INVESTIGATION OF A PULSED 1550 NM FIBER LASER SYSTEM

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Technical Paper

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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.
Investigation of a Pulsed 1550 nm Fiber Laser System

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Motivation for Work

• Need for a tracking illuminator for tactical and strategic applications of high energy laser systems
  • Requirement: Eye safe (1500-1600 nm) pulsed laser with high energy per pulse
  • Eventual system will more than likely involve either a solid state laser or a hybrid fiber/solid state laser
  • Investigating the development of pulsed fiber laser at 1550nm
Related Work

• All previous work has unpolarized output

• The following papers account for interpulse power in pulse energy estimate:
  
  – Pulse energy [1] 1 mJ (35 µm core, \(M^2\) not specified), [2] .5 mJ (HOM, \(M^2\) not specified), [3] .1 mJ (\(M^2 = 1.04\))

• Interpulse power not discussed in the following:
  
  – Pulse energy [4] 1.15 mJ (\(M^2 = 1.6\)), [5] 1.5 mJ (\(M^2 = 1.65\))

Experimental Layout

Waveform shaping

1550 nm 50 mW

1st EOM

EOM

25/300 EYFA

976 nm 1 W

WDM

7/125 EFA

1st Stage

Delay

1st ASE filter

EOM

976 nm 15 W

TFB

10/125 EYFA

2nd Stage

ASE filter

MFA

Pump dump and splice

10/125 EYFA

3rd Stage

Pump dump and splice

976 nm 7.6 W

TFB

ASE filter

2nd ASE filter

4th Stage

976 nm 15 W

MFA

Multimode fiber to OSA or photodiode

980 HR 1550 LR

Power meter

Polarization maintaining throughout

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Output Pulse from 2nd stage of system in 10/125 fiber with no shaping

- Unshaped pulse out of second stage of system – notice extreme steepening of leading edge of pulse

Pulse steepening must be mitigated by shaping the input pulse to avoid premature damage to the fiber
Computer generated pattern

- Computer generates an arbitrary waveform in Python and feeds it to the TSW1400EVM which is a high speed data capture and pattern generation platform (configured for 700 mega samples per second). The TSW1400EVM repetitively produces a digital waveform which is fed to the DAC3482EVM, a digital to analog converter. This board then produces an analog waveform which is fed to two THS3201EVM’s in series in order to amplify the signal to the 4 V’s required to open the electro-optic modulator (EOM).
Temporal pulse shapes after the 2\textsuperscript{nd} stage of system

- Increased leading edge steepening with reduction in repetition rate.
- 2\textsuperscript{nd} EOM turn on is visible prior to leading edge of pulse.
Study of the output of 2\textsuperscript{nd} stage of the system

- Waveform shaping
- 1550 nm 50 mW
- EOM
- 25/300 EYFA
- TFB
- 976 nm 15 W
- MFA
- 980 HR 1550 LR
- Pump dump and splice
- 976 nm 1 W
- WDM
- 7/125 EFA
- 1\textsuperscript{st} EOM
- 10/125 EYFA
- TFB
- 976 nm 15 W
- Delay
- EOM
- 1\textsuperscript{st} ASE filter
- 1\textsuperscript{st} Stage
- ASE filter
- ASE filter
- 2\textsuperscript{nd} EOM
- 10/125 EYFA
- TFB
- 2\textsuperscript{nd} ASE filter
- 2\textsuperscript{nd} Stage
- Multimode fiber to OSA or photodiode
- Pump dump and splice
- Pump dump and splice
- Power meter
- Waveform shaping
- Delay
- 1\textsuperscript{st} ASE filter
- 2\textsuperscript{nd} ASE filter
- 3\textsuperscript{rd} Stage
- Measurements taken here after 2\textsuperscript{nd} ASE filter
- Power meter

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Pulses out of 2\textsuperscript{nd} stage with both ASE filters present and switching (on/off) of 2\textsuperscript{nd} EOM (300 ns pulses)

- No interpulse spiking when 2\textsuperscript{nd} EOM is active
- Even with second ASE filter, without the 2\textsuperscript{nd} EOM pulsing, there is significant power between the pulses that must lie within the ASE filter passband.
Pulses out of 2nd stage with both ASE filters present and 2nd EOM switching (on and off) (1 µs pulses)

- No interpulse spiking when 2nd EOM is active as seen with 300 ns PW.
Spectra after second stage before and after ASE filter for 300 ns PW

Before ASE filter

After ASE filter

- The 1535 nm power is reduced by 30 dB due to the ASE filter
- Higher 1535 nm power when 2nd EOM pulsed is due to higher inversion since the noise between pulses is reduced.
Setup to measure spectrum and power between pulses

- EOM intensity modulation is polarization dependent so need to couple to slow axis of PM fiber
- Attenuates output power below damage limit of EOM
• The 1st EOM is driven with a shaped pulse to prevent front edge steepening (pulse is shown as square below for illustration purposes)
• The 2nd EOM is driven with a square pulse that opens <100 ns before the pulse arrives from the 1st EOM and closes 2 µsec later
• To pass the intrapulse power, the 3rd EOM is opened <200 ns before the pulse arrives and is closed 3 µsec later thus blocking the interpulse power
• To pass the interpulse power, the bias on the EOM is adjusted to close the EOM <200 ns before the pulse arrives and to open the EOM 3 µsec later thus blocking the intrapulse power
Suppression of intrapulse power by 3\textsuperscript{rd} EOM

- The intrapulse energy is effectively blocked by the 3\textsuperscript{rd} EOM when measuring interpulse spectra.
The spectra of the power between the pulses is identical to the spectra of the intrapulse power. This could be because the interpulse spikes are reflections.
Results from 3rd stage output

1st Stage
- 1550 nm, 50 mW
- EOM
- WDM
- 976 nm, 1 W
- 25/300 EYFA
- TFB
- MFA
- 976 nm, 15 W

2nd Stage
- 976 nm, 15 W
- EOM
- ASE filter
- ASE filter
- 976 nm, 7.6 W
- TFB
- 10/125 EYFA
- Pump dump and splice

3rd Stage
- Multimode fiber to OSA or photodiode
- Pump dump and splice

4th Stage
- Power meter
- Measurements taken here after 3rd stage

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Leading edge power spikes from 3rd stage in PM10/125 fiber when 2nd EOM turns on

- For 10 kHz rep rate
- The bottom are normal pulses and the top are triggered from high peaks of the PD output – indication that there is a lot of variability in the shape of the pulse
Spectra out of 3rd stage
10/125 EYFA

- Without 3rd EOM (not separating interpulse and intrapulse power)
- Increased 1535 nm power compared to 2nd stage (both interpulse & intrapulse power)

2 EOMs + 2 ASE filters

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Output of 3\textsuperscript{rd} stage $<-20\text{dB}$ interpulse noise relative to pulse peak

- **10 kHz, 1 \( \mu \text{s} \) pulsewidth**, zoomed
- **20 kHz, 1 \( \mu \text{s} \) pulsewidth**
- **10 kHz, 300 ns pulsewidth**
- **20 kHz, 300 ns pulsewidth**

2 EOMs + 2 ASE filters
Results from 4th stage output

1st Stage
- 1550 nm 50 mW
- EOM
- WDM
- 976 nm 1 W
- 7/125 EFA

2nd Stage
- 976 nm 15 W
- TFB
- 1st ASE filter

3rd Stage
- 10/125 EYFA
- 976 nm 7.6 W
- TFB
- 2nd ASE filter

4th Stage
- Pump dump and splice
- Waveform shaping
- 25/300 EYFA
- TFB
- MFA
- 980 HR 1550 LR

Measurements taken here after 4th stage

Multimode fiber to OSA or photodiode

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Spikes at 3 and 6.6 kHz visible above noise. (more visible at lower rep rates)

The increase in the level of the interpulse noise with time after pulse is probably due to increased inversion not any capacitive effect

2 EOMs + 2 ASE filters
• Interpulse energy is not removed from the above estimates
• Pulse energy increases inversely with rep rate
• Pulse energy more than doubles after each stage.
• Intrapulse energy fraction increases with increased inversion
Energy of pulses from 4th stage with interpulse power removed

- Scope data shows that pulse is blocked by 3rd EOM
- Full spectrum (intrapulse) shows no 1064 power from Yb.

Fraction of power intrapulse was 0.32 giving 0.3 mJ as the energy per pulse for 300 ns and 1 µs pulse widths, 3 kHz rep rate.

3 EOMs + 2 ASE filters
Comparison of interpulse and intrapulse spectra from 4\textsuperscript{th} stage

- Higher 1535 power compared to 3\textsuperscript{rd} stage.
- No significant spectral difference between interpulse and intrapulse power.

3 EOMs + 2 ASE filters

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• The relationship between the gain, core diameter, input pulse energy and output pulse energy can be approximated by the Franz-Nodvik equation:

\[ W_{out} = W_s \ln \left( 1 - e^\alpha \left( 1 - e^{\frac{W_i}{W_s}} \right) \right) \]

where \( W_i \) is the input pulse energy fluence and \( W_{out} \) is the output pulse energy fluence, \( W_s = \frac{h \nu}{2\sigma} \) is the saturation fluence, and \( \sigma \) is the emission cross section of the dopant ion, small signal gain of \( e^\alpha \), \( \alpha \) is the natural log of small signal gain.
Comparison of predicted and measured pulse energies

• Measured 4.2, 12.7, 166, 330 µJ out of 1\textsuperscript{st}, 2\textsuperscript{nd}, 3\textsuperscript{rd}, 4\textsuperscript{th} stages, respectively, at 10 kHz in both 300 ns and 1 µs pulses. Allowing for losses through isolators, this implies that the 2\textsuperscript{nd} stage has 30 dB, 3\textsuperscript{rd} stage >30 dB and the 4\textsuperscript{th} stage <10 dB of gain.

• 4\textsuperscript{th} stage gain was limited because higher pump power resulted in damage to fiber
Prediction of pulse energy for a 5th stage in 60 micron core diameter fiber

Expect 2-5 mJ out of 60 micron core in 300-1000 ns pulses at a 10 kHz repetition rate
Summary

• 0.3 mJ pulses achieved with 4 stages in 300 ns and 1 µs pulses at a 10 kHz repetition rate. There was a 18 dB SNR between pulses which will impede obtaining higher pulse energy in subsequent stages
  – Need higher power modulation to remove interpulse power e.g. 5 W AOM, higher power Pockel’s cell
• In-band spikes between pulses have same spectrum as pulses so ASE filters aren’t effective at removing spikes between pulses
• 60 micron core for future stage should enable output pulses of 2-5 mJ in 300-1000 ns pulses at 10 kHz
• Will utilize solid state amplifier to obtain higher energy pulses
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