us to produce an output within the 2030 – 2050 nm window simply by changing the GMRF in the cavity. The linewidth is 390 pm at 10 dB below the spectral peak with a center wavelength of 2033.5 nm. The output power is 3.2 W for 12 W of launched pump, and the PER is 18 dB.

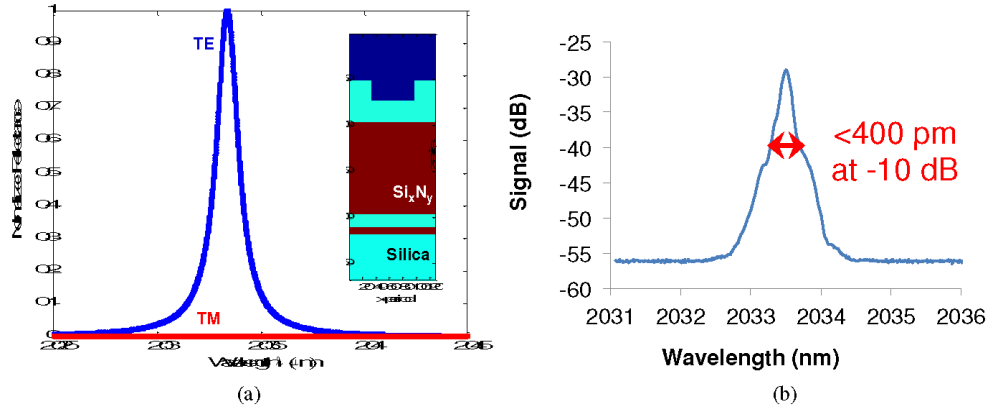


Fig. 2. (a) GMRF simulated spectral response. The insert shows the GMRF structure, with the SWG on top, the main waveguide layer below it, and the ARROW pair structure below the waveguide. The materials are color coded as: Silica-light (blue), and Silicon Nitride-dark (maroon). The TE and TM responses are labeled. (b) Oscillator output spectrum centered at 2033.5 nm. The spectral width is 390 pm at  $-10$  dB from the spectral peak.

The output of the oscillator is spliced to a dual stage fiber coupled optical isolator with PM 10/130 fiber pigtailed manufactured by Shinkosha Co., rated for a maximum incident power of 3 W with  $>55$  dB return loss, 0.5 dB insertion loss,  $>35$  dB PER. It should be noted that this level of performance has only recently become available commercially for 2  $\mu\text{m}$ , whereas large insertion loss and low optical isolation significantly complicated system design in previous integrated systems [8,9]. The output of the isolator is spliced to the input of a fiber MFA from ITF Labs, which couples the PM 10/130 fiber of the oscillator to the PM 25/400 large mode area (LMA) fiber of the amplifier. The MFA connects the oscillator to the amplifier with a minimal insertion loss of 0.5 dB and no apparent degradation of polarization. After transmission through the isolator and MFA, the output power is 2.6 W. The single mode output of the oscillator is effectively coupled to the fundamental mode of the amplifier fiber.

## 2.2 Amplifier

The amplifier is Tm-doped PM LMA fiber made by Nufern, with 25  $\mu\text{m}$  diameter/0.09 NA core and 400  $\mu\text{m}$  diameter/0.44 NA cladding. The design and glass chemistry of the active fiber have been optimized to enable 4 wt.% doping with  $\text{Tm}_2\text{O}_3$  to facilitate cross-relaxation and improve laser efficiency [14]. In order to avoid photodarkening and promote pump cross-relaxation, the active core must also be co-doped with aluminum [15]; however, this in turn increases the refractive index of the core to a level where guidance would be highly multimode. Thus, the fiber design includes a high-index pedestal around the core such that the active core NA is 0.09 while the NA difference between the core and the non-pedestal cladding is  $>0.14$ . This combination of 0.09 NA and 25  $\mu\text{m}$  core diameter supports  $\text{LP}_{02}$  and  $\text{LP}_{11}$  higher order transverse modes. Recent  $S^2$  measurements indicate this higher mode content is  $\sim 5\%$  of the total power for 11 cm coiling diameter [16].

The amplifier is pumped with six individual 80 W, 793 nm diodes manufactured with 200/220  $\mu\text{m}$  diameter multimode delivery fibers manufactured by QPC Lasers. The diode delivery fibers are spliced to the input arms of a 6 + 1:1 tapered fiber bundle (TFB) pump combiner manufactured by ITF Labs, consisting of six pump input fibers with 200  $\mu\text{m}$  diameter/0.22 NA and a signal pass through fiber matched to the active PM LMA 25/400. The maximum available pump power is limited by the 300 W power rating of the TFB and the experimentally measured 75% pump coupling efficiency; however the fabrication of such TFBs is rapidly improving in terms of power handling and coupling efficiency.

As shown in Fig. 1, the output of the MFA is spliced to the input of the 6 + 1:1 pump combiner with little reduction in PER or mode quality. The pump combiner output is spliced to a 4-m length of Tm-doped PM 25/400 and the opposite end of the active fiber is spliced to a 1-m length of passive fiber. The active fiber is wrapped around an 11 cm diameter mandrel, and the mandrel and fiber splices are water-cooled for thermal management. The output facet is angle-cleaved to prevent feedback.

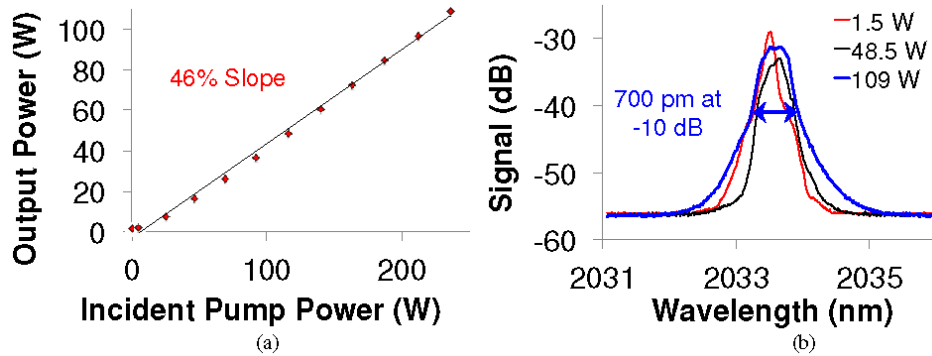


Fig. 3. (a) Amplifier output power vs. pump power with 49% slope efficiency; (b) Output linewidth as a function of output power, the width at maximum power is 690 pm at 10 dB below the spectral peak.

The slope efficiency of the amplifier is 46% with respect to launched pump power, Fig. 3(a), and the output linewidth broadens during amplification from 390 pm FW(-10dB)M to 690 pm FW(-10dB)M at 109 W output power, Fig. 3(b). The output PER is consistent and >15 dB up to the maximum power. The degradation of PER from 18 dB in the oscillator to >15 dB in the amplifier is primarily the result of ~6% of the total output light trapped in the cladding. The output beam quality, including cladding light, has an  $M^2$  of 1.19 and 1.25 along X and Y axes respectively (Fig. 4). During amplification, the  $M^2$  increases slightly from a value of 1.15 at 10 W output power.

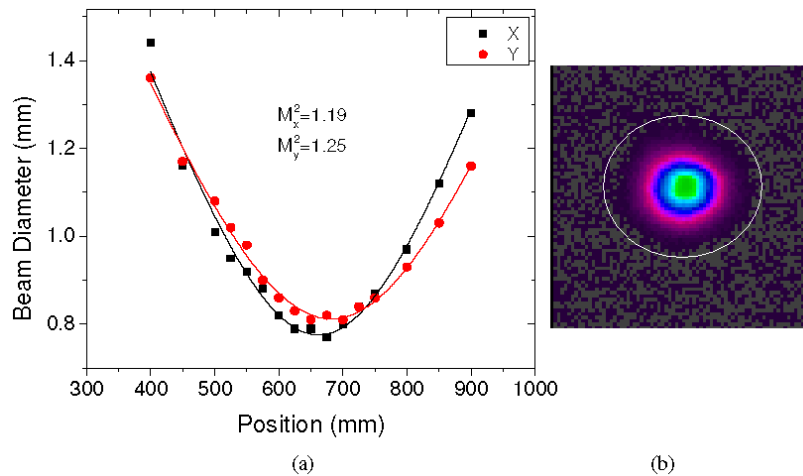


Fig. 4. (a) Beam quality measurement data, corresponding to an  $M^2$  of 1.19 along X and 1.25 along Y; (b) Near field beam profile of the output at 109 W.

While the 46% slope efficiency demonstrates efficient cross-relaxation, it is lower than achieved in [11] at the same wavelength with bi-directional pumping. In these experiments, we did not investigate counter or bi-directional pumping due to the risk of damage to the TFB.

The significantly higher absorption of the polymer coating at 2  $\mu\text{m}$  relative to 1  $\mu\text{m}$  make TFBs much more susceptible to catastrophic damage from scattered signal light for in Tm: fiber relative to Yb: fiber. This is aggravated in counter or bi-directional pumping by scattering caused by the splice between active and passive fibers. Finally, although  $>1$  kW average power has been achieved using TFBs in a non-PM Tm: fiber laser system [1], the integration of the PM pass-through fiber complicates the design and fabrication of the TFB. As such, to the best of our knowledge, the 109 W polarized output presented in this work represents the highest power achieved from an all-fiber amplifier using PM Tm-doped fiber.

### **3. Conclusion**

We describe the performance of an integrated Tm: fiber MOPA laser system. The  $>100$  W average power, linearly polarized output, and narrow linewidth demonstrate that fiberized PM components have matured significantly for operation in the 2  $\mu\text{m}$  wavelength regime. Further power scaling is primarily limited by the high power TFB pump combiner used in the amplifier. While non-PM pump combiners have proven easier to fabricate due to the absence of stress applying structures in the signal pass-through fiber, further improvements are required in PM systems particularly for pulsed lasers and to limit performance fluctuations resulting from environmental changes. Improvements in the power handling and pump coupling efficiency of PM TFBs will enhance available pump power, and should enable to fabrication of amplifiers with more efficient cross relaxation and overall optical efficiency.

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