Power scalable >25 W supercontinuum laser from 2 to 2.5 μm with near-diffraction-limited beam and low output variability

Vinay V. Alexander,[1,*] Zhennan Shi,[1] Mohammed N. Islam,[1,2] Kevin Ke,[2] Michael J. Freeman,[2] Agustin Ifarraguerri,[3] Joseph Meola,[4] Anthony Absi,[4] James Leonard,[4] Jerome Zadnik,[5] Anthony S. Szalkowski,[6] and Gregory J. Boer[7]

[1]*Electrical and Computer Engineering Department, University of Michigan, Ann Arbor, Michigan 48109, USA*

[2]*Omni Sciences Inc., Dexter, Michigan 48105, USA*

[3]*SAIC, Arlington, Virginia 22203, USA*

[4]*Air Force Research Labs, Wright Patterson Air Force Base, Ohio 45433, USA*

[5]*EOIR technologies, Fredericksburg, Virginia 22408, USA*

[6]*Booz Allen Hamilton Inc, McLean, Virginia 22102, USA*

[7]*National Geospatial-Intelligence Agency, Springfield, Virginia 22150, USA*

**Corresponding author: vinalex@umich.edu*

Received March 27, 2013; revised May 28, 2013; accepted May 29, 2013; posted May 29, 2013 (Doc. ID 187687); published June 26, 2013

A power scalable thulium-doped fiber-amplifier-based supercontinuum (SC) laser covering the shortwave infrared region from 2 to 2.5 μm is demonstrated. The SC laser has an average power up to 25.7 W and a spectral density of >12 dBm/nm. Power scalability of the laser is proven by showing that the SC laser maintains a nearly constant spectral output, beam quality (M^2 measurements), and output spectral stability as the SC average power is scaled from 5 to 25.7 W average output power. We verify that the SC laser beam is nearly diffraction limited with an $M^2 < 1.2$ for all power levels. Output spectral stability measurements with power scaling show a radiometric variability of <0.8% across the entire SC spectrum.

OCIS codes: (060.2310) Fiber optics; (060.2390) Fiber optics, infrared; (060.3510) Lasers, fiber; (320.6629) Supercontinuum generation.

http://dx.doi.org/10.1364/OL.38.002292

We demonstrate a >25 W all-fiber supercontinuum (SC) laser covering the shortwave infrared (SWIR) wavelength bands from 2 to 2.5 μm with a spectral density of >12 dBm/nm, which is the highest SC spectral density reported in this spectral range, to our knowledge. One unique aspect of this SWIR SC laser is that it is truly a power scalable laser as verified by a nearly constant spectrum, beam quality, and output stability, as the average power is scaled from 5 to 25.7 W. Average power scaling is achieved by increasing the repetition rate, and a corresponding increase in pump power helps to maintain a nearly constant peak power, resulting in a nearly constant spectral output. The SC beam quality with power scaling is studied and seen to be nearly diffraction limited with $M^2 < 1.2$ for all power levels. Output stability measurements with power scaling show a radiometric variability <0.8% across the entire SC spectrum.

SWIR light sources covering the ~1–2.5 μm wavelengths are attractive for a variety of remote sensing and medical applications. High-average-power SC laser sources covering parts of the SWIR region have been widely studied. Most of these SC lasers are ytterbium-doped fiber (YDFA)-based systems and use photonic crystal fibers for SC generation [1–3]. Recently, a 70 W SC spanning from ~1.06 to beyond 1.7 μm was reported in a nonlinear YDFA using an all-fiber master oscillator power amplifier configuration [4]. A review of high-power SC lasers using YDFA-based sources is reported in [5]. In most of these cases, the SC architecture does not allow for convenient scaling of the repetition rate and hence the average power. A gain-switched system has also generated SC spanning from 0.5 to 2.25 μm with an average power of ~12 W, corresponding to a spectral density of ~6 dBm/nm in the 2–2.25 μm region. [6].

Thulium-doped fiber amplifiers (TDFAs) have lately become of interest for mid-IR SC generation> ~2 μm [7–12]. For example, a 2.37 W SC laser spanning from ~1.75 to 2.7 μm was recently reported as the highest average power SC generated from a single-mode thulium-doped fiber [8]. In this Letter, we focus on a power scalable all-fiber 25.7 W TDFA-based SC laser specifically for the 2–2.5 μm region with a spectral density of >12 dBm/nm and study the SC beam quality and spectral stability performance with power scaling.

Figure 1 shows the optical layout of the 25.7 W SC laser. A two-stage approach is used for SC generation. The first stage consists to two ~1.5 μm amplification stages (pre-amp and mid-amp), followed by the second ~2 μm amplification stage (power-amp) and the SC

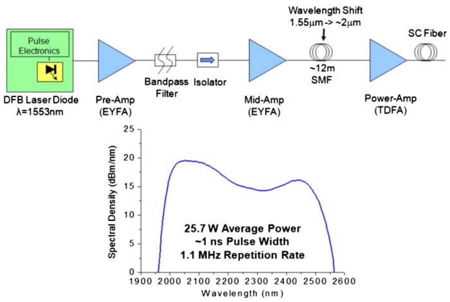

Fig. 1. Optical layout of the 25.7 W SC laser (top). 25.7 W SC output spectrum from 1.95 to 2.55 μm (bottom).

generation fiber. The amplified 1.5 μm laser source consists of a 1553 nm seed laser with an ~1 ns pulse at 1.1 MHz repetition rate amplified using two Er:Yb fiber amplifier stages, similar to the setup in [7]. Pulse breakup of nanosecond pulses into several hundred femtosecond pulses through modulation instability (MI) and long wavelength shifting through Raman processes [10] in an ~12 m standard single-mode fiber (SMF) give rise to a first-stage SC consisting of ~2 μm pulsed light components for input to the second-stage TDFA. Thus, the MI-initiated SC in the SMF eliminates the need for a mode-locked laser for high-peak-power pulse generation at 2 μm and allows the use of standard telecommunication components in an all-fiber architecture.

The entire output of the first-stage SC is then spliced onto the second-stage TDFA power amplifier stage using a mode field adapter. Mode adaptation is usually achieved by heating the fiber to diffuse the cores and/or tapering the fiber to change the core size, thus changing the size of the mode field. The goal is to preserve the energy in the fundamental mode and make the transition in the mode field adapter as adiabatic as possible [13]. The power amplifier consists of an ~8 m long 25/400 μm (core/cladding diameter) TDFA pumped by four 35 W 793 nm pump diodes coupled through a 6×1 pump combiner. By pumping the system with ~112 W in the counterpropagation configuration, we are able to generate ~25.7 W SC at the output. In this case, the 2 m 25/400 μm (core/cladding diameter) silica fiber of the combiner serves as the SC generation fiber. The corresponding SC spectrum is shown in Fig. 1 and spans from ~1.95 to 2.55 μm with an average power of 25.7 W across the entire spectrum.

The average power of the SC system is seen to be linearly scalable with repetition rate, while maintaining nearly the same spectral shape. In our SC systems, the repetition rate couples with the pulsewidth to determine the duty cycle of the laser system. The spectral width is set by the peak output power, which increases with the reduction of the pulse repetition rate, i.e., pulse duty cycle, and vice versa. Thus, by increasing the repetition rate and the pump power accordingly, we can maintain a nearly constant spectrum, while scaling up the total SC average power. This is seen in Fig. 2, which shows the linear scaling of the SC average power from 5 to 25.7 W with repetition rate, and the corresponding output spectrum at each of the power levels.

The beam profile of the SC laser with power scaling is studied by projecting the fiber output on a Spectralon target placed 1.05 m from the SC fiber output, and observing the beam profile using an SWIR camera. The camera has an indium antimonide detector and covers the spectral range from ~1 to 5 μm. The detector resolution is specified as 640×512, 15 μm pixels. For each power level, the beam profile obtained using the camera is fit to a Gaussian profile, from which the beam diameter is then extracted. For example, Fig. 3 shows the camera image of the 25.7 W SC beam and the corresponding Gaussian fit.

Figure 4 shows the measured full width at half-maximum (FWHM) beam diameter as the power is scaled from 5 to 25.7 W. As can be seen from Fig 4, the average beam diameter is measured to be ~91 mm (±3.5%) across the different power levels. The small increase in beam diameters may be attributed to the slight increase in the spectral extent toward the long wavelength edge, as the average power is scaled up and the peak output power is not maintained exactly the same with power scaling. Figure 4 also shows about a ±2% difference between the x and y diameters at each power level, which may be attributed to the fiber output being angle cleaved. An ideal Gaussian beam at the SC average wavelength of 2.3 μm, and with an ~23 μm mode field diameter, has a calculated full angle divergence of ~0.13 rad. The SC M^2 value is then calculated as the ratio of the SC beam divergence to ideal Gaussian beam divergence, and is seen to be <1.2 for all power levels, indicating that the SC laser maintains a nearly diffraction-limited beam with power scaling. Additional M^2 measurements performed at ~47 cm from the fiber output by scanning a detector across the beam cross section also show M^2 ranging from ~1.14 to 1.18 across the various power levels.

Another attribute for the SC source to be useful as a broadband illuminator for various applications is the ability to provide stable irradiance. The output variability of the SC laser spectra with power scaling is studied using a spectroradiometer, where we measure the spectral radiance of the laser spot as projected on the Spectralon target, at 5 s intervals (the timing is limited by the

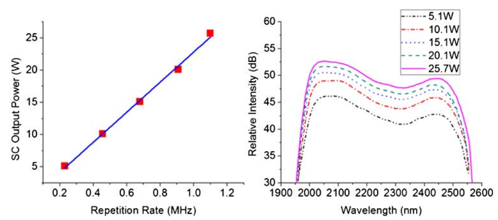

Fig. 2. Linear scaling of SC average power with repetition rate (left). Nearly constant SC output spectra with average power scaling (right).

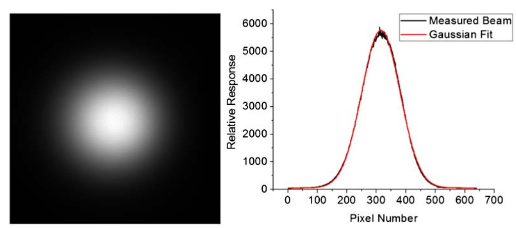

Fig. 3. SWIR camera image of the beam at 25.7 W SC (left). Corresponding Gaussian fit of the beam cross section at 25.7 W (right).

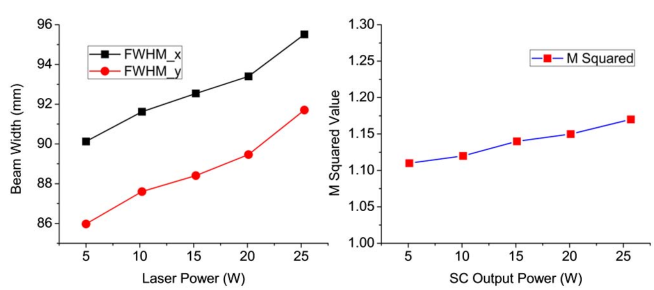

Fig. 4. Measured FWHM beamwidth with power scaling (left). Corresponding M^2 values with power scaling (right).

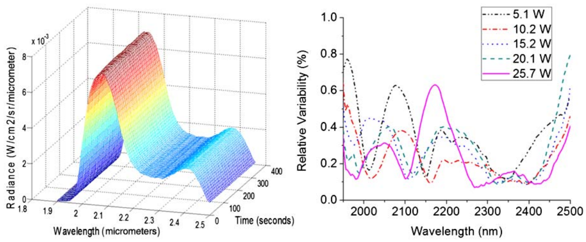

Fig. 5. Sixty scan sequence of the 25.7 W SC spectra (left). SC output relative variability with power scaling (right).

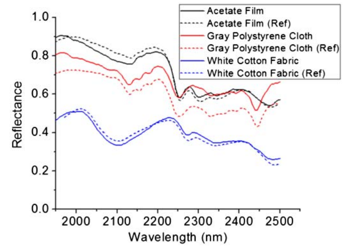

Fig. 6. Diffuse spectral reflectance measurements using the SC laser (solid) and lamp reference measurements (dashed).

software). The actual scan time for each measurement is 1 s. Figure 5 shows a sample measurement sequence of ~60 scans at 25.7 W. To quantify the relative variability, we calculate the RMS deviation of the sample-to-sample difference in radiance at each wavelength and divide by the mean radiance spectrum. As seen in Fig. 5, the relative variability of the SC laser spectra remains below 0.8% across the 1.95–2.5 μm spectral region. Thus, the SC laser maintains a low output variability across the entire SC spectrum as the power is scaled.

Unlike the spectroradiometer, the SWIR camera is able to capture the spatial characteristics of the beam as well as sample at faster rates. We use the camera to record 1000-frame sequences over a 120×120 pixel window in the center of the 25.7 W laser spot, at 10 Hz sampling with an integration time of 20 ms. After subtraction of the average background (obtained by performing the measurements with the laser off), the relative variability at 10 Hz is measured to be 0.48%, which is consistent with the spectroradiometer results.

High-power SWIR SC sources are attractive for long-distance applications such as remote sensing due to the high atmospheric transmittance bands in this spectral region. As an application example for spectroscopy, we also perform diffuse spectral reflectance measurements of various samples in the lab using the SC laser. In this case, the power is scaled down to 5 W to avoid detector saturation. Three samples—acetate sheet, polystyrene cloth, and cotton cloth—are chosen. The reflectance spectra for the samples measured using the SC laser and the corresponding reference measurement performed using a conventional halogen lamp source are shown in Fig. 6, and the spectral features are seen to be in good agreement. Another potential application of the SC source presented here is as a pump source for high-power mid-IR SC sources [7].

Although we have demonstrated power scalability up to 25.7 W, which is limited by our available pump power, the average SC output power should be further scalable by increasing the repetition rate and by adding more pump lasers. The maximum average power handling capability of the fiber may be limited to when the temperature of the fiber core rises close to its melting point. Using the formula in [14], we estimate the average power handling limit of the 25/400/550 μm (core/cladding/buffer diameter) fiber used in our system to be >100 W. However, very good thermal management and careful low-loss splices will be required as the power is scaled up. The data presented in this Letter suggest that the spectrum, near-diffraction-limited beam quality, and low output variability should still be maintained with power scaling.

In summary, we demonstrate a 25.7 W SC laser with the highest spectral density (>12 dBm/nm) reported in the SWIR band from ~2 to 2.5 μm wavelength region using an all-fiber platform. The spectrum, beam quality, and output stability are studied and show that the SC laser maintains a nearly constant spectral output, has a near-diffraction-limited beam with $M^2 < 1.2$, and has a radiometric variability of <0.8% across the entire spectrum, as the power is scaled from 5 to 25.7 W. Thus, a truly power scalable SC laser system is presented, where the spectrum, beam quality, and output stability are seen to be approximately the same with power scaling.

This work was supported by NGA, AFRL, SAIC, and Omni Sciences, Inc. M. N. Islam is also affiliated with Omni Sciences, Inc.

References

1. B. A. Cumberland, J. C. Travers, S. V. Popov, and J. R. Taylor, Opt. Express **16**, 5954 (2008).
2. K. K. Chen, S. Alam, J. H. V. Price, J. R. Hayes, D. Lin, A. Malinowski, C. Codemard, D. Ghosh, M. Pal, S. K. Bhadra, and D. J. Richardson, Opt. Express **18**, 5426 (2010).
3. X. Hu, W. Zhang, Z. Yang, Y. Wang, W. Zhao, X. Li, H. Wang, C. Li, and D. Shen, Opt. Lett. **36**, 2659 (2011).
4. R. Song, J. Hou, S. Chen, W. Yang, and Q. Lu, Opt. Lett. **37**, 1529 (2012).
5. J. C. Travers, Pramana **75**, 769 (2010).
6. C. Larsen, D. Noordegraaf, P. M. W. Skovgaard, K. P. Hansen, K. E. Mattsson, and O. Bang, Opt. Express **19**, 14883 (2011).
7. O. P. Kulkarni, V. V. Alexander, M. Kumar, M. J. Freeman, M. N. Islam, F. L. Terry, Jr., M. Neelakandan, and A. Chan, J. Opt. Soc. Am. B **28**, 2486 (2011).
8. J. Swiderski and M. Michalska, Laser Phys. Lett. **10**, 035105 (2013).
9. D. Buccoliero, H. Steffensen, O. Bang, H. Ebendorff-Heidepriem, and T. M. Monro, Appl. Phys. Lett. **97**, 061106 (2010).
10. V. V. Alexander, O. P. Kulkarni, M. Kumar, C. Xia, M. N. Islam, F. L. Terry, Jr., M. J. Welsh, K. Ke, M. J. Freeman, M. Neelakandan, and A. Chan, Opt. Fiber Technol. **18**, 349 (2012).
11. J. Geng, Q. Wang, and S. Jiang, Appl. Opt. **51**, 834 (2012).
12. W. Q. Yang, B. Zhang, J. Hou, R. Xiao, Z. F. Jiang, and Z. J. Liu, Laser Phys. Lett. **10**, 055107 (2013).
13. M. Faucher and Y. K. Lize, in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies* (IEEE, 2007), paper CFI7.
14. C. Xia, Z. Xu, M. N. Islam, J. Fred, L. Terry, M. J. Freeman, A. Zakel, and J. Mauricio, IEEE J. Sel. Top. Quantum Electron. **15**, 422 (2009).