AFRL-RD-PS-
TP-2016-0006

AFRL-RD-PS-
TP-2016-0006

INVESTIGATION OF A PULSED 1550 NM FIBER LASER SYSTEM

Leanne Henry, et al.

15 December 2015

Technical Paper

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
Directed Energy Directorate
3550 Aberdeen Ave SE
AIR FORCE MATERIEL COMMAND
KIRTLAND AIR FORCE BASE, NM 87117-5776

NOTICE AND SIGNATURE PAGE

AFRL-RD-PS-TP-2016-0006 HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION IN ACCORDANCE WITH ASSIGNED DISTRIBUTION STATEMENT.

//LEANNE HENRY//
LEANNE HENRY, DR-III, DAF
Work Unit Manager

//KENTON WOOD//
KENTON T. WOOD, DR-IV, DAF
Chief, Laser Division

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
15-12-2015

2. REPORT TYPE
Technical Paper

3. DATES COVERED *(From - To)*
1 Oct 2012- 14 Dec 2015

4. TITLE AND SUBTITLE
Investigation of A Pulsed 1550 nm Fiber Laser System

5a. CONTRACT NUMBER
In-House

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Leanne J. Henry, *Michael Klopfer, *Ravinder Jain

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
D08T

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The University of New Mexico
ECE Building, Room 125
Albuquerque, NM 87131-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
3550 Aberdeen Ave SE
Kirtland AFB, NM 87117-5776

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/RDLT

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-RD-PS-TP-2016-0006

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release: Distribution unlimited. OPS-15-1037, 15 December 2015.

13. SUPPLEMENTARY NOTES
Presented at the 18th Annual Directed Energy Symposium; Jan 8, 2016. Albuquerque, NM. "Government Purpose Rights."

14. ABSTRACT
There is a strong need for a pulsed laser system at eye safe wavelengths for illuminator applications. High power pulsed 1550 nm fiber lasers systems are able to generate, shaped, pulses at various repetition rates and as such, may be useful for seeding a high power solid state amplifier stage. An electro-optic modulator as well as amplified spontaneous emission filters were used to enable pulses with high contrast relative to the power between pulses. Pulse energies of approximately 0.3 mJ with a PER of 15 dB and an M^2 of 1.12 were obtained from the four stage pulsed fiber laser system. This result is superior to comparable results in the scientific literature. It is expected that seeding of a fifth and final stage in 60 micron core fiber with the output of this four stage laser will result in output energy levels of 3-5 mJ/pulse.

15. SUBJECT TERMS
Illuminator

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Leanne Henry
Unclassified	Unclassified	Unclassified	SAR	8	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Investigation of a pulsed 1550 nm fiber laser system

Michael Klopfer[(1)], Leanne J. Henry[(2)], and Ravinder Jain[(1)]

(1) The University of New Mexico
(2) Air Force Research Laboratory

Abstract

There is a strong need for a pulsed laser system at eye safe wavelengths for illuminator applications. High power pulsed 1550 nm fiber lasers systems are able to generate, shaped, pulses at various repetition rates and as such, may be useful for seeding a high power solid state amplifier stage. An electro-optic modulator as well as amplified spontaneous emission filters were used to enable pulses with high contrast relative to the power between pulses. Pulse energies of approximately 0.3 mJ with a PER of 15 dB and an M^2 of 1.12 were obtained from the four stage pulsed fiber laser system. This result is superior to comparable results in the scientific literature. It is expected that seeding of a fifth and final stage in 60 micron core fiber with the output of this four stage laser will result in output energy levels of 3-5 mJ/pulse.

1. Introduction

There is a strong need for a pulsed laser system at eye safe wavelengths for illuminator applications. Considerations which impact the wavelength to be used are the transmissivity of the atmosphere and the responsivity of the detector. The maximal atmospheric transmission window for eye safe wavelengths lies roughly between 1550 and 1850 nm with the atmospheric transmission falling off rapidly on either side. Erbium doped glasses can be used to generate wavelengths between roughly 1525 and 1610 nm with maximal gain occurring at roughly 1535 nm. Although the gain of erbium is a maximum at1535 nm, because the atmospheric transmission drops off substantially at this wavelength, 1550 nm was chosen to be the wavelength of the pulsed fiber laser system in this work. It should be noted that the gain of erbium at 1550 nm is about 70% of that at 1535 nm.

Recently [1], 1 mJ 100 ns width 1550 nm pulses with repetition rates from 1-10 kHz were obtained in a 30 micron core, non-PM, Er doped, single mode fiber, i.e., the power between pulses was measured and factored into the calculation of the energy per pulse. In [2], pulse energies of 0.5 mJ at 1560 nm with a repetition rate of 10 kHz were obtained in a higher order mode erbium doped fiber amplifier. The power between the pulses reached ~20% of the total power. In [3], pulse energies of 0.1 mJ with a repetition rate of 100 kHz at 1550 nm were obtained from a MOPA design with a cladding pumped 12 micron core erbium-ytterbium fiber final stage amplifier. The M^2 was 1.04 with the interpulse power reaching 80 % of the total power at 50 kHz while the interpulse power was only 3% of the total output power at 100 kHz. In [4], a pulse energy of 1.5 mJ and a M^2 of 1.6 at a repetition rate of 0.3 kHz was achieved from a 40 micron core Er doped fiber amplifier at 1550 nm when pumped at 1535 nm. Unfortunately, the interpulse power was not measured leaving a question as to how much of the measured energy actually lies in-between the pulses, i.e, the energy per pulse is usually calculated by dividing the total measured energy by the repetition rate. Earlier pulse energies of 1.15 mJ and M^2 of 1.6 were demonstrated in [5] but again the interpulse power was not explicitly measured.

2. Design of laser

The laser in this work was designed in order to increase the energy per pulse to as high of a level as possible while suppressing the interpulse power and the amplified spontaneous emission. Because of the limited quantity of gain media in an optical fiber as well as the fact the 1550 nm seed has a power level of 50 mW, a multi-stage laser is necessary in order to substantially increase the energy per pulse. For an illuminator system, narrow linewidth is not a requirement but a linearly polarized system could have some benefits. For the fiber laser system in this work, a 50 mW narrow linewidth 1550 nm seed is broadened using white RF noise to approximately 20 GHz. The laser is comprised of four stages of polarization maintaining fiber of sizes 7/125 (single clad, erbium), 10/125 (2 stages) (double clad, erbium/ytterbium), and 25/300 (double clad, erbium/ytterbium). The various stages are pumped continuous wave with 976 nm either through a wavelength division multiplexer for single clad fiber, or a taper fiber bundle for double clad fiber. The pulses are formed using an electro-optic modulator (EOM) which opens to let light through and closes to block the light of the continuous wave seed. If the EOM opens at the maximum possible rate creating a square pulse shape, severe front edge steepening is the result since the leading edge of the pulse sees the maximal inversion whereas, the trailing edge of the pulse sees an inversion which has been depleted. Severe front edge steepening is a problem since the average energy per pulse will be limited by intensity levels at the front edge of the pulse which will need to stay below the threshold for material damage. To avoid this, the pulse output from the EOM needs to be shaped to have less power in the front edge relative to the trailing edge of the pulse. This will result in a lower amplified level in the front edge of the pulse by the maximal inversion and a greater amplified level in the trailing edge of the pulse by an inversion which isn't quite as depleted. The net result should be a pulse with a more uniform energy profile from the front to the trailing edges. Shaping of the pulses was accomplished by a home built arbitrary waveform generator comprised of a Texas Instruments TSW1400EVM high speed data capture and pattern generation board which has been configured for 700 mega samples per second, a Texas Instruments DAC3482EVM digital to analog converter, and two THS3201EVM's in series. The TSW1400EVM repetitively produces a digital waveform that is then fed to the DAC3482EVM, a digital to analog converter, which then produces an analog waveform that is fed to the two THS3201EVM's in series in order to amplify the signal to the 4 V's required to open the electro-optic modulator (EOM).

Once the pulses are formed by the initial EOM and are amplified as they pass through the PM 7/125 fiber first stage, they next pass through a second EOM which effectively blocks any power between the pulses which may have arisen via amplified spontaneous emission or amplification of noise. The pulses then encounter an amplified spontaneous emission (ASE) filter which blocks any power outside of the passband which is approximately 1 nm around 1550 nm. The pulses then pass through a second stage in PM 10/125 fiber and then pass through a second ASE filter. It is to be noted that the ASE filter will not absorb light in the passband around 1550 nm that lies between the pulses. Also, after the second stage and beyond, an EOM can't be used because the power levels exceed the damage threshold of the component. After passing through the second ASE filter, the pulses then enter a third stage in PM 10/125 fiber followed by a fourth stage in PM 25/300 fiber. Beyond the third stage, an ASE filter can't be used because the power levels exceed the damage threshold of the component. In addition, neither an EOM or ASE filter exist for the large mode area 25/300 fiber. Because of the lack of components that can tolerate higher power levels and/or large mode area fiber, the only way to control the power between the pulses would be to pulse the pump diodes. Currently, the pump diodes in this system are run continuous wave. In the future, the plan is to investigate controlling the power between the pulses for the higher power stages by pulsing the pump diodes. Finally, the output of this laser system will eventually be used to seed a high power Er/Yb stage with a 60 micron core from the University of Southampton. This fifth and final stage will be in-band pumped with 1480 nm.

3. Predictions of modeling

Modeling can provide predictions about the increase in the pulse energy by each stage. This can estimated from the Franz-Nodvik equation which has the following form: $W_{out} = W_s \cdot ln(1 - exp(\alpha) \cdot (1 - exp(w_i/w_s)))$ where W_i is the input pulse energy fluence and W_{out} is the output pulse energy fluence, $W_s = h\nu/2\sigma$ is the saturation fluence, σ is the emission cross section of the dopant ion and e^{α} is the small signal gain. It should be noted that the output pulse energy from a given stage is reduced upon passing through an isolator as well as other components prior to entering the next amplifier stage. The Franz-Nodvik equation can also make predictions for different levels of optical gain by adjusting e^{α}. Based on the Franz-Nodvik equation, for a pulse energy of 0.3 mJ from the high power fourth stage, energy levels per pulse of 3.5 mJ (for 20 dB gain) up to 5.5 mJ (for 30 dB gain) can be expected from the fifth and final stage in the 60 micron core fiber stage in 60 micron core fiber. It is expected, that multiple mJ per pulse should be achievable.

4. Experimental results

The laser system described in this work was evaluated for pulse lengths of 300 ns and 1 μs as well as repetition rates ranging from 3 to 40 kHz. As more stages were added to the laser system, the energy per pulse was found to increase as expected for both the 300 ns and 1 μs pulses for a given repetition rate. A pulse energy of approximately 0.3 mJ was found for both the 300 ns and 1 μs pulses for repetition rates of approximately 3 kHz out of the 4^{th} stage in 25/300 fiber. The PER associated with this was 15 dB and the M^2 was 1.12. Previously, it had been found that the energy per pulse was higher for multimode lasers where the beam quality is significantly degraded. This is the highest reported pulse energy at 1550 nm for an all PM fiber laser with $M^2 \leq 1.12$. In addition, significant amplified spontaneous emission power was found to exist between each pulse after the fourth and final stage because of the fact that the EOM and ASE filters were placed after the earlier stages. Because such components were not placed after the third and fourth stages, interpulse power was allowed to build from noise to significant levels in the later stages.

In order to measure the power between pulses, cladding light was first stripped by removing the low index polymer buffer followed by recoating of the region with a high index polymer. The free space beam then passed through a highly reflective 980 nm dichroic, a first half waveplate, a polarizing beam splitting cube, a second half waveplate, and a lens, prior to entering a 10/125 micron passive fiber, an electro optic modulator and finally into a photodiode to observe the power on an oscilloscope or a power meter. The EOM was modulated by a delay generator that turned on 100 ns before the pulse and closed 4 microsecond later. By adjusting the DC bias on the EOM, the power between pulses or the power within the pulse could be blocked. Once the bias was adjusted, the output power of the beam was measured giving an interpulse or intrapulse power. This allowed the determination of an intrapulse power of .3 mJ for both a 300 and 1000 ns pulsewidth at a 3 kHz repetition rate.

The peak power of the noise between pulses relative to the peak pulse power was measured since this is important for illuminator applications. To accomplish this, the 4th stage output was focused into a photodiode (PD), whose output was captured on an oscilloscope. The 4th stage output was attenuated so that the PD pulse peak was ~.5 V where the PD is still linear. The PD output was then captured at the lowest scale on an oscilloscope which had a minimum noise level of 1 mV. This allowed a determination of the magnitude of the power spikes between pulses relative to the power associated with the pulse peaks. For stages 1-3, the magnitude of the power spikes between the pulses was not recordable by the oscilloscope and thus >20 dB below that of the pulse peaks. For the 4th stage, the power spikes between pulses reached as high as 18 dB below that of the pulse peaks. From spectral measurements of the pulses, we observed a peak at 1535 nm that was 10 dB below the peak at the signal wavelength of 1550 nm after the 3rd stage. After the 4th stage, this peak became approximately equal to the peak at 1550 nm. This occurred because erbium has a higher gain at 1535 than at 1550. Although the transmission in the atmosphere is reduced, power during the pulse at 1535 nm is tolerable for illuminator applications since the detector will not distinguish between wavelengths. Finally, by focusing light into a third EOM after the 25/300 stage to block the power in certain time periods, the spectral content of the power intrapulse and interpulse can be determined. This allowed us to also more accurately determine the pulse energy. Current results show no pronounced change between the interpulse and intrapulse spectra suggesting that the power between pulses is due to amplified reflections.

5. Conclusion

High power pulsed 1550 nm fiber lasers systems are able to generate, shaped, pulses at various repetition rates and as such, may be useful for seeding a high power solid state amplifier stage. On a down note, such lasers are plagued with amplified spontaneous emission intrapulse because of the higher erbium gain at 1535 nm than at 1550 nm. But on a positive note, such power is not detrimental to the usage of the laser system as a tracking illuminator. Usage of EOMs and ASE filters to control the interpulse power is limited to the lower power, smaller mode area stages and are effective in reducing the power between pulses to minimal levels. Pulsing of the pump diodes will need to be considered for control of interpulse power for the higher power stages as well as stages in large mode area fiber. Pulse energies of approximately 0.3 mJ with a PER of 15 dB and an M^2 of 1.12 were obtained from the four stage pulsed fiber laser described above. This result is superior to comparable results in the scientific literature. It is expected that seeding of a fifth and final stage in 60 micron core fiber with the output of this four stage laser will result in output energy levels of 3-5 mJ/pulse.

References

[1] L. Kotov, M. Likhachev, M. Bubnov, O. Medvedkov, D. Lipatov, A. Guryanov, K. Zaytsev, M. Jossent, and S. Février " Millijoule pulse energy 100-nanosecond Er-doped fiber laser", Optics Letters 40(7)(2015)1189.

[2] J. W. Nicholson, J. M. Fini, A. M. DeSantolo, X. Liu, K. Feder, P. S. Westbrook, V. R. Supradeepa, E. Monberg, F. DiMarcello, R. Ortiz, C. Headley, and D. J. DiGiovanni, "Scaling the effective area of higher-order-mode erbium-doped fiber amplifier", Optics Express 20(22)(2012)24575.

[3] I. Pavlov, E. Dülgergil, E. Ilbey, and F. Ö. Ilday, "Diffraction-limited, 10-W, 5-ns, 100-kHz, all-fiber laser at 1.55 μm", Optics Letters 39(9)(2014)2695.

[4] E. L. Lim, S. Alam, and D. J. Richardson, "High-energy, in-band pumped erbium doped fiber amplifers", Optics Express 20(17)(2012)18803.

[5] V. Philippov, J. K. Sahu, C. Codemard, W. A. Clarkson, J.-N. Jang, J. Nilsson, and G. N. Pearson, "All-fiber 1.15 mJ eye-safe optical source", Proc. of the SPIE 5335 (2004)1.

DISTRIBUTION LIST

DTIC/OCP 8725 John J. Kingman Rd, Suite 0944 Ft Belvoir, VA 22060-6218	1 cy
AFRL/RVIL Kirtland AFB, NM 87117-5776	1 cy
Leanne Henry Official Record Copy AFRL/RDLT	1 cy