Two-color fiber amplifier for short-pulse, mid-infrared generation

R. Romero-Alvarez, R. Pettus, Z. Wu, and D. Strickland*

Department of Physics and Astronomy, Guelph-Waterloo Physics Institute, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada

**Corresponding author: strickla@uwaterloo.ca*

Received January 31, 2008; accepted March 10, 2008;
posted April 10, 2008 (Doc. ID 92350); published May 9, 2008

A short-pulse, two-color Yb:fiber laser system has been developed for mid-infrared generation. To date, 20 μW of average power at a wavelength of $\sim$18 μm is generated by difference-frequency mixing 300 mW average power from the two-color Yb:fiber amplifier. The mid-infrared power was not limited by two-photon absorption, allowing it to be scaled by increasing the amplifier power. © 2008 Optical Society of America

OCIS codes: 140.3510, 140.7090, 190.4223.

Ultrashort-pulse, high-repetition laser sources are now available throughout the spectrum, from the ultraviolet ($\sim$200 nm) to the mid-infrared ($\sim$4 μm) because of the tunability of Ti:sapphire lasers along with harmonic conversion to the ultraviolet and optical parametric oscillation (OPO), which extends the wavelengths out to the mid-infrared. Extending the spectral range further into the mid-infrared requires difference-frequency mixing two different wavelengths. The typical approach is a two-step nonlinear process where the Ti:sapphire wavelength is first converted into two wavelengths, namely, the signal and idler beams of an OPO, which are then difference-frequency mixed to generated wavelengths out to 20 μm [1,2]. This two-step technique has garnered the highest average power of 2 mW in the mid-infrared at a wavelength of 8 μm [2]. High-repetition-rate, mid-infrared pulses have also been generated by directly mixing the output of a two-color, mode-locked Ti:sapphire oscillator [3]. More recently, mixing of spectral components within a single ultrashort pulse from a Ti:sapphire oscillator has produced broadband mid-infrared [4,5]. Directly mixing the radiation from a Ti:sapphire oscillator offers simplicity over the two-step process, but the pump power is limited by two-photon absorption (TPA) owing to the higher energy pump photons. An average power level of just 5 μW has been achieved at wavelengths longer than 10 μm by both direct methods [3,5]. All these sources are limited by the 2.5 W average power that can be achieved with a Ti:sapphire oscillator. Fiber lasers have now been demonstrated to generate far higher average powers than conventional solid-state lasers because of greatly reduced thermal stresses [6]. An average power of 131 W at a 73 MHz repetition rate has been achieved with a Yb-doped fiber laser system [7]. For the application of mid-infrared generation by direct difference-frequency mixing, Yb:fiber laser sources have an added advantage over Ti:sapphire lasers, in that the wavelength is longer and so will allow a higher TPA power limit in the nonlinear mixing crystal. We report here on mid-infrared generation from difference-frequency mixing the output from a two-color Yb:fiber amplifier in a GaSe crystal, which to date has generated 20 μW of average power at a wavelength of $\sim$18 μm, with a relatively modest pump power of 300 mW.

Dual-wavelength, mode-locked oscillators were first developed with Ti:sapphire gain media because of the extremely broad gain spectrum [8–10]. The wavelength separation could be as much as 150 nm [10], which if difference-frequency mixed would generate mid-infrared radiation at wavelengths from 4 to 20 μm. The 20 μm limit is due to the transmission edge of the standard difference-frequency mixing crystals, AgGaSe or GaSe. A dual-wavelength, mode-locked Nd:fiber laser has also been demonstrated [11]. The bandwidth of the Nd:fiber laser yielded only a wavelength separation of 40 nm, which is insufficient to generate mid-infrared wavelengths less than the 20 μm transmission limit. For our initial study of developing a two-color fiber system for mid-infrared generation, we chose to generate the two colors by Raman conversion in a photonic crystal fiber rather than develop a dual-wavelength oscillator. The two colors were then amplified together in a two-stage Yb:fiber amplifier.

Yb:fiber gain media offers both very high power and a broad gain profile from 900 to 1200 nm. However, the absorption band overlaps the emission band. This is because the absorption and emission bands are so close that Yb:fiber lasers can operate at high power owing to the low thermal energy loss. However, because the absorption band extends up to 1050 nm, the amplified spontaneous emission (ASE) peak wavelength increases with the length of the fiber [6]. We chose a 10 m length of fiber, where as shown in Fig. 1, the peak ASE is at 1045 nm for 5 W pump power and gain was experienced for wavelengths between 1030 and 1110 nm.

The overall system layout is depicted in Fig. 2. The

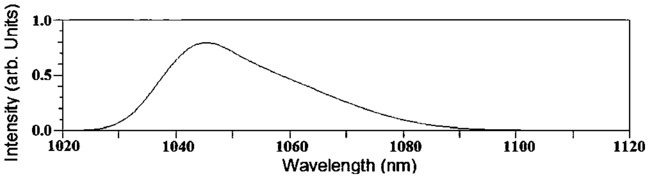

Fig. 1. Spectrum of ASE from 10 m Yb:fiber, pumped at 5 W.

0146-9592/08/101065-3/$15.00

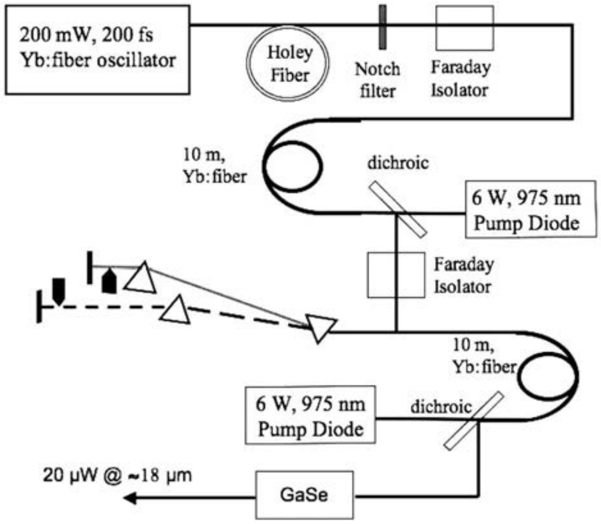

Fig. 2. Schematic of two-color fiber laser system.

front end of the system is a commercial (Polaronyx) mode-locked, Yb:fiber laser operating at a peak wavelength of 1030 nm. The laser generates a 200 mW average power pulse train of 200 fs pulses at a 50 MHz repetition rate. The two-color seed for the Yb:fiber amplifier is generated by focusing the mode-locked pulses with a 40× microscope objective into a 5 m length of photonic crystal fiber [Institut national d'optique (INO)] having the dispersion null at 985 nm. The maximum output power from the photonic crystal fiber that could be achieved was 27 mW. Because the seed laser wavelength of 1030 nm is longer than the dispersion null of the photonic crystal fiber, a Raman-shifted spectrum is excited rather than a continuum spectrum [12]. The wavelength shift varies with coupling efficiency. The two-color spectrum of the 22 mW output from the photonic crystal fiber is shown in Fig. 3(a). The peak wavelengths are separated by ~80 nm, with the Raman shifted peak intensity 1 order of magnitude lower than the laser pulse. The shifted wavelength could be moved out to 1120 nm, but wavelengths beyond 1120 nm experienced no gain. The pulse can easily be moved to shorter wavelengths and with higher energy, but then the wavelength separation is not sufficient to generate mid-infrared with a GaSe crystal.

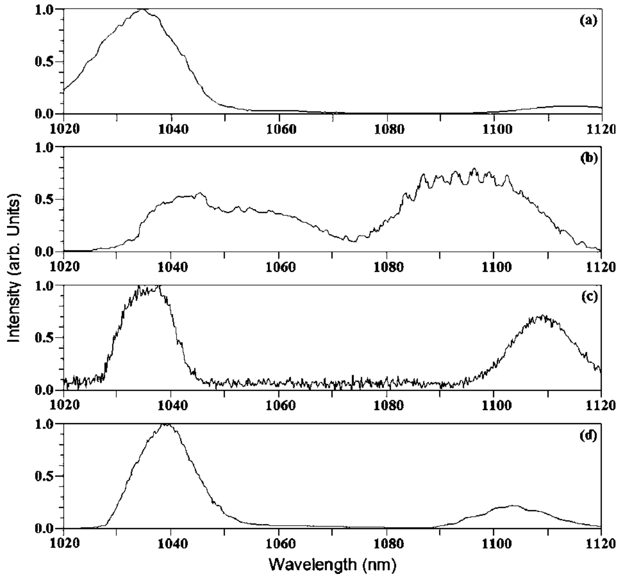

Fig. 3. Two-color spectra, (a) after the holey fiber, (b) output from first amplifier, (c) input to the final amplification stage, after the two-color selector, (d) after final amplifier.

To further eliminate seed wavelengths near the gain peak of the fiber amplifier, the seed beam is passed through an interference filter, which has a 50 nm wide notch in the transmission, centered around 1060 nm. A Faraday isolator is placed before the first amplification stage to protect the oscillator from a backward propagating beam. At the input of the first amplification stage, the seed power is just 5 mW. The first amplifier consists of a double clad Yb-doped fiber, 10 m in length, and a doping concentration of approximately 1.6% by weight. Both bare ends of the fiber amplifier are angle cleaved at 8° to prevent feedback of the signal in the core. This amplifier is counterpumped by a 5 W, 975 nm multimode fiber coupled laser diode. A 10× microscope objective is used to both couple the pump into the inner cladding of the Yb:fiber and collimate the amplified signal output from the core. At the output of the first amplification stage, the total power is 900 mW. Because of the low input power, much of the output power is ASE near the gain peak, as shown in Fig. 3(b). To eliminate the ASE and select the two amplified colors, a three-prism dispersion line is used. A half-wave plate is used to rotate the polarization of the amplifier output to maximize the transmission through the Brewster prisms. The amplified spectrum is dispersed by an SF10 prism and is split into two collimated beams by two matched prisms placed ~3 m from the first prism in a folded geometry. The long separation does not compensate for the temporal dispersion of the fiber but simply maps the spectrum sufficiently onto space. Knife edges are used in both beams to allow only the extreme limits of the amplified spectra to be further amplified. Two mirrors are used to reflect the two spectrally filtered beams and combine them back on the first prism, just below the input beam. One mirror is on a translation stage so that the pulses can be both cross-correlated and temporally overlapped. The combined beam is then passed through a second Faraday isolator. At the output of the isolator, the power is 60 mW. The spectrum of the input to the second amplification stage is shown in Fig. 3(c). The second amplification stage is identical to the first stage. At the output of the second amplifier, the power is 300 mW, with two colors peaked at 1038 and 1103 nm. Because of the increased input power, there is very little ASE present after the second stage, as can be seen in Fig. 3(d). A fast diode also monitored the output to ensure that the signal was amplified seed pulses and not ASE. Sum frequency in a β-barium borate crystal was used to temporally overlap and cross correlate the two colors. The correlation had a FWHM of 4.5 ps, which is what is expected from the dispersion of 10 nm bandwidths in 20 m of fiber. There was no attempt to compress the pulses at the output of the fiber.

The two-color beam is focused with a 100 mm focal length lens into a 1 mm thick GaSe crystal to generate radiation at the difference frequency of ~18 μm. The polarization is rotated using a half-wave plate so that the input polarization was 45° to the crystal axis. The focused spot is 1:1 imaged, using a 5 cm focal length spherical gold mirror onto a liquid nitrogen cooled HgCdTe detector. A lock-in amplifier is used to measure the signal. A chopper wheel is placed in the pump beam to provide an FM signal at a kilohertz repetition rate. The average pump power is reduced to 200 mW at the crystal. A 1 mm thick Ge filter is used to block the input. Mid-infrared radiation is detected for a phase-matching angle of ~45°. Taking into account the 35% transmission of Ge at a wavelength of ~18 μm, we measured an average power of 20 μW, which gives a photon conversion efficiency of 0.002. This conversion efficiency is low because of the low pump intensity of 100 $\mathrm{MW/cm^2}$. The filter transmits 3 μW of input power at 1030 nm. This power was used to calibrate the detector signal as measured with the lock-in amplifier. To ensure that the detected signal was from difference-frequency generation, the signal was measured with one color blocked in the prism line. When the long wavelength was blocked, the 3 μW signal was detected; when the short wavelength signal was blocked, the measured signal was 1 order of magnitude lower. We also measured the cross correlation of the two-color fiber output by again translating one of the back mirrors of the prism line but this time detecting the difference-frequency signal. The difference-frequency correlation showed the same 4.5 ps duration as measured by sum frequency. The 18 μm peak wavelength is inferred from the difference of the two peak wavelengths 1039 and 1103 nm. The cross-correlation widths are the same whether measured with difference or sum frequency, which indicates frequency conversion of the full bandwidth, because both colors are chirped in the same direction by propagation in the fiber. The mid-infrared spectrum could not be detected using a 156 mm focal length monochromator with a grating line density of 50 $\mathrm{mm^{-1}}$. The zero order was detected at 1 order of magnitude power above the noise signal, but the first-order signal was below the noise, indicating that the bandwidth was significantly broader than the 100 nm transmitted bandwidth. No attempt has yet been made to interferometrically measure the spectrum.

It has been demonstrated that crystal damage in GaSe occurs at an intensity of 7 $\mathrm{GW/cm^2}$ for 70 ps pulses but that TPA occurs at an intensity of just 100 $\mathrm{MW/cm^2}$ with a pump wavelength of 700 nm [13]. These results show that TPA rather than damage will limit the maximum pump intensity. Both wavelengths of the Yb:fiber system, although longer than 700 nm, are still sufficiently short to allow the competing nonlinear effect of TPA. In a previous study with a two-color Ti:sapphire laser, we showed that TPA in the nonlinear mixing crystal, $\mathrm{AgGaS_2}$, was greatly reduced for the longer wavelength of 885 nm compared to the shorter wavelength of 800 nm, even though both wavelengths were well below the 1.3 μm TPA cutoff wavelength [14]. To determine if we were limited by TPA with the Yb:fiber pump, we measured the transmitted power through the focus in GaSe as a function of increasing pump power. The transmitted power linearly increased with pump power up to the maximum pump power, indicating that there was no measurable TPA. This measurement demonstrates that the nonlinear mixing efficiency can be further increased with higher input intensity. After reaching the TPA limit, the mid-infrared power can be linearly scaled with pump power by increasing the focused spot size to maintain the maximum pump intensity.

In conclusion, we have demonstrated that mid-infrared radiation near 20 μm can be efficiently achieved with a compact, two-color Yb:fiber amplifier, and that the power can be scaled by increasing the pump power. In the future, we plan to increase both the average and peak powers of the system by employing fiber chirped-pulse amplification. The pulses will be stretched to support higher powers in the fiber and the output pulses will be compressed to generate shorter, higher intensity pulses. The difference-frequency mixing efficiency should be increased with the increased pump intensity.

The authors acknowledge funding support from the Canadian Institute for Photonic Innovations, The Ontario Photonics Consortium, and the Natural Science and Engineering Research Council of Canada. The authors also thank INO (Institut national d'optique) for the donation of the photonic crystal fiber.

References

1. J. M. Fraser, D. K. Wang, A. Hache, G. R. Allan, and H. M. van Driel, Appl. Opt. **36**, 5044 (1997).
2. S. Ehret and H. Schneider, Appl. Phys. B **66**, 27 (1998).
3. M. R. X. de Barros, R. S. Miranda, T. M. Jedju, and P. C. Becker, Opt. Lett. **20**, 480 (1995).
4. A. Bonvalet, M. Joffre, J. L. Martin, and A. Migus, Appl. Phys. Lett. **67**, 2907 (1995).
5. R. A. Kaindl, F. Eickemeyer, M. Woerner, and T. Elsaesser, Appl. Phys. Lett. **75**, 1060 (1999).
6. H. M. Pask, R. J. Carman, D. C. Hanna, A. C. Tropper, C. J. Mackechnie, P. R. Barber, and J. M. Dawes, IEEE J. Sel. Top. Quantum Electron. **1**, 2 (1995).
7. F. Roser, J. Rothhard, B. Ortac, A. Liem, O. Schmidt, T. Schreiber, J. Limpert, and A. Tunnermann, Opt. Lett. **30**, 2754 (2005).
8. M. R. X. de Barros and P. C. Becker, Opt. Lett. **18**, 631 (1993).
9. D. R. Dykaar and S. B. Darack, Opt. Lett. **18**, 634 (1993).
10. J. M. Evans, D. E. Spence, D. Burns, and W. Sibbett, Opt. Lett. **18**, 1074 (1993).
11. M. H. Ober, G. Sucha, and M. E. Fermann, Opt. Lett. **20**, 195 (1995).
12. F. M. Mitschke and L. F. Mollenauer, Opt. Lett. **11**, 659 (1986).
13. K. L. Vodopyanov, S. B. Mirov, V. G. Voevodin, and P. G. Schunemann, Opt. Commun. **155**, 47 (1998).
14. J. F. Xia, J. Song, and D. Strickland, Opt. Commun. **206**, 149 (2002).