Sub-picosecond pulse amplification in a short length, highly doped erbium/ytterbium phosphate fiber amplifier

Arturo Chavez-Pirson, Wenyan Tian, Shibin Jiang,
NP Photonics Inc., 9030 S. Rita Road, Tucson, Arizona 85747
chavez@npphotonics.com

Gregory Katona, Jane Lee, Axel Schülzgen, Nasser Peyghambarian
Optical Sciences Center, University of Arizona, Tucson, Arizona 85721

Abstract: We demonstrate sub-picosecond pulse amplification in a single mode, high gain, and short length (8cm) erbium-ytterbium phosphate fiber amplifier. The amplifier operates in saturation producing 100 mW of average power and 2 nJ per pulse.

OCIS codes: (060.2320) Fiber optics amplifiers and oscillators; 060.7140 Ultrafast processes in fibers; (060.2410) Fiber, erbium

1. Introduction

Compact optical amplifiers exhibiting short length, low latency, high gain, high power, and low noise are becoming important in diverse application areas, particularly outside standard telecommunications. Conventional erbium-doped fiber amplifiers (EDFA) contain many meters of optical fiber, suffer from long latency (>10 ns), temporal pulse broadening and undesirable nonlinear effects for short (<1 ps) optical pulses. Short path length is highly desirable for amplification of short optical pulses (< 1ps) with high peak intensity since stimulated nonlinear processes rapidly build-up in long fibers–requiring complicated and inconvenient pulse compression elements to restructure the pulse. Short pulses amplified in and delivered by optical fiber are useful in frequency doubling/mixing and continuum generation – as well as in high speed optical processing.

In previous work, we demonstrated a single mode pumped erbium-ytterbium phosphate fiber amplifier with a high gain per unit length (5dB/cm) [1] and high solubility for rare earth ions without ion clustering. We also demonstrated high gain (>20 dB) in multimode pumped erbium-ytterbium phosphate fiber amplifiers [2] and amplifier arrays. [3] The high Er^{3+} and Yb^{3+} concentrations (several percent by weight) in phosphate glass fibers enable high performance fiber amplifiers with short fiber length and low latency. In this paper, we demonstrate sub-picosecond pulse amplification in a short length, single mode phosphate fiber amplifier –which intrinsically manages the effects of dispersion and nonlinearity to generate high peak power and energy from a single mode fiber.

2. Fiber Amplifier Design and Characterization

The fiber amplifier consists of a highly doped (5.5% Er; 0.5%Yb) single mode phosphate fiber with core size of 4.6-microns and with numerical aperture of 0.25. The active fiber is energized with forward and backward pumping by single mode pump diodes operating at 975 nm. The signal and pump beams are single mode throughout the amplifying device. The short length (8 cm) of active fiber is packaged into a pencil-like cylinder with micro-optic lenses and filters such that signals propagate a minimum of physical length in the amplifying section. (< 10 cm) Input (L_i=46cm) and output (L_o=40cm) fiber pigtails of SMF-28 are attached to the packaged fiber device to facilitate fiber coupling into and out of the amplifying section. Figure 1 shows the saturated cw gain spectrum of the amplifier for an input signal of + 2dBm. Over the wavelength range of 1530nm to 1565nm (C-band), the gain is approximately 20 dB.

3. Experimental Configuration and Results

The amplifier is seeded by a sub-picosecond pulse train from an IMRA (Model #B-4-FC) mode-locked Er:fiber oscillator running at 48 MHz. The oscillator produces ~ 300 fs pulses centered at 1555 nm directly out of a fiber connector at the exit aperture. The light is coupled to 46 cm of passive, SMF-28 fiber, with zero dispersion wavelength between 1302 nm and 1320 nm, corresponding to normal GVD values of 22.5 and 23.79 ps^2/km at the spectral peak. The pulse broadens in the fiber to 725-750 fs before entering the gain region, after which it propagates through another 40 cm. Complete spectra for all the amplified pulses are measured separately by an optical spectrum analyzer. Intensity and phase measurements are obtained using the standard SHG-FROG or spectrally-resolved autocorrelation [4]. The 780 nm, second harmonic signal is generated with a 6.667 fs overlap-delay, within a standard 1 mm thick, BBO-crystal, spectrally resolved using a 1/4 meter, 600/mm, Jarrell-Ash spectrometer and captured by Pulnix-1018, 10 bit camera.

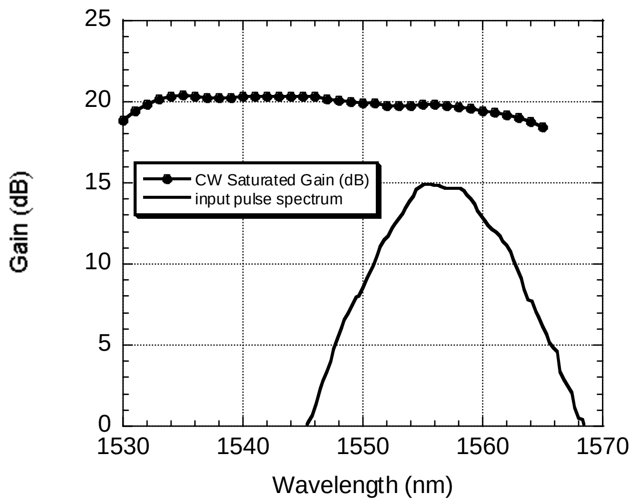


Fig. 1. Saturated CW gain spectrum of short length amplifier at maximum pumping condition. CW input signal power is + 2dBm. For reference, the spectrum of the sub-picosecond pulses from the fiber oscillator after 1m of SMF is shown.

Figure 2 shows the autocorrelation traces derived from the SHG-FROG data. The input pulses are amplified from 5.3 mW of average power up to 8.3, 25, 50, 75 and 100 mW as a function of diode pump currents in the amplifier.

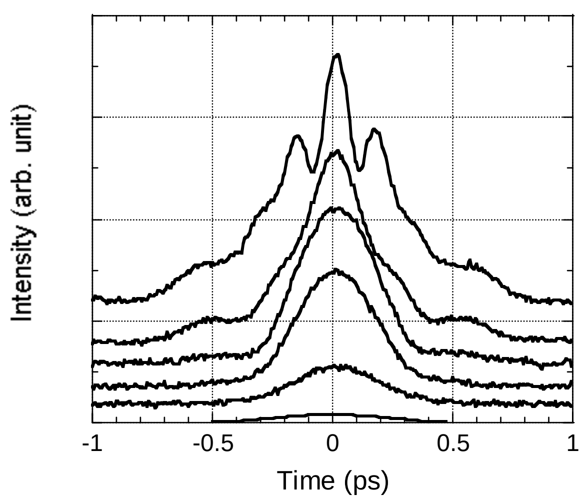
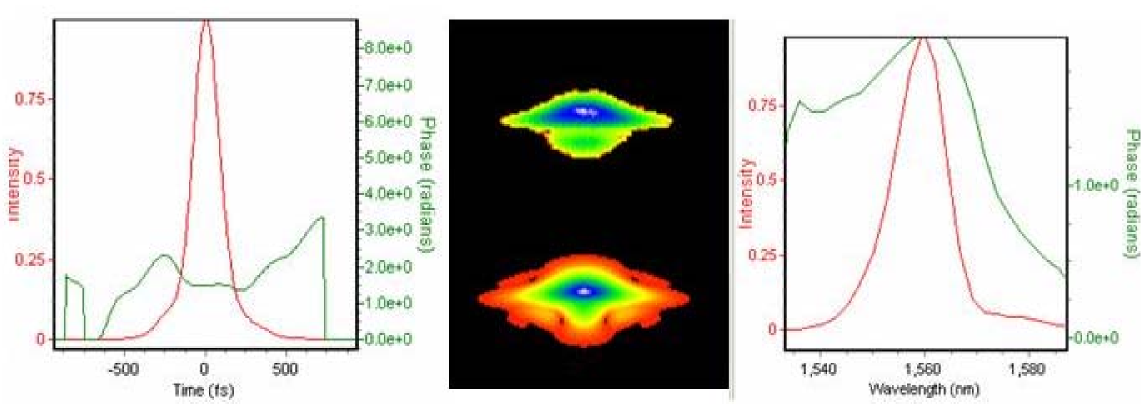


Fig.2. Autocorrelation traces of the amplified pulses for different levels of amplified output power. Input power into amplifier is 5.3 mW (bottom-most trace) and increases with amplifier gain to 8.3, 25, 50, 75, and 100 mW (top-most). Baselines are shifted for clarity.

Figure 3 shows the experimental FROG traces as well as the temporal/spectral phases and intensities for an amplified power of 8.3 mW. The retrieved temporal width is 222 fs with a corresponding autocorrelation of 330 fs (in good agreement with Fig. 2). The 256 x 256 data set is re-sampled along the delay axis top to the sech, transform-limited, time bandwidth product (TBP) of 0.315 and then treated with spectrum, edge and lowest pixel noise filters to obtain a retrieval error of < 0.0065 and a TBP of 0.339. Considering that the length of the BBO crystal is 1mm, we are confident the measurement reliably captures the pulse amplification at this power. At the higher amplified output powers, the pulses are still within the phase matching bandwidth of the crystal, but the long propagation length over which the 2nd harmonic signal and fundamental wavelength pulse need to overlap is too long to overcome intrinsic dispersion. This results in undesired group velocity mismatch, which causes the inversion algorithm to have problems. However, at this 8.3 mW power level where the retrieval is well behaved, we see the interesting effect that the pulses leaving the output fiber pigtail are temporally shorter than those entering the amplifier by a factor of >2. This result implies that the peak powers from the gain region are approaching 1 kW or better and that the temporal narrowing is enough to overcome the normal GVD in the 40 cm output SMF. We suspect this mechanism is related to background index changes during saturation and at lower signal amplification, perhaps nonlinear refractive index changes, stemming from dipole moment alteration when approaching saturation. As the average power increases to 25mW and 50 mW, the pulse widths from the autocorrelation still remain less than 0.5 ps – indicating that the amplifier is preserving temporal integrity without gross distortions. However, the reliability of the SHG-FROG traces at the highest power levels requires more careful study.



(a) (b) (c)

Fig.3. Experimental FROG trace of amplified output pulse for 8.3 mW average power. (a) retrieved temporal pulse field intensity and phase; (b) experimental [top] and theoretically derived [bottom] SHG-FROG trace where time is along the horizontal axis and wavelength is along the vertical axis; (c) retrieved spectral pulse field intensity and phase.

4. Conclusions

We successfully demonstrate sub-picosecond pulse amplification in a short length, highly doped erbium-ytterbium phosphate fiber amplifier. The high gain in a short (8 cm) single-mode amplifying fiber minimizes temporal pulse broadening and distortion due to dispersion and nonlinear effects commonly observed in long fibers. Under certain gain conditions, we observe pulse compression, which we believe is related to nonlinear refractive index changes in the active fiber. Importantly, the amplified sub-ps pulses are produced completely in fiber with active Er:Yb phosphate fiber and passive SMF-28 fiber pigtails - without special pulse compressing elements. The amplifier operates in saturation producing up to 100 mW of average power and 2 nJ per pulse – making it attractive as a seed source for further amplification or for frequency doubling/mixing, continuum generation, or in high speed optical processing.

6. References

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