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An Eye-Safe, SBS-Free Coherent Fiber Laser LIDAR Transmitter with Millijoule Energy and High Average Power

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Abstract: We report on an eye-safe, transform-limited, millijoule energy, and high average power fiber laser. The high gain and short length of the NP phosphate-glass fibers enable the SBS-free operation with kW level peak power. The output energy is up to 1.3 mJ, and the average power is up to 23 W at an 18 kHz repetition rate with 600 ns pulses (peak power > 2.1 kW). The PER is ≈16 dB and the M^2 of the beam is 1.33 × 1.18. The coherent LIDAR Figure Of Merit (FOM) is 174 mJ*sqrt(Hz), which to our knowledge is the highest reported for a fiber laser. We also report 0.75 mJ energy and >3.7 kW peak power with down to 200 ns pulses and up to 1.21 mJ energy with a 3–5 kHz repetition rate operation of the current system.

Keywords: fiber laser; eye-safe pulsed fiber laser; SBS-free fiber laser; high energy fiber laser; coherent LIDAR

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1. Introduction

The market for coherent Doppler wind Light Detection and Ranging (LIDAR) sensors is growing rapidly as the air travel and clean wind energy sectors continue to expand. Especially for airports, coherent wind LIDAR can provide vital, high-resolution, and real-time information on 3D wind vectors, turbulence, and wake-vortices to improve safety for landing and take-off. These coherent wind LIDARs at the airports are expected to operate at moderate ranges of ≈15 km, with high wind velocity and spatial resolution. NP Photonics' high energy, single frequency transform-limited fiber laser and amplifier technologies fit perfectly for the task of creating a coherent LIDAR transmitter. In this paper, we describe such a single-mode and single-polarization eye-safe coherent fiber laser system at 1550 nm wavelength.

Present-day coherent transform-limited pulsed laser technologies can be divided into two subcategories: the high energy, low repetition rate diode-pumped solid state (DPSS) lasers and amplifiers, and the low energy, high repetition rate fiber lasers. The eye-safe DPSS systems can produce tens of millijoules of energy with Hz to kHz repetition rates [1,2]. They are usually optimized to operate in a narrow range of pulse widths and repetition rates, offer low efficiency, and have high maintenance costs (servicing and realignment). The beam quality can degrade as the energy and thermal load increase. In contrast, fiber lasers at the eye-safe wavelengths are inherently long-term stable and have no need for realignment. Fiber lasers offer high repetition rates of kHz to GHz with flexible pulsing, high efficiency, and low cost of ownership. The biggest drawback of the fiber lasers has been the limited energy output, and the energy is mainly limited by nonlinearities [3–5]. For narrow linewidth transform-limited pulsed fiber lasers, stimulated Brillouin scattering (SBS) is the dominant nonlinearity. The SBS scales with peak power and fiber length, and it can grow rapidly in a gain fiber with a small mode field diameter (MFD) along meters of propagation due to weak gain per unit length. Higher gains per unit length can be

achieved with higher rare-earth doping; however, for silica-glass based fibers this does not work well due to undesirable effects such as clustering, upconversion, quenching, and photodarkening.

In the past two decades, NP Photonics has pioneered the highly-doped specialty-glass fiber technologies to improve upon silica-glass based fibers. Our phosphate-glass fibers can be very highly doped (two orders of magnitude higher than silica) without the undesirable effects described earlier. NP phosphate-glass fiber amplifiers have also been shown to have improved photodarkening [6,7]. These fiber amplifiers have been shown to produce greater than 1 dB/cm gain, high power, high energy, and orders of magnitude increases in SBS thresholds (up to tens of kW) [8–12]. Combining the high-doping concentration with an increased MFD of the fiber yields the highest SBS nonlinearity thresholds. Based on these unique technologies, we have developed a fiber laser that operates with a transform-limited optical linewidth, single polarization, and near single-mode at the eye-safe 1550 nm band. The output energy of the laser is ≈1.3 mJ at ≈23 W average power and an 18 kHz repetition rate with 600 ns pulses (peak power > 2.1 kW). We have also tested the system at shorter pulse widths down to 200 ns. The polarization extinction ratio (PER) was measured as ≈16 dB directly out of the laser, and was greater than 23 dB after an output isolator. The beam is near single-mode with measured M^2 of 1.33 × 1.18. The coherent LIDAR Figure of Merit (FOM) is 174 mJ*sqrt(Hz), which to our knowledge is the highest reported FOM for a fiber laser.

2. Materials and Methods

The fiber laser MOPA system (Figure 1) begins with NP Photonics' single-frequency CW Rock seed laser at the 1550 nm band. This laser can produce down to 500 Hz optical linewidth (free running), and CW power up to 200 mW with very little relative intensity noise (RIN) and optical frequency noise. The seed laser output PER was measured to be greater than 23 dB. The output of the seed laser is externally pulsed with a high extinction ratio to preserve the optical linewidth and frequency noise characteristics. The pulse width and repetition rate are flexible due to the external pulsing, and we operated at 200–800 ns pulse width at 18 kHz repetition rate for the contents of this paper. A fast arbitrary waveform generator is used to pre-shape the pulse in order to compensate for the gain-steepening effects in the amplifiers. The gain-steepening causes pulse shape deformation and tilt, thereby increasing the peak power of the pulse and limiting the amplifier's operation due to SBS.

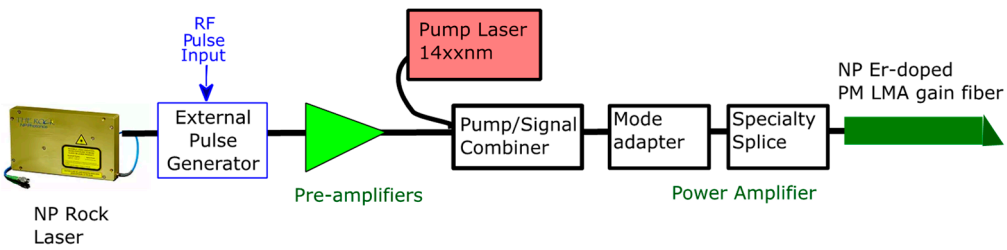


Figure 1. Eye-safe SBS-free coherent fiber laser architecture.

Following the pulsed seed laser, the signal is pre-amplified using multiple fiber amplifier sections that utilize NP's proprietary polarization maintaining (PM) LMA Er/Yb co-doped phosphate fiber amplifiers (EDFA). The whole MOPA fiber laser system utilizes an all-PM fiber configuration to maintain the single-polarization operation. Optical isolators are used between each pre-amplifier stage to maintain the low-noise operation and prevent parasitic-lasing. The output of the final pre-amplifier provides up to 160 µJ of energy (≈3 W average power at 18 kHz) to feed into the final power amplifier EDFA stage.

The power amplifier utilizes a PM LMA Er-doped (Yb-free) phosphate-glass gain fiber with 20–30 cm length and a mode field area of approximately 1000 μm^2. A phosphate-glass

endcap with an 8-degree angle is placed at the output of the gain fiber to minimize back reflection and damage risks. The power amplifier is water-cooled and in-band pumped with a high power 1480 nm fiber laser. Up to 50 W of pump power can be launched into the core of the gain fiber using proprietary mode matching components and specialty splicing. The in-band core pumping enables us to utilize the smaller quantum defect and maximum pump/signal overlap to achieve more efficient amplification [13,14]. This is again where the high gain per unit length specialty-fiber technology shines. The absorption of the 1480 nm band is weak in the silica-glass EDFA, and many meters of gain fiber are required to absorb the pump and produce respectable gain. On the contrary, NP Er-doped gain fibers can easily achieve greater than 10 dB absorption at the 1480 band for less than 30 cm of gain fiber, along with absolute optical-to-optical conversion efficiencies above 40%.

3. Results

The MOPA fiber laser was operated with a Gaussian-like shaped pulse waveform as shown in Figure 2. This yielded an acceptable output pulse shape with the particular gain and the pulse-steepening in our system; however, there may be other shaped pulse waveforms that may achieve similar or better results. The pre-amplifiers were optimized to produce greater than 150 µJ of energy with a PER of 20 dB, and very clean optical spectrum with >40 dB suppression of amplified spontaneous emission (ASE). The very high quality of the launched signal is critical to maximizing the energy extraction from the power amplifier stage.

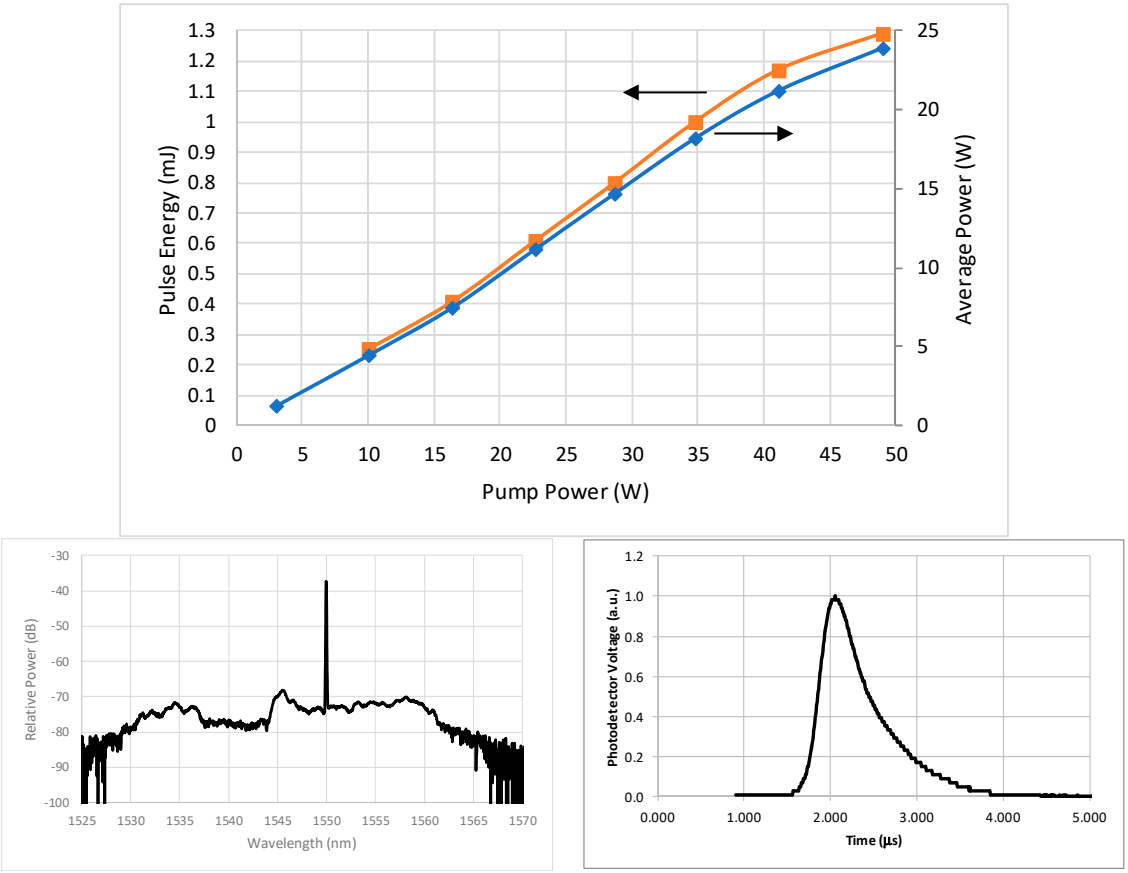


Figure 2. Energy and Average Power vs. pump power, optical spectrum, and pulse shape at 1.3 mJ and 18 kHz with 600 ns pulses.

The output energy and average power vs. launched pump power, the output spectrum, and the pulse shape at maximum energy is shown in Figure 2. The maximum energy was

measured with an energy meter before the isolator as ≈1.3 mJ at 18 kHz with 600 ns pulses. This yielded a coherent LIDAR FOM of ≈174 mJ*sqrt(Hz) (defined as energy times the square root of the repetition rate). This is the highest reported FOM for a fiber laser to our knowledge, with the next best published result being [5]. The average power was greater than 23 W and the optical spectrum has a >30 dB signal to ASE ratio without any lasing peak (0.1 nm resolution). The absolute optical-to-optical conversion efficiency from the 1480 nm pump to the signal was ≈50%. The peak power is estimated to be greater than 2.1 kW based on the pulse width and energy measurements. The output energy was limited by the available pump power and the increased ASE at the maximum pump levels, and not the SBS in the gain fiber. The SBS threshold for peak power was calculated to be greater than 7 kW in our current configuration.

The PER and the beam quality were measured directly at the output of the pump-dump filter, and after the output isolator. The PER was measured as ≈16 dB at the output of the pump-dump filter. We believe that the PER measurement was skewed by the small amount of ASE and cladding fiber modes. After the output isolator, most of the cladding modes are cut out by the small isolator aperture, and the ASE is reduced by half due to unpolarized nature of the ASE. The overall signal loss is ≈5% due to the isolator. We measured the PER as greater than 23 dB after the isolator, and the output was very stable in terms of power and polarization for different output power levels. The beam quality of the output appears near single-mode (Figure 3) and the M^2 values for both axes were measured as 1.33 and 1.18, respectively. Some of the beam distortion can be attributed to cladding fiber modes and non-ideal collimating lens alignment. Now, one can calculate the revised FOM that includes the beam quality based on this formula: FOM * $2/(1 + (M^2)^2)$. If we take the worst case $M^2 = 1.33$, the revised FOM becomes ≈125 mJ*sqrt(Hz).

We also conducted experiments with our current setup at the reduced pulse width of ≈200 ns at ≈16 kHz (Figure 4), and with ≈500 ns pulses at the reduced repetition rates of 3–5 kHz (Figure 5). For the first set of experiments with the 200 ns pulse width operation, the energy started to saturate at ≈0.75 mJ (peak power of ≈3.7 kW) at the pump power of 40 W. The energy extraction was limited due to increased ASE, and reduced preamp signal because of increased SBS. The reason for increased SBS is that the preamps were optimized for ≈500–1000 ns pulse width, and not optimized for these shorter pulses. This can easily be fixed in future work. For the second set of experiments with reduced repetition rates of 3–5 kHz, we could obtain up to ≈1.2 mJ of energy with 35 W of pump power and ≈500 ns pulses using the same setup. The limitations again were due to ASE and non-optimized preamps at these lower repetition rates. In the future, with better optimized preamps for each scenario, we anticipate that higher energy levels will be obtained with the shorter pulse widths and lower repetition rates.

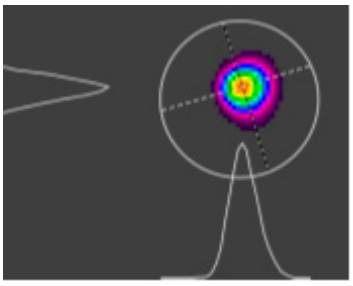
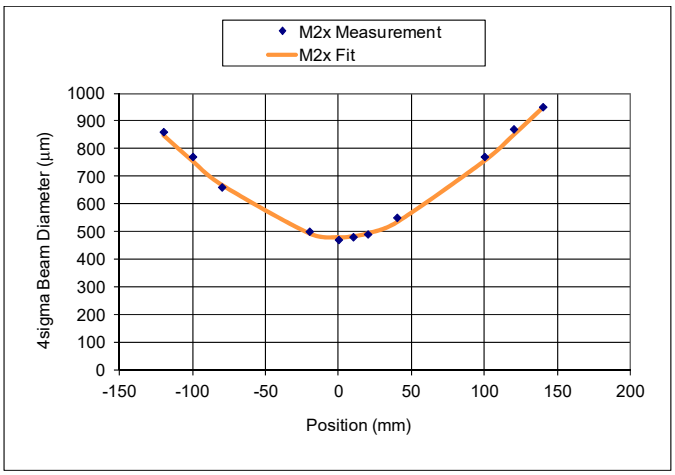


Figure 3. *Cont.*



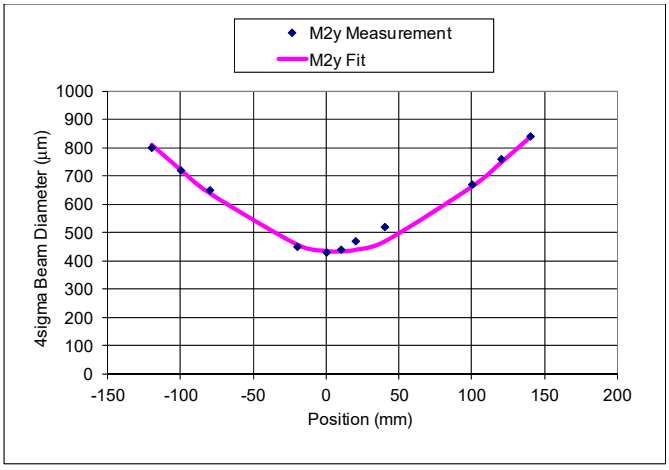


Figure 3. Beam shape and M^2 measurement at 1.3 mJ and 18 kHz with 600 ns pulses.

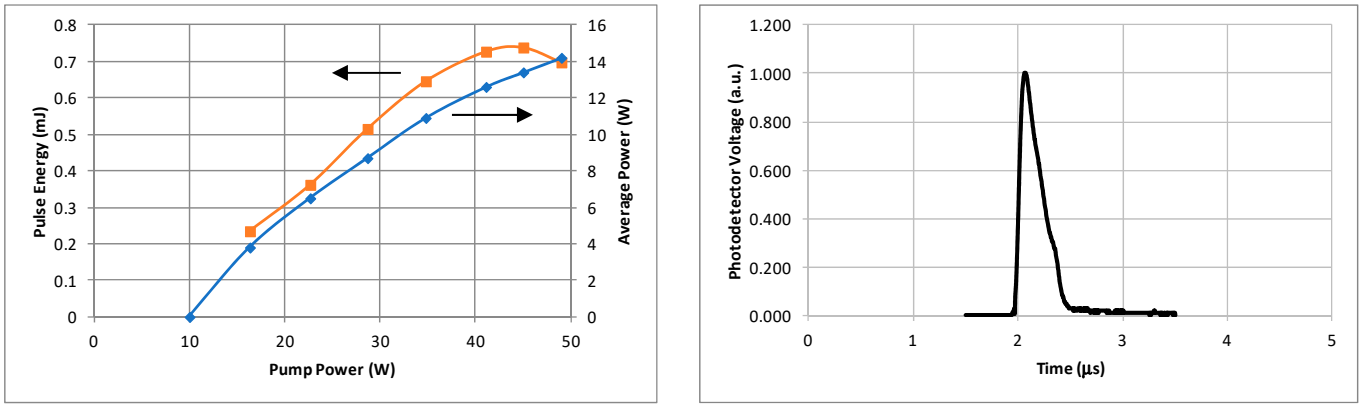


Figure 4. Energy vs. pump power and pulse shape at 0.75 mJ and 16 kHz with 200 ns pulses.

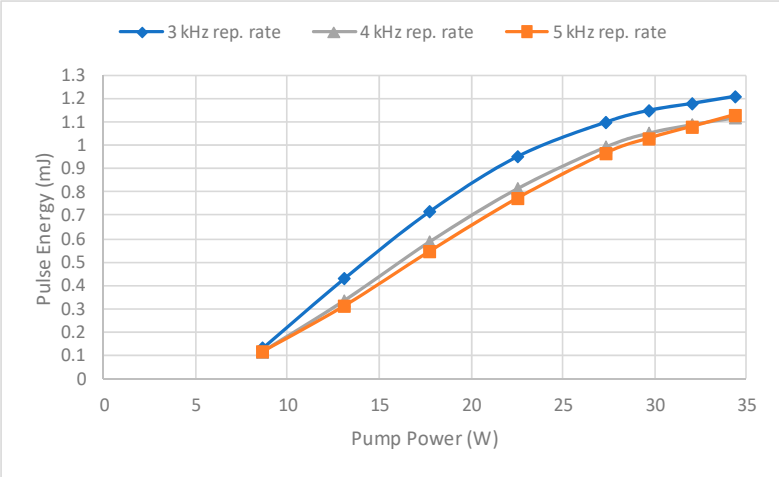


Figure 5. Energy vs. pump power 3–5 kHz repetition rate results.

4. Conclusions

In conclusion, we have demonstrated a millijoule class, tens of Watts average power, single-mode, single-polarization, transform-limited pulsed fiber laser for coherent Doppler wind LIDAR applications. The laser achieved a coherent LIDAR FOM of 174 mJ*sqrt(Hz). To our knowledge, this is the highest FOM from a fiber laser based coherent LIDAR transmitter.

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References

1. Sakimura, T.; Watanabe, Y.; Ando, T.; Kameyama, S.; Asaka, K.; Tanaka, H.; Yanagisawa, T.; Hirano, Y.; Inokuchi, H. OSA Technical Digest (Online). In Proceedings of the Conference on Lasers and Electro-Optics, San Jose, CA, USA, 6–11 May 2012. Paper CTu2D.7 (2012).
2. Sakimura, T.; Hirosawa, K.; Watanabe, Y.; Ando, T.; Kameyama, S.; Asaka, K.; Tanaka, H.; Furuta, M.; Hagio, M.; Hirano, Y.; et al. 1.55-µm high-peak, high-average-power laser amplifier using an Er, Yb: Glass planar waveguide for wind sensing coherent Doppler lidar. *Opt. Express* **2019**, *27*, 24175–24187. [CrossRef] [PubMed]
3. Akbulut, M.; Hwang, J.; Kimpel, F.; Gupta, S.; Verdun, H. Pulsed coherent fiber lidar transceiver for aircraft in-flight turbulence and wake-vortex hazard detection. In *Laser Radar Technology and Applications XVI*; International Society for Optics and Photonics: Bellingham, WA, USA, 2011; Volume 8037, p. 80370R.
4. Nicholson, J.W.; Desantolo, A.; Yan, M.F.; Wisk, P.; Mangan, B.; Puc, G.; Yu, A.W.; Stephen, M.A. High energy, 1572.3 nm pulses for CO 2 LIDAR from a polarization-maintaining, very-large-mode-area, Er-doped fiber amplifier. *Opt. Express* **2016**, *24*, 19961–19968. [CrossRef] [PubMed]
5. Lee, W.; Geng, J.; Jiang, S.; Yu, A.W. 1.8 mJ, 3.5 kW single-frequency optical pulses at 1572 nm generated from an all-fiber MOPA system. *Opt. Lett.* **2018**, *43*, 2264–2267. [CrossRef] [PubMed]
6. Lee, Y.W.; Urbanek, K.E.; Digonnet, M.J.F.; Byer, R.L.; Jiang, S. Measurement of the stimulated Brillouin scattering gain coefficient of a phosphate fiber. *Proc. SPIE* **2007**, *6469*, 64690L.
7. Lee, Y.W.; Sinha, S.; Digonnet, M.J.F.; Byer, R.L.; Jiang, S. Measurement of high photodarkening resistance in heavily Yb3+-doped phosphate fibres. *Electron. Lett.* **2008**, *44*, 14–16. [CrossRef]

8. Akbulut, M.; Miller, A.; Wiersma, K.; Zong, J.; Rhonehouse, D.; Nguyen, D.; Chavez-Pirson, A. High energy, high average and peak power phosphate-glass fiber amplifiers for 1micron band. In *Fiber Lasers XI: Technology, Systems, and Applications*; International Society for Optics and Photonics: Bellingham, WA, USA, 2014; Volume 8961, p. 89611X.
9. Kotov, L.; Akbulut, M.; Chavez-Pirson, A.; Zong, J.; Peyghambarian, N. More than 100W, 18cm Yb-doped phosphate fiber amplifier. In *Fiber Lasers XVI: Technology and Systems*; International Society for Optics and Photonics: Bellingham, WA, USA, 2019; Volume 10897, p. 108970X.
10. Lee, Y.W.; Sinha, S.; Digonnet, M.J.F.; Byer, R.L.; Jiang, S. 20 W single-mode Yb 3+-doped phosphate fiber laser. *Opt. Lett.* **2006**, *31*, 3255–3257. [CrossRef] [PubMed]
11. Fang, Q.; Shi, W.; Kieu, K.; Petersen, E.; Chavez-Pirson, A.; Peyghambarian, N. High power and high energy monolithic single frequency 2 μm nanosecond pulsed fiber laser by using large core Tm-doped germanate fibers: Experiment and modeling. *Opt. Express* **2012**, *20*, 16410–16420. [CrossRef]
12. Shi, W.; Petersen, E.B.; Yao, Z.; Nguyen, D.T.; Zong, J.; Stephen, M.A.; Chavez-Pirson, A.; Peyghambarian, N. Kilowatt-level stimulated-Brillouin-scattering-threshold monolithic transform-limited 100 ns pulsed fiber laser at 1530 nm. *Opt. Lett.* **2010**, *35*, 2418–2420. [CrossRef] [PubMed]
13. Yilmaz, T.; Vaissie, L.; Akbulut, M.; Gaudiosi, D.M.; Collura, L.; Booth, T.J.; Jasapara, J.C.; Andrejco, M.J.; Yablon, A.D.; Headley, C., III; et al. Large-mode-area Er-doped fiber chirped-pulse amplification system for high-energy sub-picosecond pulses at 1.55 μm. *Proc. SPIE* **2008**, *6873*, 68731I.
14. Peng, X.; Kim, K.; Mielke, M.; Jennings, S.; Masor, G.; Stohl, D.; Chavez-Pirson, A.; Nguyen, D.; Rhonehouse, D.; Zong, J.; et al. Monolithic fiber chirped pulse amplification system for millijoule femtosecond pulse generation at 1.55 μm. *Opt. Express* **2014**, *22*, 2459–2464. [CrossRef] [PubMed]