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Spectral beam combining of 2 μm Tm fiber laser systems

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ABSTRACT

Output beams from three independently frequency-stabilized thulium master-oscillator power-amplifier fiber laser systems were spectrally combined using a plane-ruled metal diffraction grating. Two laser channels were frequency-stabilized with guided mode resonance filters and the third was stabilized using a plane-ruled metal diffraction grating. The systems had output wavelengths between 1984 and 2015 nm, each with a spectral width of 100–450 pm and output powers between 40–120 W. The combined beam had powers up to 49 W and was 32% efficient with respect to the launched pump power.

1. Introduction

Interest in high average power (kW level) lasers with excellent beam quality for directed energy applications, remote sensing, and materials processing is growing steadily. In many cases these applications require long distance propagation through the atmosphere where there is a risk of eye exposure due to reflected or scattered laser light. The exposure risk associated with such applications requires lasers operating in the eye-safe wavelength regime where few high power laser sources are currently available.

Thulium emits at eye-safe wavelengths so it is attractive for applications that involve exposure risks. Tm fiber lasers possess all the characteristic advantages of the fiber laser architecture: excellent thermal management, high efficiency, and near-diffraction limited beam quality. Advantages unique to Tm include its wide range of laser emission (1.8–2.1 μm), and readily available high power 790 nm pump diodes. Optimization of the Tm concentration allows efficient excitation by 790 nm light [1], taking advantage of the well-known cross-relaxation process that can occur between adjacent Tm ions [2]. Through this process, Tm lasers can achieve optical efficiencies greater than the Stokes limit (~40%) and approach the theoretical limit of ~80%.

Despite the potential efficiency of fiber lasers, scaling the power of a single laser channel to the multiple kW level and beyond is constrained by single fiber aperture size [3]. Nonlinear effects such as stimulated Brillouin and stimulated Raman scattering, as well as damage to the fiber core, limit the maximum achievable power [4]. The current power record for a Tm fiber laser is 1 kW [5] approaching power levels where thermal effects limit further power scaling. The primary issue is the heat induced by non-radiative decay related to both the quantum defect and quantum efficiency [4]. Even with efficient 2-for-1 cross relaxation when pumping with 790 nm light, the non-radiative heat load in Tm fiber is several times higher than for Y fiber which in turn limits the maximum power that can be generated from a single aperture Tm fiber laser system. In recent efforts to reach the 100 kW power-level, several methods have been investigated to circumvent single-aperture limitations by combining the beams from several lasers into a single beam [6].

The two most prominent methods for beam combining are coherent and spectral [7]. Spectral beam combining (SBC) uses two or more laser channels at slightly different wavelengths and either a diffractive or a wavelength selective element to spatially overlap each wavelength channel into a single beam while maintaining the nearly diffraction-limited beam quality of the individual channels. The highest power SBC demonstrations to date have utilized Yb fiber lasers at 1 μm [8] with up to the 2 kW in the combined beam [9]. Also using Yb fiber lasers, ns pulses has been combined to a maximum average power of 208 W and a combined pulse energy of 6.3 mJ [10].

In the 2 μm wavelength regime, one previous SBC experiment has been conducted using Tm fiber [11]. In this system, four separate fiber laser beams transmit through a transform lens onto a diffraction grating which functioned as a common output coupler for the four oscillators. Using this approach to combination produced a beam with 14 W of combined power for ~85 W of pump. Here we present SBC of three Tm master-oscillator power-amplifier (MOPA) systems with two of the channels spectrally stabilized by guided mode resonance filters (GMRF).

2. Guided mode resonance filters

SBC require multiple channels with spectrally stabilized narrow linewidth output to avoid issues of spatial dispersion and adverse effects related to beam quality. GMRFs are sub-wavelength diffractive

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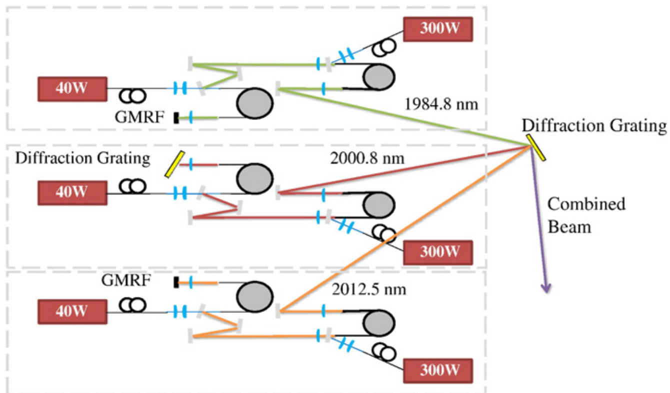

Fig. 1. Schematic of three channel beam combination.

waveguide structures, which provide spectral selection and stabilization [12]. While a variety of components such as volume Bragg gratings, diffraction gratings, and fiber Bragg gratings enable spectral control, GMRFs allow high quantity production with deterministic spectral control of the filters. The ability to deterministically control wavelengths enables production of multiple filters with tight wavelength spacing over a large bandwidth. GMRFs are used for two of the master-oscillators in this demonstration. The structure of the GMRFs is engineered such that waves at normal incidence on a GMRF's surface are diffracted into multiple evanescent diffractive orders by a sub-wavelength diffractive array of holes in the top layer. The layer below the diffractive array of holes acts as waveguide structure for only one of the diffracted orders while all the rest pass through unguided. Due to the index modulation formed from the array of holes, the mode confined in the waveguide leaks back and provides resonant feedback to incident beam [13]. By carefully selecting values for each of the structure's parameters the peak reflectivity, linewidth, and central wavelength are controllable. When used as an external feedback element, output linewidths ranged from 50–400 pm depending on output power. GMRFs have been used as external feedback elements for 1 W power levels at 1.55 μm wavelengths [12] and for 10 W power levels at 2 μm wavelengths [14].

3. Experimental setup

Both oscillator and amplifier stages of the three frequency-stabilized MOPA lasers contained 4–5 m of Tm doped (4 wt.%) large mode area fiber (Nufern 25 μm 0.09 NA circular core and 400 μm 0.46 NA octagonal cladding) (Fig. 1). The oscillator cavities were completed using a highly reflective element and the 4% Fresnel reflections from a flat cleaved fiber; the fiber facet directed at the highly reflecting element was angle-cleaved (8°) to mitigate parasitic lasing. Two of the laser oscillators were frequency stabilized by GMRFs at wavelengths of 1984.8 and 2012.8. The third laser was stabilized by a thermoelectrically-cooled gold-coated copper reflection grating with a ruling of 600 line/mm. This channel operated at a wavelength of 2008.8 nm and had a linewidth of 100–200 pm. This source was originally designed to function as a tunable high power source for atmospheric propagation tests [15] and provided a convenient tunable laser source.

The three power amplifiers (PA) were each seeded with ~1.5 W of frequency-stabilized output from the three master oscillators (MO), and pumped by 300 W diodes (LIMO) operating at 790 nm. Both fiber facets of the PAs were angle-cleaved (8°) to mitigate parasitic lasing. Slope efficiencies of the individual PA varied between 50–60%, but M^2 values were consistently ~1.2. Each PA was capable of producing powers ranging between 40 and 120 W. An intra-stage isolator was necessary to amplify beyond 50 W, but only one of the MOPAs was so configured at the time of these experiments. The output from each amplifier was collimated with an uncoated 100 mm focal length fused-silica plano-convex lens incurring an 8% loss in output power due to Fresnel reflections.

The collimated beams traversed ~6 m with a beam diameter of 18 mm to be overlapped on the beam-combiner. The combiner was a water-cooled (14 °C) plane-ruled gold-coated copper reflection grating (600 line/mm) blazed for 1850 nm in the Littrow condition with a (manufacturer's (Richardson Gratings) specified) diffraction efficiency of ~70% for unpolarized light at 2 μm.

4. Results and discussion

The combined beam was characterized at distances of ~2 m, ~5 m and ~8 m from the combiner by observing the spatial overlap of the three beams with a Spiricon Pyrocam III (Fig. 2). Fig. 3 shows the output spectrum measured for the combined beam at 20 W with an optical

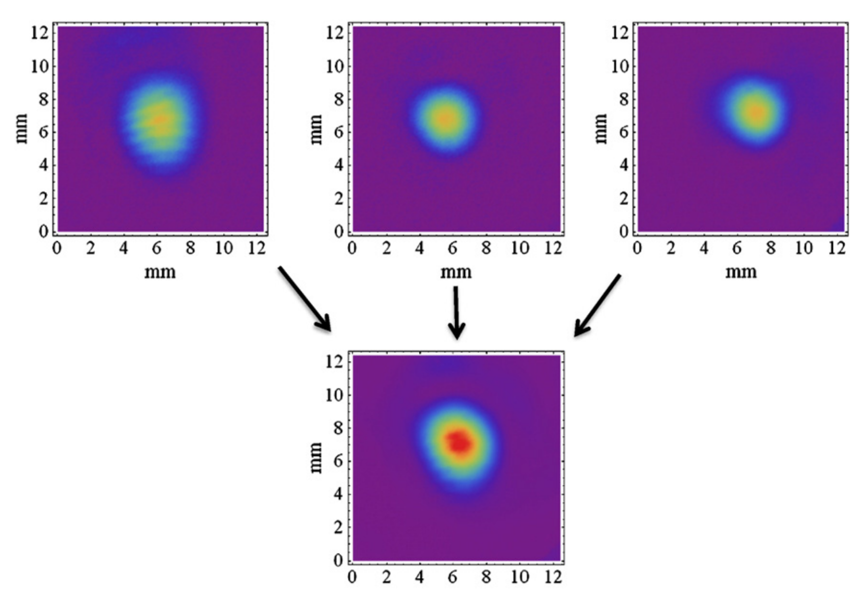

Fig. 2. Beam profiles of each channel and the combined beam 8 m from the combiner Intensity values of the large Pyrocam pixels were smoothed with software to produce cleaner images. Interference fringes on the beams are artifacts of the neutral density filters used to attenuate the beam to below the damage threshold of the camera.

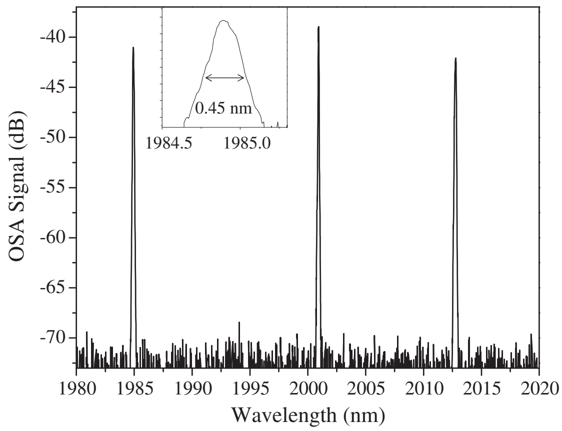

Fig. 3. Spectrum of the combined beam at 35 W. Inset shows close up of the 1984.8 line.

spectrum analyzer (Yokogawa AQ 6375). The three wavelengths (1984.8 nm, 2000.8 nm, and 2012.5 nm) from the individual lasers are clearly visible more than 30 dB above the noise floor. The maximum combined power was 49 W, with a total power of 73 W on the grating with ~25 W from each channel. The combining efficiency at 2 μm was 67%, and 32 with respect to the diode pump power in the amplifiers.

The far-field beam quality of the combined beam was characterized ~5 m from the combination grating (Fig. 4). The beam quality of each of the individual beams was measured with 20 W incident on the grating and the combined beam quality was measured at a power level of 35 W. Individual channels exhibited M^2 values of ~1.6 in the plane orthogonal to the grating plane and between 1.5–1.7 in the parallel plane. Increases in the M^2 from the individual channel measurements were expected in the plane orthogonal to the grating plane due to spatial dispersion. It is expected that the parallel plane increased due to wavefront distortion added from the sub-optimal plano-convex lenses and the multiple elements that the beam passed through. At the combined power of 35 W, thermal distortions from the combining grating and subsequent beam guiding components resulted in M^2 values of ~1.9 and ~2.6 in the planes orthogonal and parallel to the diffractive plane, respectively. This axial shift arises from astigmatism introduced by thermal lensing. It is expected that the M^2 degradation at the 35 W combined level would be present if a single channel was operating at similar levels due to the absorption and subsequent heating of the gold-coated diffraction grating causing thermal degradation.

Sub-optimal beam quality arises from multiple absorbing elements in the beam path prior to the M^2 measurement. For similar high power experiments, we have observed thermal lens effects from the absorption of 2 μm light in the fused silica lenses and optical wedges used to attenuate and guide the beam. In order to minimize these effects, less absorbing lenses and optical wedges made from materials such as Infrasil will be used in future experiments to minimize these thermal issues.

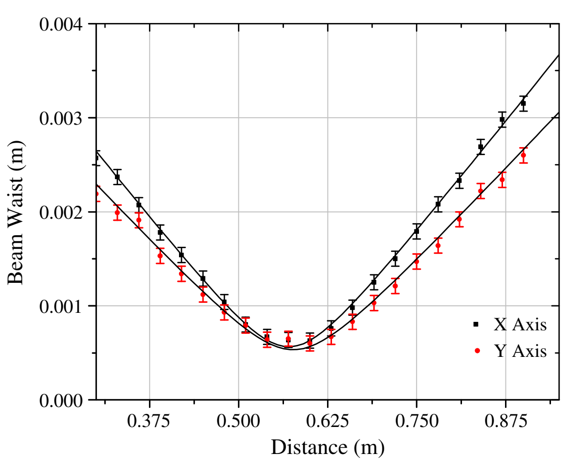

Fig. 4. Beam profile fits used to determine M^2 for the 10 W combined beam. Error bars denote accuracy of the 80 μm pixel size.

The other factor that contributed to sub-optimal beam quality was the relative pointing stability of the individual laser channels prior to combination. In the experimental setup two optical tables were used to accommodate the three laser systems. It was therefore necessary for the beams to travel ~5 m before being combined on the appropriate grating. This long path adversely affected the pointing stability, with subtle vibrations of the individual tables causing variations in the measurement of M^2 ~5 m from the combining grating (a total of 10 m from the source outputs). The small angular separation of the diffracted orders, along with the physical size of the mirrors and mirror mounts used, dictated a wavelength separation of >10 nm between the source wavelengths and a path length of 2 m between the grating and the final folding mirrors to prevent beam clipping on the opto-mechanical components.

In order to optimize system performance and further scale the combined power, a number of critical improvements need to be implemented. Incorporation of PM fibers and polarized GMRF stabilized seed lasers, in conjunction with optical isolators, will greatly assist power scaling of individual channel powers with narrow linewidths. These improvements were made to the diffraction grating based feedback system and increased the power beyond 200 W after the SBC tests were completed [15]. Amplifying a GMRF stabilized oscillator operating at 4 W in the power amplifier described in [15] resulted in average powers up to 160 W.

A combining grating with a greater efficiency and damage threshold would be able to withstand higher incident powers before thermal deformation destroys beam quality [3]. However, grating based beam combination does not facilitate closely spaced wavelengths due to the physical constraints associated with beam alignment.

Another approach incorporates long-wavelength bandpass spectral filters to combine beams via a sharp transition edge from high reflectivity to high transmission in a narrow wavelength range. This concept has been demonstrated with >90% combining efficiency [16]. This system, as well as one using a VBG as the combining element [17], has the advantage that wavelength spacing between channels can be minimized to increase spectral density. Using such architectures will facilitate scaling to the kW power level using many moderately powered individual laser systems.

5. Conclusion

In this paper we have reported on SBC of three Tm fiber MOPA systems. The SBC tests combined the three beams to a power of 49 W with a combination efficiency of 67% and with M^2_x of ~1.9 and M^2_y ~2.6 reported at 35 W. This work serves as an initial demonstration of the feasibility of SBC at 2 μm using GMRFs for wavelength stabilization of the individual channels, and to examine associated issues/limiting factors. Improvements need to be made in the combining element and in the implementation of highly transparent materials at 2 μm. Addressing these issues for use with single wavelength systems that have been demonstrated at hundreds of Watts, will push average power levels in 2 μm wavelength regime beyond multi-kW.

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References

[1] S.D. Jackson, S. Mossman, Appl. Opt. 42 (2003) 2702.
[2] S.D. Jackson, Opt. Commun. 230 (2004) 197.
[3] IPG Photonics Successfully Tests World's First 10 kW Single-Mode Production Laser, in, 2009.
[4] J.W. Dawson, M.J. Messerly, R.J. Beach, M.Y. Shverdin, E.A. Stappaerts, A.K. Sridharan, P.H. Pax, J.E. Heebner, C.W. Siders, C.P.J. Barty, Opt. Express 16 (2008) 13240.
[5] T. Ehrenreich, R. Leveille, I. Majid, K. Tankala, G.A. Rines, P.F. Moulton, in: K. Tankala (Ed.), SPIE Photonics West, San Francisco, CA, 2010.
[6] S.J. McNaught, C.P. Asman, H. Injeyan, A. Jankevics, A.M. Johnson, G.C. Jones, K. Hiroshi, J. Machan, J. Marmo, M. McClellan, R. Simpson, J. Sollee, M.M. Valley, M. Weber, S.B. Weiss, Frontiers in Optics, Optical Society of America, 2009, p. FThD2.
[7] T.Y. Fan, IEEE J. Sel. Top. Quantum Electron. 11 (2005) 567.
[8] S.J. Augst, J.K. Ranka, T.Y. Fan, A. Sanchez, J. Opt. Soc. Am. B 24 (2007) 1707.
[9] C. Wirth, O. Schmidt, I. Tsybin, T. Schreiber, T. Peschel, F. Brückner, T. Clausnitzer, J. Limpert, R. Eberhardt, A. Tünnermann, M. Gowin, E. ten Have, K. Ludewigt, M. Jung, Opt. Express 17 (2009) 1178.
[10] O. Schmidt, C. Wirth, D. Nodop, J. Limpert, T. Schreiber, T. Peschel, R. Eberhardt, A. Tünnermann, Opt. Express 17 (2009) 22974.
[11] W.A. Clarkson, V. Matera, A.M. Abdolvand, T.M.J. Kendall, D.C. Hanna, J. Nilsson, P.W. Turner, QEP-15, Glasgow, UK, 2001.
[12] A.A. Mehta, R.C. Rumpf, Z.A. Roth, E.G. Johnson, IEEE Photonics Technol. Lett. 19 (2007) 2030.
[13] S.S. Wang, R. Magnusson, Appl. Opt. 32 (1993) 2606.
[14] R.A. Sims, T. Dax, Z.A. Roth, T.S. McComb, L. Shah, V. Sudesh, M. Poutous, E.G. Johnson, M. Richardson, Photonics West LASE, SPIE, San Francisco, 2010.
[15] T.S. McComb, V. Sudesh, L. Shah, R.A. Sims, M. Richardson, in: W.A. Clarkson, N. Hodgson, R.K. Shori (Eds.), Solid State Lasers XVIII: Technology and Devices SPIE, San Jose, CA, 2009, p. 71931I.
[16] R. Kestutis, H. Kai-Chung, R. Gediminas, G. Almantas, Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies, Optical Society of America, 2008, p. CMA4.
[17] O. Andrusyak, V. Smirnov, G. Venus, V. Rotar, L. Glebov, IEEE J. Sel. Top. Quantum Electron. 15 (2009) 344.