Latest developments in high power, tunable, CW, narrow line thulium fiber laser for deployment to the ISTEF

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ABSTRACT

We have designed and developed a grating based thulium (Tm) doped fiber laser with ~150 nm tuning range which is used as the master oscillator in a master oscillator power amplifier (MOPA) thulium fiber laser system. Due to thermal instability in the grating used for tuning, the MO could produce a power up to 4.5 W, beyond which the oscillator became unstable. Injecting the seed laser into a bidirectionally pumped large mode area (LMA) Tm fiber amplifier, a stable, tunable, narrow linewidth high beam quality amplified signal of >100 W was achieved. In the absence of stable and sufficiently high power from the seed laser, the amplifier could not be tested to its full potential. The amplifier was also, converted into an oscillator to investigate its power handling capability. An excellent beam quality and ~200 W of power were achieved by running the power amplifier as an oscillator. Operation stability of the oscillator was measured to be more than one hour with a minimum power fluctuation of 0.5%. Currently efforts are underway to increase the seed laser power to ~10 W, large enough to reduce ASE and mitigate feedback to the master oscillator to demonstrate a 200 W, tunable (150 nm) and narrow linewidth (0.15 nm) MOPA system.

The MOPA system will be one of a number of new state-of-the-art high power lasers to be located at the Innovative Science & Technology Experimentation Facility, creating a unique laser range facility for next generation studies and tests across a broad range of sciences and technologies.

Keywords: Fiber laser, Amplifier, Tunable laser, Thulium, Eye-safe, MOPA, Atmospheric Propagation, ISTEF

1. INTRODUCTION

The rapid increase in the use of laser emission in open environments demands that operating wavelengths are chosen appropriately to ensure the eye safety of those at risk of exposure. Wavelengths beyond 1.4 μm fall in the retina-safe, or more popularly known as eye-safe, region of the electromagnetic spectrum. Trivalent thulium (Tm) is interesting as a laser dopant due to the fact that its emission spectrum spans from 1.8 μm to beyond 2.1 μm. Thulium fiber lasers, in particular, are especially suitable for several applications, as their inherent excellent beam quality and its 2 μm wavelength enables long distance propagation through the atmosphere due to low absorption spectral windows in the 2 μm range. In addition, lasers based on Tm can generate up to two laser photons for every absorbed pump photon due to well-known two-for-one cross-relaxation process, resulting in the potential for twice the pump quantum efficiency.

Shown in Fig. 1 is atmospheric transmission spectrum calculated using MODTRAN [1]. Both path transmission and path radiance for the atmospheric conditions along a path 45° relative to the ground in Central Florida between 2.0 and 2.1 μm are shown. It should be noted that the spectrum is produced from MODTRAN, which has 1 cm^{-1} resolution. This should be re-performed using LINTRAN, which has higher spectral resolution needed for laser line analysis. The MODTRAN result, however, gives a general trend and has enough information for the proposed atmospheric propagation study. The spectrum reveals that there are at least two atmospheric transmission windows within the gain region of the Tm ion. So, narrow linewidth light matched to the peak transmission will require less power for such investigations which, in turn, makes operating a laser safer in open environments. A tunable laser system will help meet the challenges associated with the variability in the atmospheric transmission window due to the fact that atmospheric transmission is a function of weather conditions and physical locations.

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In addition to the narrow linewidth and tunability requirements, the laser system for multi-km atmospheric propagation studies must meet other stringent requirements such as power stability, and good beam quality. A portable system will be useful as it can be easily moved in and out of the laser laboratory. Preliminary calculations indicated that 200 W of laser power will be sufficient for such experiments.

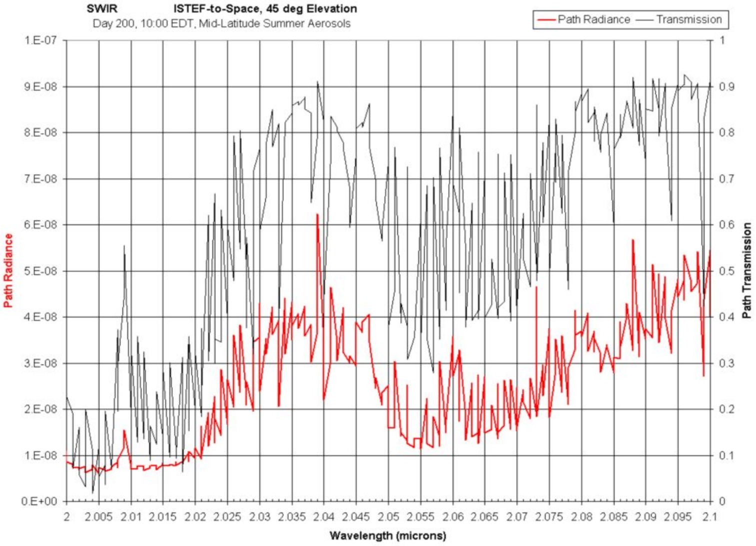

Fig. 1: Atmospheric transmission spectrum in the vicinity of 2 μm

The Innovative Science & Technology Experimentation Facility (ISTEF), a laser ranging facility on the Air Force property on south Merritt Island, close to Kennedy Space Flight Center in Central Florida, has long been used by the University of Central Florida (UCF) scientists, students and engineers for a wide range of laser experiments. The operation of this facility, currently performed by an outside contractor to Missile Defense Agency (MDA) through Space and Naval Warfare Systems Command (SPAWARS) will soon be taken over by the Townes Laser Institute of UCF, under a Cooperative Research and Development Agreement (CRADA). This will allow far greater use of the facility by UCF, other universities and university consortia, and defense laboratories and contractors. Classified studies can also be performed at this facility. The ISTEF is a fully equipped laser range facility with > 10 km range, of which 1 km is fully secured. Fig 2 shows a bird's-eye view of the ISTEF facility, showing the laser lab and the dome containing the transmitter and receiver (not shown in the figure).

Fig. 2: A bird's eye-view of the ISTEF, showing the laser laboratory and the dome containing the transmitter and receiver.

A master oscillator power amplifier (MOPA) design for the laser system is selected due to the difficulties associated with implementing a tunable oscillator system at the required 200 W power. A grating based tunable oscillator system operating at 200 W puts high demand on the heat handling capability of the grating due to absorption in the metal coating. In addition, since a commercially available grating is only ~75% reflective, it negatively impacts the overall efficiency of the oscillator. Finally, due to the relatively low spatial dispersion of diffraction gratings at 2 μm and large fiber core sizes, a relatively wide bandwidth will be reflected into the fiber from the grating in the Littrow condition, thus the linewidth of the laser would be relatively large (on the order of 0.5 – 1 nm) when operating at high powers which is undesirable for the application for which this laser is intended. A MOPA system, on the other hand, removes these drawbacks, by using a grating based tunable seed laser with the desired spectral characteristics at modest powers, reducing the demand on the thermal handling capability of the grating. Efficiency is sacrificed due to the grating in the low power master oscillator rather than in the overall high power system, thus making the high power pump diodes more effective in the power amplifier and thus reducing the heat load on the system as a whole and opening the door for further power scaling by addition of pump power or amplifier stages.

In this paper we present the latest progress and associated issues in the development of tunable, high power, continuous wave, narrow linewidth thulium fiber laser based MOPA system for deployment to the ISTEF facility. The deployment of this new, state-of-the-art laser system to ISTEF will broadly increase its capabilities and potential for laser ranging in the atmosphere and near space. This laser will be, to our knowledge, the first high power (>200 W) tunable (> 150 nm), narrow linewidth (< 0.15 nm) laser operating at a wavelength of 2 μm, a spectral region rich in atmospheric molecular absorption features, for laser propagation, sensing and related studies.

2. EXPERMENTAL SETUP

Shown in Fig 3 is a schematic of the MOPA setup consisting of a tunable seed source at a moderate power level (master oscillator) and a bidirectionally pumped single pass power amplifier. In the following paragraphs we describe the seed source and the power amplifier in greater detail.

2.1 Tunable Seed Source: The octagonal shaped Tm doped silica fiber (400 μm flat-to flat, 0.46 NA octagonal shaped cladding and a 25 μm diameter, 0.08 NA circular core) used in developing the seed source was ~5 m long and with ~2 m section of undoped NA and core size matched fiber spliced on each end to mitigate thermal stress on the directly end-pumped fiber. The cross-relaxation efficiency of Tm ions is highly temperature dependent and hence the 5 m gain region of the fiber was wrapped around a water-cooled 11 cm diameter aluminum heat sink (~14 C). Both ends of the fiber were sandwiched between water-cooled copper clamps. The intracavity end of the fiber was angle-cleaved (~10 deg) whereas the output end of the fiber was spliced to a mode field adapter (MFA), fabricated using 25 μm/400 μm core/clad, 0.105 NA fiber tapered down to match the mode field diameter of 9 μm/125 μm core/clad, 0.13 NA single mode fiber (SMF). This SMF was subsequently perpendicularly cleaved to provide laser feedback. The laser resonator was formed on one side by the Fresnel reflection from the cleaved end of the SMF fiber and on the other side by a 50 mm focal length uncoated achromat lens followed by a grating blazed at 1850 nm oriented in the Littrow configuration to provide tunability. 40 W of 795 nm diode light from 0.22 NA, 400 μm core fiber was launched through a dichroic mirror M1 designed to be broadband HT at 2 μm and HR at 795 nm at a mirror angle of ~22°.

2.2 Power Amplifier: The bidirectionally pumped, single pass > 200 W power amplifier consisted of ~6 m of the same Tm doped LMA fiber as was used in the seed source. Matching ~ 2 m long undoped fibers were spliced to both ends of the active fiber to reduce thermal issues in the fiber. The fiber is also wrapped around an 11 cm diameter water-cooled to ~14 C aluminum mandrel. Thermally conductive paste was applied to the mandrel and the fiber to further improve heat extraction efficiency from the amplifier module. The passive fiber ends were placed in V-grooves in two water cooled ~ 50 mm long copper blocks and held in place by copper cover plates in order to avoid thermal damage to the polymer coatings caused by absorption of stray pump light. The output end of the fiber had a large angle-cleave to increase the oscillation threshold and direct ASE away from the master oscillator, reducing the immediate need for an isolator between the seed laser and the power amplifier.

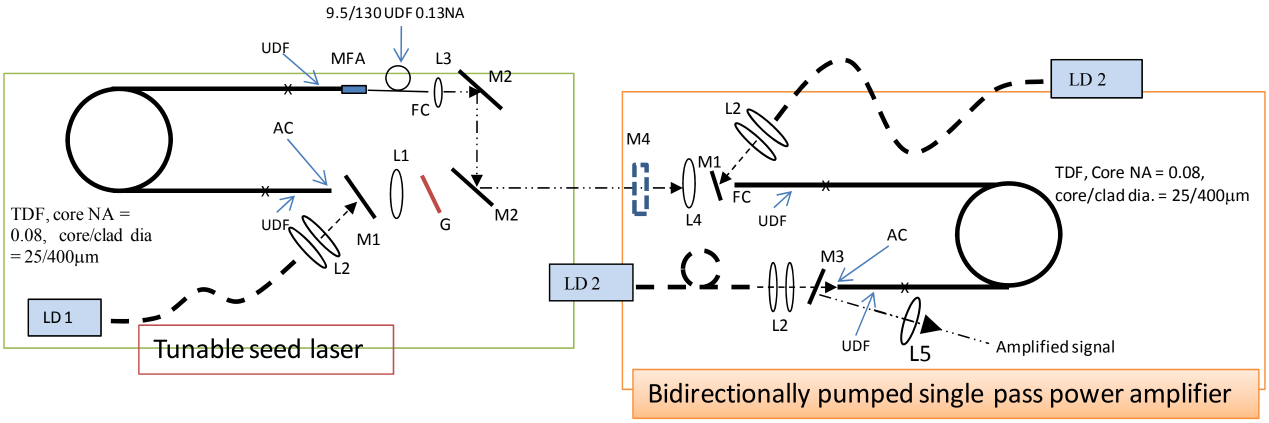

Fig. 3: Schematic of the Master Oscillator Power Amplifier (MOPA) system. Legends: AC- angle cleave; FC- Flat cleave; TDF- thulium doped fiber , UDF- undoped fiber, M1- dichroic mirror HR 790 nm and broadband HT 2 µm, M2- dichroic mirror HR 2 µm and HT 790 nm, M3- broadband HR 2 µm at a ~22° angle, M4- HR 2 µm mirror location to make the PA into an oscillator with a flat cleaves on both end of the fiber, G- 600 l/mm diffraction grating, L1- 50 mm FL uncoated achromat; L2- 100 mm FL 5 cm diameter NIR achromat; L3- 26 mm FL aplanatic triplet; L4- 50 mm FL aplanaitc triplet, L5- output collimating lens, X - splice, LD1- 40 W Spectra Physics fiber coupled diode, LD2 – 300 W LIMO fiber coupled diodes. Line codes: Dashed line- pump delivery fiber; Continuous line- Doped and Undoped fiber, Thin dashed line - pump light, and Long dash dot dot line – 2 µm light.

For the single pass 200 W power amplifier, a train of lenses and dichroic mirrors (HR at 2 µm) were utilized to match the spot size and the NA of the core of the SMF to that of the amplifier gain module. The stable, narrow linewidth, tunable seed laser light was coupled to the amplifier through dichroic mirrors M2 at ~45°. The dichroic mirror M2 which is broad band HR at ~2 µm and HT at 790 nm allows the seed laser to reflect and to transmit the pump laser. Pump light was coupled to the FC end of the amplifier by a dichroic mirror M1. The pump coupling efficiency in this configuration was measured to be 70-75%. Output from the amplifier is taken by reflection off of a dichroic mirror M3 that is HR at 2 µm and HT around 790 nm. The HT at 790 nm allows the pump light to be launched straight into the output end of the amplifier. The maximum power available at the output end of the delivery fiber of the fiber coupled (400 µm core, 0.22 NA), cladding mode stripped 793 nm diodes was ~320 W. It should be noted that when testing the power amplifier as an oscillator, a broadband HR at 2 µm (M4) was inserted (Fig 3).

3. RESULTS AND DISCUSSION

3.1 Tunable seed laser: Performance of the tunable seed laser is shown in Fig. 4 which shows slope efficiencies with respect to the incident pump power, and corresponding lasing thresholds, at various laser wavelengths starting from ~1945 nm to ~2100 nm. The slope efficiencies were relatively low (25-45%) compared to earlier published slope efficiencies for Tm fiber lasers of > 60% [2]. The lower values are due to insertion of the MFA in the cavity, which adds non-uniformly distributed losses on the fiber modes. In addition, there are a combination of other losses in the cavity namely, the lossy intracavity lenses, dichroic mirror, and 70-80% grating reflectivity. A typical laser linewidth had a FWHM of <150 pm, as measured on the optical spectrum analyzer (Yokogawa AQ 6375).

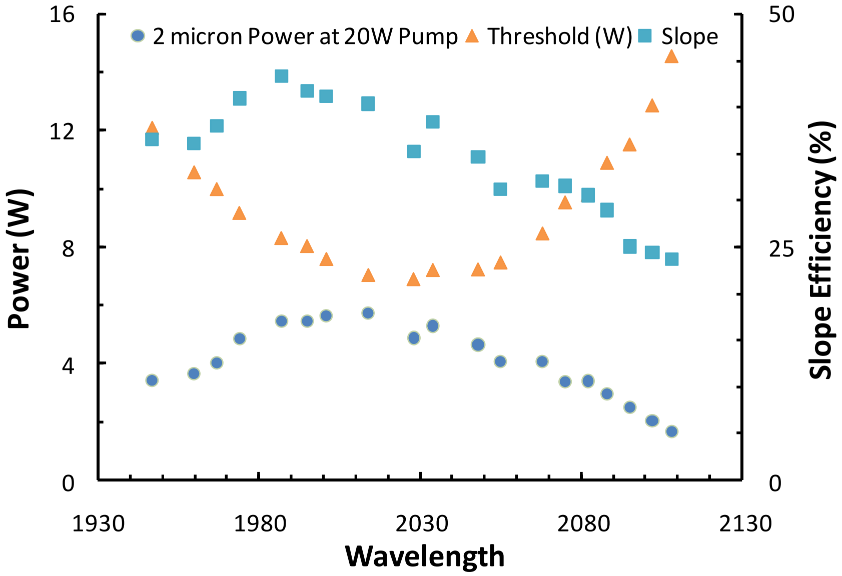

Fig. 4: Performance of the seed laser. The slope efficiency is with respect to the launched pump power.

The seed laser output power (~2 W to ~ 6 W) is limited by stability of the laser over time due to thermal misalignment of the grating. The highest possible pump power (20W of launched pump power) allowed stable operation over the entire spectrum and was selected for use in the tuning curve. Wavelengths, at long and short ends of the measured spectrum had significantly higher laser thresholds, resulting in their lower output power at the fixed pump power.

3.2 Master Oscillator Power Amplifier system: Approximately 4.5 W of seed was injected in the power amplifier. The maximum achieved amplified power was 115 W, a gain of ~14 dB, at wavelengths of 1974 and 1995 nm. Fig. 5 shows the amplifier performance (slope efficiency, output power, and amplifier gain) at various wavelengths. Slope efficiencies with respect to the launched pump power at lower wavelengths (1974 nm and 1995 nm) are identical (62%). The amplifier was tested over the tuning range of the seed laser where more than 4.5 W of power was available (1974 – 2075 nm). The amplified powers reached >100 W levels and have slope efficiencies between 52% and 63% with the shorter wavelengths tending to have higher slope efficiencies, due to the significantly higher emission cross section in thulium at these wavelengths. Fig 5 shows that at longer wavelengths (2055 and 2075 nm), the amplified output powers are lower than powers at shorter wavelengths. This is due to lower emission cross-section, and lower output mirror reflectivity at the longer wavelengths. Power levels were limited to ~100 W due to instability induced by signal and ASE feedback to the seed laser, limiting the maximum gain to ~14 dB. At longer wavelengths, this instability was more severe and further limited the maximum output power. Based on slope efficiency at 2055 and 2075 nm the output power can be extrapolated to show that 100 W levels would be reached if the same maximum pump power were used. Installation of an optical isolator between the seed laser and the amplifier will improve system performance. The laser emission spectra from the amplifier were found to be similar in linewidth to that of the seed and there was no measurable drift in wavelengths, and very low percentage of ASE.

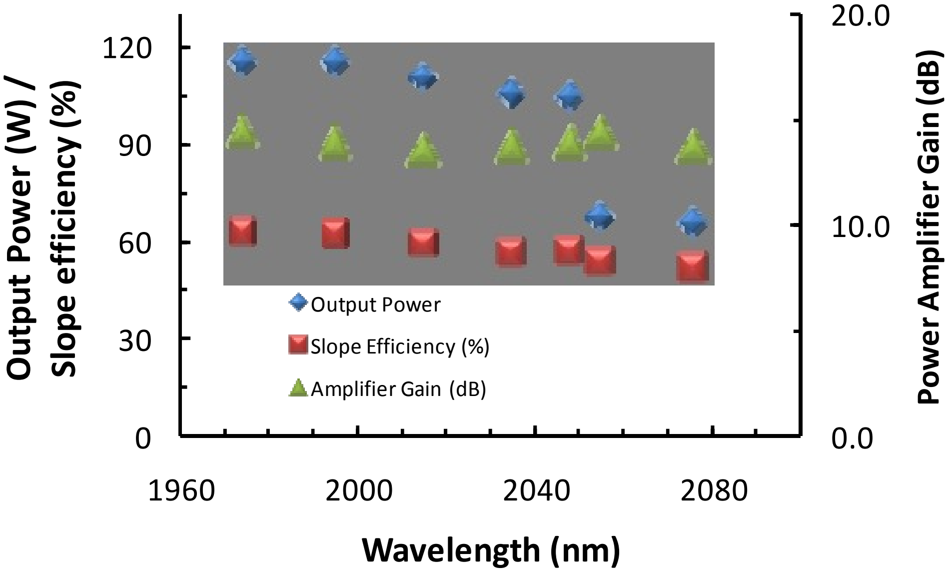

Fig. 5: MOPA system performance. The slope efficiency is with respect to the launched pump power.

3.3 Power amplifier stability tests: As discussed in section 3.2, the amplifier could not be operated at its full potential due to the lack of sufficient stability and high seed power to saturate the amplifier. To meet the goals of the ISTEF atmospheric propagation experiment, a tunable, narrow linewidth, eye-safe 200 W laser is required. Tests confirming the amplifier module's thermal handling capability and its slope efficiency were preformed in preparation for future. The amplifier module was converted into an oscillator by flat-cleaving the angle cleaved end of the fiber and inserting a broadband HR mirror H4 at 2 μm as shown in Fig 3 by dotted line. The other parameters and physical design remained the same to that of the amplifier.

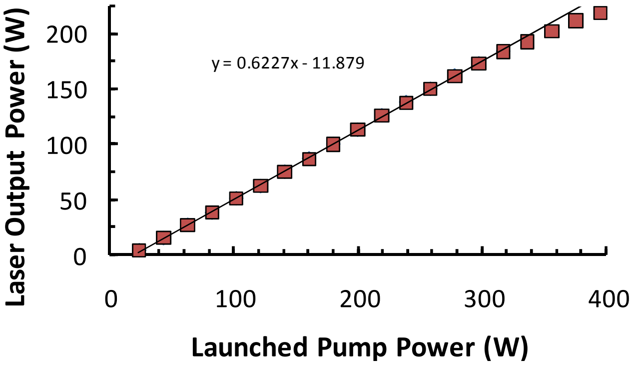

Fig. 6: PA in oscillator configuration output power vs. pump power**.**

Shown in Fig. 6 is the slope efficiency of the amplifier tested as an oscillator with respect to the incident pump power. As expected, the laser linewidth is very broad containing several randomly fluctuating peaks around the 2030 nm lasing wavelength, which is red-shifted from the 1930 nm ASE peak by re-absorption losses in the Tm fiber. At the highest powers the pump diode wavelength drifts from optimal absorption, resulting in decreased pump absorption and a roll off in slope efficiency. The slope efficiency of the oscillator was > 62% with respect to launched pump power.

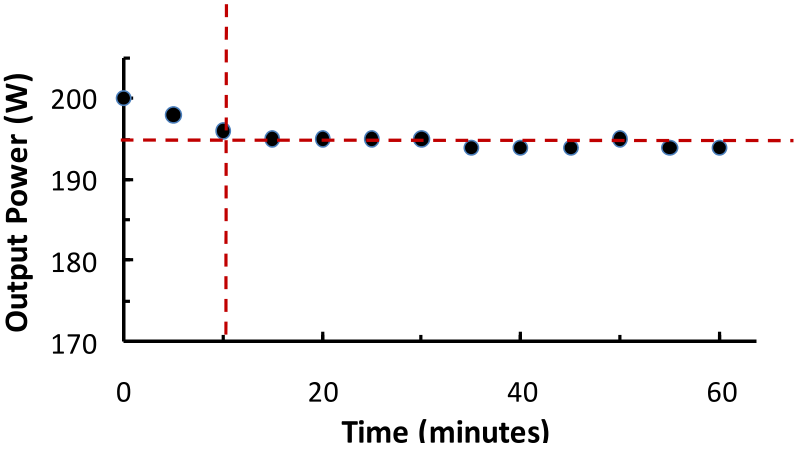

Fig. 7: Power stability curve for the 200 W amplifier-converted-oscillator.

Since the MOPA needs to operate stably over 15-20 minutes to make atmospheric measurements, the stability of the system was tested for 60 minutes to ensure a stability cushion. There was an initial temperature stabilization which took ~10 min (shown in Fig. 7 by the vertical line). After the stabilization, the laser operation was very stable and output power remained at 195 W (a fluctuation of 0.5% was measured as shown in Fig 7 by the horizontal line. The amplifier-converted-oscillator experiments demonstrate that with the enough seed power to saturate the amplifier, we should be able to easily demonstrate a tunable, narrow linewidth MOPA at the desired power of 200 W.

The M^2 of the amplifier output was measured using the NanoMode Scan (Photon Inc) and was found to be <1.2 in both axes for powers up to 100 W. The knife edge technique was used as opposed to the standard second moment diameter technique as recommended by the International Standard Organization [3] due to the fact that the cladding light was producing errors in the measurement with the second moment technique.

4. CONCLUSIONS AND FUTURE WORK

We have demonstrated a MOPA system based on a low power, tunable over more than 150 nm, narrow linewidth seed source pumped high power Tm doped- LMA fiber amplifier. The amplifier output maintained its beam quality at high powers and also maintained the narrow linewidth of the seed laser. The issues related to the seed laser stability and potential solutions were discussed. Many issues including use of a copper substrate gold coated metal grating (for better thermal management), PM fiber for laser output with stabilized polarization to ensure efficient operation of an isolator, optics with correct AR coatings, and usage of 2-μm isolators between seed laser and amplifier are currently being implemented. Due to low seed power, the amplifier could not be sufficiently saturated and the seed was susceptible to feedback from the power amplifier and hence the full potential of the amplifier could not be tested. However, the measurements on the power amplifier run as an oscillator indicated that once a stable seed laser of the order of 10 W and insertion of an isolator will produce a good beam quality (M^2~1.2), high power (~200 W) and tunable narrow linewidth MOPA. The power trend of the power amplifier running as an oscillator was stable within 0.5% for one hour after initial 10 minutes of stabilization. The MOPA system will soon be integrated into the atmospheric propagation test system at ISTEF for the multi-km atmospheric transmission measurement experiments.

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