High power and high energy monolithic single frequency 2 \( \mu \)m nanosecond pulsed fiber laser by using large core Tm-doped germanate fibers: experiment and modeling

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Abstract: We report a high power and high energy all-fiber-based single frequency nanosecond pulsed laser source at \(-1918.4\) nm in master oscillator-power amplifier (MOPA) configuration. The pre-shaped pulsed fiber laser seed with a variable pulse duration and repetition rate were achieved by directly modulating a continuous wave (CW) single frequency fiber laser using a fast electro-optical modulator (EOM) driven by an arbitrary waveform generator (AWG). One piece of single mode, large (30 \( \mu \)m) core, polarization-maintaining (PM) highly thulium-doped (Tm-doped) germanate glass fiber (LC-TGF) was used to boost the pulse power and pulse energy of these modulated pulses in the final power amplifier. To the best of our knowledge, the highest average power 16 W for single frequency transform-limited \(-2.0\) ns pulses at 500 kHz was achieved, and the highest peak power 78.1 kW was achieved at 100 kHz. Furthermore, mJ pulse energy was achieved for \(-15\) ns pulses at 1 kHz repetition rate. Theoretical modeling of the large-core highly Tm-doped germanate glass double-cladding fiber amplifier (LC-TG-DC-FA) is also present for 2 \( \mu \)m nanosecond pulse amplification. A good agreement between the theoretical and experimental results was achieved. The model was also utilized to investigate the dependence of the stored energy in the LC-TGF on the pump power, seed energy and repetition rate, which can be used to design and optimize the LC-TG-DC-FA to achieve higher pulse energy.

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References and links

1. Introduction

Single frequency fiber lasers have been receiving intense interests due to their diverse applications in interferometric sensing, coherent LIDAR, spectroscopy and nonlinear conversion. Such kinds of lasers at 1 μm, 1.55 μm and 2 μm have been developed and commercialized with a very short laser cavity in combination with narrowband fiber Bragg gratings and high unit gain active fibers for robust single-frequency operation [1–3]. Some applications, such as nonlinear frequency conversion, benefit from pulsed single-frequency lasers, which are able to provide high peak powers. To achieve this, Q-switched single-frequency fiber lasers were reported [4, 5]. Another way to get single-frequency laser pulses is to use an electro-optic or acousto-optic modulator (EOM or AOM) to directly modulate a continuous wave (CW) single-frequency laser. This allows the pulse parameters (duration, repetition rate, pulse shape, etc.) to be freely adjusted [6, 7].

Single-frequency fiber oscillators usually can only provide limited power or pulse energy. In the high power or high pulse energy regime, a single-frequency fiber laser source is typically configured as a high-gain master oscillator power amplifier (MOPA) seeded by a low power laser for both CW regime [8–12] or pulsed regime [7, 13–15]. Power and energy scaling for these lasers is more challenging due to their narrow bandwidth, which leads to lower threshold
of Stimulated Brillouin Scattering (SBS). So, usually a large-core gain fiber is used in the final power amplifier to mitigate the SBS [7]. G. D. Goodno et al. reports a 608 W CW single frequency fiber laser source at 2040 nm, which is the highest reported average power achieved from any single-frequency, single-mode fiber laser [11]. C. D. Brook et al. reported a single frequency pulse laser at 1062 nm with >1 mJ pulse energy and >1 MW peak power [13]. However, these systems contain a lot of bulk components, which to some extent sacrifices the benefits of fiber laser sources.

The transition \( \left( ^{3}F_{4} \rightarrow ^{3}H_{6} \right) \) of trivalent thulium provides radiation near 2 µm, which is eye-safe and has wide applications including remote sensing, LIDAR, military and medical applications. It also provides higher conversion efficiency to be used in nonlinear frequency generation for mid-IR and THz sources [16, 17]. Besides, thulium (Tm)-doped fibers are promising medium for building high power fiber laser sources due to the availability of commercial efficient high power 790 nm diode pumps and the 200% theoretical quantum efficiency because of the energy cross-relaxation process (two Tm ions can be excited by one pump ion) [18]. Some thulium-doped fiber lasers/amplifiers with up to 68% slope efficiency have been demonstrated due to this high quantum efficiency although the quantum defect is big [19, 20] (quantum defect is ~58.3% in ref [19]). In order to induce the energy cross-relaxation process, the host material should be chosen to have high solubility of the thulium ions. Heavy metal oxide glasses including germanate glass and fluoride glass, usually have high solubility for thulium ions. Silicate glass can also be heavily doped by thulium ions [20]. In contrast, silica glass has lower thulium solubility and cannot be highly thulium doped. Another concern for choosing host materials is the phonon energy. Higher phonon energy leads to faster multi-phonon relaxation and thus results in lower cross-relaxation rate. Furthermore, the rate of non-radiative decay is higher for materials with higher phonon energy [21]. Silica and silicate have high phonon energy that can extend to 1100 cm\(^{-1}\) [21]. Fluoride glass has very low phonon energy (around 500 cm\(^{-1}\)). But the low mechanical strength and low damage threshold limit its application in high power or energy fiber laser systems. However, the germanate glass has lower phonon energy (900 cm\(^{-1}\)) and it also has better mechanical strength and higher damage threshold than that of the fluoride glass. In this paper, we report a 2 µm all-fiber based single frequency nanosecond pulsed laser system by using a newly developed large core (30 µm) highly thulium doped germanate fiber. Over 16 W average power and nearly 1 mJ pulse energy were achieved for ~2.0 ns pulses at 500 kHz and ~15 ns pulses at 1 kHz repetition rate, respectively. To our best knowledge, this is the highest average power and pulse energy for such kind of all fiber single frequency nanosecond pulsed laser source in the 2 µm regime. All fiber-based construction of this pulsed fiber laser system in MOPA configuration enables robust, maintenance-free and high performance operation. A theoretical model was developed to simulate the performance of the LC-TG-DC-FA. The calculated pulse average power and pulse energy have good agreement with the measured data. The model was also utilized to calculate the dependence of the stored energy in the LC-TGF on the pump power, seed energy and the repetition rate, providing guidance to extract higher pulse energy given a piece of active fiber.
2. Pulse pre-shaping and single frequency nanosecond pulse seed at 2 µm

Figure 1 shows the diagram of our single frequency nanosecond pulse generation system, which consists of an electro-optic modulator (EOM) to directly modulate the CW fiber laser, a Tm-doped pre-amplifier to boost the power of these pulses, an acousto-optic modulator (AOM) (time synchronized to the EOM) to remove the in-band amplified stimulated emission (ASE) and increase the extinction ratio, another Tm-doped preamplifier to further boost the power of these pulses, and a narrow band-pass filter (combining a PM circulator and a fiber Bragg grating) for removing out-of-band ASE generated by the amplifier. A CW single-frequency seed laser was used, which provides ~50 mW linearly polarized laser output at ~1918.4 nm [22]. So the generated nanosecond pulses have very low average power. For example, the average power of ~2 ns pulses at 100 kHz repetition rate is only ~10 µW.

In the fiber amplifier for ns pulses, gain depletion over the time scale of the pulse always distorts the pulse shape [23]. Figure 2(a) shows this pulse distortion with an initial rectangular pulse after the EOM and its amplified version (after the filter shown in Fig. 1). To mitigate this, an arbitrary waveform generator (AWG) was used to drive the EOM to pre-shape the pulses and make its leading edge gently sloped to limit its gain or steepening (see Fig. 2(b)). In addition, the pulse duration and repetition rate can be freely adjusted in our system. Figure 3 demonstrates several pulses with different pulse duration at the output of the nanosecond pulse system. These pulses keep good pulse shape and have large signal to noise ratio (>40 dB) in spectral domain, which makes them suitable seed sources for power and energy scaling.

Fig. 1. Diagram of single frequency nanosecond pulse generation system.

Fig. 2. Initial and amplified pulses (after the filter) for (a) rectangular pulse, (b) shaped pulse.
3. Large-core highly Tm-doped germanate double-cladding fiber amplifier (LC-TG-DC-FA): power scaling

In order to boost the power of the generated nanosecond pulses, an all-fiber chain of two stage double-cladding (DC) fiber amplifiers were used as shown in Fig. 4. Two meters Tm-doped DC-fiber with 10 µm core (from Nufern Inc.) was utilized in the first stage. This was followed by a large core highly Tm-doped germanate fiber (LC-TGF) for the final power amplifier stage. It was designed and drawn in-house based on the rod-in-tube technique. Germanate glasses have higher rare-earth ion solubility, thus highly doped germanate fibers enable shorter laser amplifier length with higher SRS and SBS threshold [24]. The new developed fiber has core and cladding sizes of 30 µm and 300 µm, which has a weight Tm-doping concentration of 4%. The fiber contains two stress rods to produce a birefringence that maintains the polarization of the amplified fiber laser pulses (see the cross-section of the fiber in Fig. 4). One commercial PM (6 + 1) × 1 signal pump combiner was used to combine the 2 µm laser signal and the ~793 nm multimode pump. The end of the output fiber of the combiner was stripped and then was fusion spliced to one end of the ~41 cm LC-TGF based on an asymmetric fusion splicing technique. The fusion splice joint and the whole LC-TGF were fixed in a v-groove in a copper plate (see Fig. 4) under fans for air cooling. A low index polymer was coated around the stripped fiber near fusion splice joint to confine the pump power in the inner cladding.

In order to get the high power and high peak power at the same time, we choose to amplify ~2ns fiber laser pulses at high repetition rate (100 kHz to 500 kHz). This high repetition rate enables enough power (9.2 mW @ 100 kHz, 19.3 mW @ 300 kHz, 25.7 mW @ 500 kHz), output from the pulse generation system (shown in Fig. 1), to seed the first DC-amplifier. After the first DC-amplifier, the power was amplified to ~350 mW, ~420 mW, ~450 mW for 100 kHz, 300 kHz, 500 kHz repetition rate, respectively and no nonlinearities were observed from their spectrum.
Figure 5(a) shows the output power of the final large-core Tm-doped germanate fiber amplifier under different pump levels at three different repetition rates. The maximum average power of 16.01 W was achieved at 500 kHz repetition rate. This is the highest average power for all fiber based single frequency nanosecond pulses in the 2 µm regime. One can see that there is no big difference between the average powers for amplified pulses at the three repetition rates (100 kHz, 300 kHz and 500 kHz). The pump power shown in Fig. 5(a) is the power after the combiner. The power conversion efficiency for the power amplifier stage is ~17.1% in respect to the launched pump power (after the combiner). The low efficiency mainly results from the big propagation loss for both the laser signal and the pump in the germanate fiber. The pulse shape for the high power pulses (at ~16.01 W) from the final output is recorded by a fast detector and one oscilloscope as shown in Fig. 5. The pulse keeps a good shape and the pulse duration is ~2.0 ns. For the amplified pulses, the spectrum was measured using a modified optical spectrum analyzer (OSA) as shown in one inset of Fig. 5. One can see that the signal to noise ratio (SNR) is > 40 dB from the spectrum. The good pulse shape and >40 dB SNR in spectrum domain ensure that the peak power can be calculated using average power and repetition rate shown in Fig. 5(b), which was calibrated by a fast pulse energy meter (Ophir PE9F-SH) when the repetition rate was below 20 kHz. The maximum of ~73.1 kW peak power was achieved, which is also the reported highest peak power of all fiber single frequency laser source in the 2 µm regime. One scanning Fabry-Perot interferometer was built to measure the spectra of our single frequency laser pulses at high power regime. The FSR and the bandwidth of the interferometer is ~3 GHz and 9.6 MHz. The inset in Fig. 5(b) shows the typical Fabry-Perot scanning spectra of the ~2 ns second pulses with over 10 W average power. The linewidth was measured to be ~277 MHz, which is close to transform limited. The beam profile was measured by using a Spiricon Pyrocam III (see inset in Fig. 5(b)). The measured $M^2$ of the output pulses is about 1.3. In the previous papers, highly doped active fibers are usually utilized for pulse energy scaling due to the fact that it enables short length of amplifier to effectively suppress the nonlinearities [7, 15, 22]. In this paper, the newly developed highly thulium-doped germanate fiber was successfully used for high power application to achieve over 16 W single frequency transform-limited nanosecond pulses.
Fig. 5. (a) Average power of the pulse under different pump level. Inset: Pulse shape and spectrum when the power is ~16.01 W. (b) Peak power of the pulse under different pump level. Inset: Fabry-Perot scanning spectra and the beam profile of the amplified ~2 ns pulses (over 10 W average power).

4. Large-core highly Tm-doped germanate double-cladding fiber amplifier (LC-TG-DC-FA): Modeling and Energy Scaling

Here we also present a numerical model for the LC-TG-DC-FA. Figure 6 shows the energy level diagram of Tm$^{3+}$ in germanate glass [25]. The $^3H_6 - ^3H_4$ transition corresponds to the 793-nm pump band and the $^3F_4 - ^3H_6$ transition corresponds to the signal band near 2 µm. The well-known $^3H_4 - ^3F_4$ cross-relaxation effect [16] and the inverse cross-relaxation effect were taken into account in the presented model. Equations (1–6) are a set of rate equations and propagation equations for laser signal, ASE and pump [26].

\[
\frac{\partial N_3}{\partial t} = W_{03}N_0 - \frac{1}{\tau_{31}}N_3 - K_{3011}N_3N_0 + K_{1130}N_1^2 
\]

\[
\frac{\partial N_1}{\partial t} = W_{10}N_0 - W_{10}N_1 - \frac{1}{\tau_{10}}N_1 + \frac{1}{\tau_{31}}N_3 + 2K_{3011}N_3N_0 - 2K_{1130}N_1^2
\]

\[
\frac{\partial N_0}{\partial t} = -W_{03}N_0 - W_{10}N_1 + W_{10}N_0 + \frac{1}{\tau_{10}}N_1 - K_{3011}N_3N_0 + K_{1130}N_1^2
\]

\[
\frac{1}{V_s} \frac{\partial}{\partial t} + \frac{1}{V_z} \frac{\partial}{\partial z} P_s(z,t) = \left[ \Gamma_s [\sigma_{10}(\nu_s)N_1(z,t) - \sigma_{01}(\nu_s)N_0(z,t)] - \alpha_{\text{loss-signal}} \right] P_s(z,t) 
\]

\[
\frac{1}{V_{\text{ASE}}} \frac{\partial}{\partial t} + \frac{1}{V_z} \frac{\partial}{\partial z} P_{\text{ASE}}(\nu_s, z,t) = \left[ \Gamma_s [\sigma_{10}(\nu_s)N_1(z,t) - \sigma_{01}(\nu_s)N_0(z,t)] \right] \\
- \alpha_{\text{loss-signal}} P_{\text{ASE}}(\nu_s, z,t) + \Gamma_s \sigma_{10}(\nu_s)N_1(z,t)P_0 
\]

\[
\frac{1}{V_p} \frac{\partial}{\partial t} + \frac{1}{V_z} \frac{\partial}{\partial z} P_p(z,t) = [-\Gamma_p \sigma_{03}(\nu_p)N_0(z,t) - \alpha_{\text{loss-pump}}] P_p(z,t)
\]
Fig. 6. Energy levels and transitions taken into account in the presented model for Tm$^{3+}$ in germanate glass.

Here, $N_j$ is the population of the jth level in the energy diagram shown in Fig. 6. $\tau_{31}$ and $\tau_{10}$ are the lifetime of the thulium ions. $K_{3011}$ and $K_{1130}$ are cross relaxation rate and inverse cross relaxation rate, respectively. $\Gamma_s$ is the overlap factor of the single-mode signal field and is assumed to be the same for all signal ASEs. $\Gamma_p$ is the overlap factor of the multi-mode pump field. $V_s$, $V_p$ and $V_{ASE}$ are group velocity of laser signal, pump and ASE. $\sigma_{31}$ and $\sigma_{10}$ are the absorption and emission cross sections of thulium ions from the first $3^3H_6$ level to the second $3^1F_4$ level (see Fig. 6). $\sigma_{30}$ is the absorption cross section of thulium ions from the first $3^3H_6$ level to the fourth $3^1H_4$ level (see Fig. 6). These spectroscopic parameters (cross sections, life time, etc.) of the thulium ions in germanate glass are obtained from ref [25]. $\alpha_{loss-signal}$ is the propagation loss of the laser signal in the Tm-doped germanate fiber and was measured to be $\sim 5$ dB/m. $\alpha_{loss-pump}$ is the pump propagation loss in the fiber and was estimated to be $\sim 5$ dB/m. The propagation loss of the ASE (1600nm to 2000 nm) is assumed to be same with that of the laser signal. $P_i(\lambda) = 2hc^2/\lambda^5$ indicates the contribution of the spontaneous emission into the mode. $W_{01}$, $W_{10}$ and $W_{03}$ are light-induced transition rates for laser signal and pump and can be given in Eqs. (7–9) [26].

$$W_{01} = \Gamma_s \frac{\sigma_{01}(\nu_s)P_s(z,t)}{h\nu_s A} + \sum_i \sigma_{01}(\nu_i)\left[P_{ASE}^{(i)}(\nu_i,z,t) + P_{ASE}^{(i)}(\nu_i,z,t)\right]$$  \hspace{1cm} (7)

$$W_{10} = \Gamma_s \frac{\sigma_{10}(\nu_s)P_s(z,t)}{h\nu_s A} + \sum_i \sigma_{10}(\nu_i)\left[P_{ASE}^{(i)}(\nu_i,z,t) + P_{ASE}^{(i)}(\nu_i,z,t)\right]$$  \hspace{1cm} (8)

$$W_{03} = \Gamma_p \frac{\sigma_{03}(\nu_p)P_p(z,t)}{h\nu_p A}$$  \hspace{1cm} (9)
One program was developed based on these equations mainly using 4th order Runge-Kutta method. It should be noted that pulses with Gaussian shape were utilized in this model. In order to verify the program, the average power of the pulses at 500 kHz repetition rate was calculated and compared with the measured data as shown in Fig. 7(a). We can find that the calculated data and the measured data matched very well. The measured and the calculated data also matched very well for pulses both at 100 kHz repetition rate and 300 kHz repetition rate. From the error bars of the experimental data, one can see that the power fluctuation is below 3%.

Using this model, we also calculated the pulse energy for ~15 ns pulse at 5 kHz repetition rate and compared them with the reported experimental data in ref [22], as shown in Fig. 7(b). From the error bars of the experimental data, one can see that the pulse energy fluctuation is below 3%. The important thing is that this model can be utilized to effectively and accurately evaluate and estimate the performance of the LC-TG-DC-FA.

Using this model, we investigate how to extract more pulse energy from a piece of active fiber. We calculate the stored pulse energy in the thulium-doped germanate fiber defined by Eq. (10),

\[ E_s(t) = \hbar v_s A \int_0^L N_s(z,t) dz \]  

where \( v_s \) is the frequency of the laser signal, \( A \) is the core area and \( L \) is the length of the active fiber.

![Fig. 7](image-url)

Fig. 7. (a) Simulated and measured average power of ~2 ns pulses at 500 kHz repetition rate under different launched pump power. The error bars denote the power fluctuation. (b) Simulated and measured pulse energy of ~15 ns pulses at 5 kHz repetition rate under different pump power. The error bars denote the pulse energy fluctuation.

![Fig. 8](image-url)

Fig. 8. The calculated stored energy in the active fiber for seed pulses at different repetition rate under (a) 20 W and (b) 35 W pump when the seed energy is fixed at 20 \( \mu J \).
Figure 8(a), (b) demonstrates the stored pulse energy in a ~41 cm LC-TGF with a 30 µm-diameter core at different repetition rate under 20 W and 35 W pump, respectively. Note that the seed pulse was ~15 ns Gaussian pulse with 20 µJ pulse energy. Figure 9 shows the dependence of stored energy on the seed energy. The pump and repetition rate are fixed at 20 W and 5 KHz, respectively. When the pump was launched into the active fiber, the electrons in the ground state will be excited into the upper laser energy level and thus the energy will be stored there. When a pulse propagates through the active fiber, the stored energy was extracted by the pulse and thus drops to its minimum, then starts to grow almost linearly with the time and the slope is dependent on the pump power and almost independent of repetition rate. The sharp energy drop, shown in Fig. 8, is the extracted pulse energy. We investigate the dependence of the stored energy on the repetition rate, pump power and seed energy. Specifically, when pump power and seed energy are fixed, lower repetition rate leads to more stored energy and more extracted energy; when repetition rate and seed energy are fixed, higher pump power enables more stored energy and more extracted energy; when repetition rate and pump power are fixed, higher seed energy leads to less stored energy but more extracted energy. It should be noted that, when the repetition rate was lowered to certain value under high pump level, some stored energy will be lost to the induced ASE (the rolling over of the stored energy shown in Fig. 8(b) for 1 kHz cases). Compared with 5 kHz and 10 kHz cases, much more energy could be extracted from the active fiber for 1 kHz case as shown in Fig. 8. So in the experiment, we set repetition rate at 1 kHz and boost the pulse energy. Nearly 1 mJ pulse energy was experimentally achieved as shown in Fig. 10. From Fig. 8(b), about ~2.5 mJ pulse energy can be theoretically extracted when the pump is ~35 W. There is a difference between the measured (1 mJ) and the calculated (2.5 mJ) energy. One reason is that a lot of ASE was induced in the process of amplifying 1 kHz repetition pulses, but the affect of ASE on the energy scaling has not been accurately handled in the current model. Another reason is that gaussian pulse shape is assumed in the model but the pulse distortion is heavier for low repetition rate pulse amplification. In the future, we will try to utilize pulsed pump for the low repetition rate (< 1 KHz) pulses amplification to suppress the ASE and to extract higher pulse energy.
Fig. 10. Measured pulse energy of ~15ns pulses at 1 kHz repetition rate under different pump level.

5. Conclusion

In conclusion, we have successfully implemented a monolithic pulsed fiber laser system based on MOPA configuration which can produce over 16 W average power and 73.1 kW peak power single frequency transform-limited ~2 ns pulses in 2 µm regime. The laser system can also work in high energy regime to produce nearly 1 mJ ~15 ns pulses at 1 kHz repetition rate. One numerical model was built to model the LC-TG-DC-FA and a good agreement between experiment and numerical results was reached. Using this model, we also investigated the dependence of stored energy and extracted energy on pump level, seed energy and repetition rate, which provides references to design and optimize the LC-TG-DC-FA to achieve higher pulse energy given a piece of active fiber. The reported high power, high energy transform-limited pulses can be used for coherent LIDAR, laser remote sensing and nonlinear laser frequency conversion, such as parametric THz generation [17].

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