Mitigation of Self-Pulsing in High Power Pulsed Fiber Lasers

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ABSTRACT
In this paper, we outline the challenges in amplifying low duty cycle pulses in a Yb-doped fiber laser based on the Master Oscillator Power Amplifier (MOPA) configuration. Specifically, we present the results of a Finite Difference Time-Domain (FDTD) model to study the onset of self-pulsing, and the self-pulsing mitigation strategies leading to an optimized design of the fiber amplifier. Finally, we discuss the experimental demonstration of 4.5 kW peak power pulses in 40 ns pulses at a repetition rate of 25 kHz in a fiber laser based on the above design.

Keywords: Fiber Lasers, Master Oscillator Power Amplifier, Relaxation Oscillations, Self Pulsing.

1. Introduction:
High peak power (kW level) pulsed lasers emitting tens of ns pulses at kHz repetition rate find wide applications in material processing, marking, medical surgery and defence [1]. Rare-earth doped fiber lasers are attractive for such applications as they provide advantages in terms of output beam quality, thermal management, wall-plug efficiency, and low cost of maintenance over conventional solid state lasers [2]. Specifically, the development of double clad fiber geometry facilitates pumping using high power multi-mode (MM) laser diodes providing efficient conversion from low brightness pump radiation to high brightness laser output [1,2]. An excellent example of this aspect is fiber lasers doped with Ytterbium (Yb) ions, which offer many advantages for power scaling i.e. low thermal load (due to low quantum defects), high efficiency (>70 %) and higher doping concentration (high pump absorption per unit length). Yb-doped double-clad fibers also offer a wide range of options for pump wavelength (915 nm and 975 nm absorption bands) and can provide lasing at wavelengths ranging from 975 nm to 1200 nm [3]. A specific wavelength of interest in the laser community is 1064 nm, as it is a potential replacement for bulky Nd:YAG lasers.

A popular configuration for achieving kilo-Watt level output peak powers at flexible pulselength and repetition rate required for the above applications is the Master Oscillator Power Amplifier (MOPA) configuration [2]. The key idea is to use a well controlled, stable, relatively low power master oscillator (such as a semiconductor laser diode) and amplify the output pulses using the rare-earth (Yb) doped double-clad fiber. The schematic diagram for such a setup is shown in Figure 1. The master oscillator is used to generate the pulses with the desired pulse width, pulse shape, and repetition rate at 1064 nm. The Yb-doped double clad fiber (DCF) is pumped using a multi-mode semiconductor laser diode at 915 nm. The pump combiner is used to couple the multi-mode pump power into the inner clad of the double clad fiber, while coupling the master oscillator output to the core of the double clad fiber. The pump radiation gets absorbed in the doped core region, providing the gain for the signal radiation from the master oscillator. An isolator is used at the output of master oscillator to protect it from any back reflected amplified spontaneous emission (ASE) that is typically generated across the length of double clad fiber.

![Figure 1: Schematic diagram of a high power pulsed fiber laser in the Master Oscillator Power Amplifier (MOPA) configuration.](image-url)

The above configuration has been widely used for generating kiloWatt-level optical pulses with pulselength in the order of 100 ns [2,4]. However, it is quite challenging to obtain such high peak power levels when the pulses have very low duty cycle (<1%). This is due to the long OFF duration (absence of signal at 1064 nm) for...
such a pulse train during which the gain medium is continuously pumped. Such pumping in the OFF duration in high power pulsed fiber amplifiers is likely to cause backward-propagating ASE and possibly even self-pulsing [5,6]. In addition, there may be other challenges such as non-linear effects at high power level and occurrence of pulse distortion due to gain saturation [1,7]. In such cases, one has to carefully manage the ASE, the population inversion along the gain medium, as well as the nonlinear effects by employing multiple amplifier sections.

In this paper, we discuss several of the above challenges while amplifying a pulse train with a very low duty cycle (0.1%) to kilo-Watt peak power levels. Specifically, we describe the origin of self-pulsing and study its dependence on various amplifier parameters such as amplifier length, duty cycle of input pulses, and the input signal power through a FDTD model. Finally, we present an optimized design of the fiber amplifier that addresses the above challenges, resulting in the demonstration of 4.5 kW of peak power in 40 ns pulses at 25 kHz repetition rate with a single polarization output (20 dB polarization extinction) and excellent beam quality (M² of 1.1).

2. Simulation for a pulsed Amplifier

As mentioned above, there are several challenges in realizing high power amplifiers which may be addressed through an appropriate model of the Yb-doped fiber amplifier to understand the effects of doped fiber length, pump power and signal power levels on the output pulse characteristics. Specifically, complete time domain simulations need to be performed using finite difference time domain (FDTD) technique to observe any occurrence of self pulsing [8]. Fiber lasers are known to exhibit different unstable regimes in the presence of saturable absorption inside the cavity [9]. Such saturable absorption may be due to non-uniform inversion levels across the gain medium, which is a common feature in typical fiber amplifier systems. Previous simulations show that relaxation oscillations due to population dynamics in the gain medium may result in a continuous stream of pulses under certain pumping conditions [9]. Such self-pulsing has also been previously reported through experiments in a Yb-doped fiber laser cavity [10]. They reported the generation of these pulses more prominent for laser with non-uniform inversion across fiber length which mostly occurs for lasers with low reflectivity (low finesse). A similar situation may exist in our fiber amplifier as we try to pump the gain medium with relatively high power to achieve high gain, which can result in self-pulsing even with a very small (0.01%) back-reflection from the isolators at either end of the amplifier.

The FDTD simulations were performed for the amplifier configuration shown in Figure 1. The Yb doped double clad fiber (Nufern fiber with core/inner clad dia of 5/125 μm, NA 0.13/0.45) used in our work has pump absorption of 0.55 dB/m at 915 nm. The amplifier was pumped using MM diodes at 915 nm. First, FDTD simulation was done for the case when no signal is applied at the input of an amplifier. The length of Yb-doped fiber was taken as 12 m. The reflectivity of 40 dB was considered at the ends of the fiber for the ASE band from 1000 nm to 1100 nm. This small reflectivity can possible occur due to return loss of various components. The result obtained is shown in Figure 2a. At the pump power of about 3.3 W, relaxation oscillations were observed which decays to CW lasing at 1070 nm. This implies that this small amount of reflectivity is sufficient to cause lasing in the amplifier setup at this pump power levels.

The simulations were done for the case when a 40 ns pulsed signal with 100 mW peak power and 25 kHz repetition rate (low duty cycle) is applied at the input. The simulation results obtained for various values of pump power is shown in Figure 2b. When a pulsed input signal is applied at the input, an amplified pulse arrives at the output and some part of that pulse is reflected back into the cavity due to the reflections at either ends of the fiber amplifier. This reflected pulse gets amplified and comes out as second pulse. This is continued till the gain is depleted in the cavity. The gain then again starts building up due to CW pumping in signal OFF duration. If the gain built up in the signal OFF duration is sufficient to overcome the losses in the cavity, relaxation oscillations will initiate the lasing process as shown for 2 W pump power level in Fig. 2b. The effect of reduction in length of Yb-DCF on output is shown in Figure 2c, which show that by reducing the length from 12 m to 8 m, the lasing threshold and output peak power can be increased. The increase in the lasing threshold is due to the lower generation of ASE in the OFF duration, resulting from a more uniform inversion along the fiber length. The increase in the output peak power is due to the fact that for 12 m length, the lasing is occurring in OFF duration which reduces the available gain for input signal. The lasing threshold and amplified signal power is also seen to increase with increase in the input signal power, as shown in Figure 2d.
From the above simulations, it was observed that in the amplifier with low duty cycle (longer signal OFF duration), lasing can occur in the OFF duration possibly leading to self-pulsing. It is also observed that a higher pump threshold for lasing in pulse OFF duration and higher output power can be achieved by reducing the amplifier length and increasing the input signal power. An added advantage is that it also leads to low level of ASE generation in the amplifier.

3. Experimental Observation of Self-Pulsing

Experiments were performed to observe the occurrence of self-pulsing in an amplifier using the setup illustrated in Fig. 1. Occurrence of such pulses in a pulsed amplifier is also previously reported by Sousa et. al. [12], which was limiting the gain obtained from their amplifier. They reported the reflectivity from fiber end facets as one of reasons which can generate such pulses. In our setup, the amplifier based on 12 m of Yb DCF was pumped without any input signal, similar to the case discussed in simulation when no signal is applied. As the pump power reaches about 3.3 W, the pulses were observed at the output as shown in Figure 3a. The pulse train was observed to be occurring at random instances and the corresponding optical spectrum was observed to be having a lasing peak at about 1075 nm [6]. Such generation of pulses may be related to the occurrence of a certain type of passive Q-switching known as self-pulsing, which has been reported previously [5,10,11] during CW laser operation. The occurrence of self pulsing is primarily attributed to saturable absorption effect at certain sections of Yb-DCF due to insufficient inversion. The reflectivity is added due to pump combiner and isolator spliced at both ends of the fiber. This hypothesis is confirmed by the oscillations observed in the generated pulses corresponding to the round trip time of 12 m Yb-DCF (~120 ns) as shown in inset of Figure 3a. The time period between two peaks in relaxation oscillation (Figure 2a) was observed to be similar to the time period of peaks which are observed in one experimental pulse (Figure 3a). Also, the lasing peak of self pulsing occurring in an experiment is nearly same as the lasing wavelength shown by the simulations. This shows that the relaxation oscillations can be the cause for self-pulsing [5, 6].

We also checked if self-pulses occurred in presence of pulsed input signal with larger pulse ON duration i.e. high duty cycle. The signal was applied in pulses of 1 µs with 25 kHz (40 µs) having peak power of 10 mW. As the pump power is increased to about 0.98 W, a large pulse was also observed along with the amplified pulses at the output as shown in Figure 3b. The peak power of this pulse was measured to be about 800 W with pulse-width of about 50 ns, which was high enough to generate SRS non-linearity. In the output spectrum a SRS peak for stokes component was observed at about 1130 nm. The occurrence of this pulse was found to be random in nature and it causes instability at the amplified output pulse train. The peak power of this self generated pulses were high enough that if reflected backward they can possibly damage the master oscillator and pump diodes.
Therefore the operation of an amplifier has to be limited before the occurrence of such pulses. To prevent the damage of master oscillator due to this self-pulses, we inserted an ASE filter at the input of amplifier (to filter self pulses generated at 1070nm) and also to protect pump diodes we choose the diodes with in-built ASE filter (JDSU) for our experiments.

![Figure 3: Self pulsing in MOPA with (a) no input signal, (b) pulsed input signal](image)

The experiments done with 12 m fiber length, applying signal peak power of 10 mW for 1 µs pulses with 25 kHz repetition rate whose results were shown in Figure 3b was repeated with 8 m length. For the 8 m length fiber, the self pulsing starts occurring at pump power of 1.37 W as compared to 0.98 W for 12 m length. The experimental result is shown in Figure 4a. The amplified signal peak power measured for 8 m length is found to be lower than for 12 m length, possibly due to error in experimental measurement. Now the input signal peak power was increased from 10 mW to 600 mW and threshold for self pulsing occurrence and output peak power was observed to be increased as shown in Figure 4b. This trend is in agreement with the simulation results. Now the pulse width is reduced to 40 ns from 1 µs keeping repetition rate constant and the corresponding experimental result is shown in Figure 4c. The threshold for self pulsing is reduced as expected going from high duty cycle (small OFF duration) to a lower duty cycle (larger OFF duration).

![Figure 4: Output of 8m length with (a) 10 mW signal power in 1µs pulses as input, (b) 600 mW signal power in 1µs pulses as input, (c) 600 mW signal power in 40ns pulses as input](image)

### 4. Experimental results

Based on the above results, we arrived at a optimized design for the fiber amplifier. A semiconductor laser diode stabilized using a fiber Bragg grating at 1064 nm (Lumics) is used to generate pulses of 40 ns with 25 kHz repetition rate. The maximum achievable output peak power from the laser diode is about 100 mW. As
mentioned in the previous section, self pulsing starts occurring in amplifier along with amplified pulses. In order to increase the threshold for self pulsing occurrence, the diode output was further amplified using a pre-amplifier. The pre-amplifier consisted of a 2 m long single-clad Yb doped fiber as gain medium pumped using a 976 nm semiconductor laser diode (3S Photonics). Using the pre-amplifier, the laser diode output pulses were amplified to about 10 W peak level. The amplified pulses as shown in Figure 5a are then applied as an input to the amplifier. The amplifier stage consisted of 8 m Yb-DCF (core/clad dia of 5/125 μm, NA 0.13/0.45) and was pumped at 915 nm using multi-mode (core/clad dia of 105/125 μm, NA 0.22) semiconductor laser diode. The amplified output obtained was reaching about 150 W peak power before self pulsing starts occurring in the setup. This output obtained as shown in Figure 5b. Note that the pulse shape is slightly distorted due to gain saturation effects.

![Oscilloscope trace of output pulse obtained from (a) pre-amplifier stage for pump power of 400 mW, (b)1st stage amplifier for pump power of 1.15 W](image)

Figure 5: Oscilloscope trace of output pulse obtained from (a) pre-amplifier stage for pump power of 400 mW, (b)1st stage amplifier for pump power of 1.15 W

The maximum peak power which can be obtained from the amplifier will get limited by the non-linear process of stimulated Raman scattering (SRS). The SRS threshold calculated theoretically for a 40 ns pulse in 8m fiber is about 400 W [13]. The output power can be scaled further by using a large mode area (LMA) double clad fiber [1,2]. In the LMA fiber, the nonlinear SRS threshold is increased by increasing the core area of the fiber while reducing the core-cladding refractive index difference to satisfy the single-mode condition. The larger core area also allows enhanced doping concentration of Yb ions, which results in the reduction of amplifier length and further increasing the nonlinearity threshold. An added advantage of the reduced core-cladding refractive index difference in LMA fibers is that the numerical aperture (NA) between core and inner cladding is reduced, resulting in the fiber supporting lesser cone of angles from spontaneous emission and hence helps reduce the ASE power generation. Therefore, an Yb-doped LMA DCF amplifier was used to further amplify the power obtained from the conventional DCF-based amplifier stage. The Yb-LMA-DCF (Nufern, LMA-25/250) used in our work has core and inner cladding of diameters 25 μm and 250 μm respectively. The pump absorption at 915 nm is about 1.85 dB/m. The optimum length was found out to be around 6 m through steady-state simulations using RP FiberPower, beyond which we did not observe any significant improvement in output power.

The second stage consists of 10 m Yb-DCF large mode area fiber and is also pumped using 915 nm multimode laser diodes. As shown in Figure 6a, output peak power of about 4.5 kW (4.5 W average power) is obtained with about 10 W of pump power. The output power is limited only by pump power and can be scaled further. No self-pulsing was observed to occur till this pump power level. The corresponding output spectrum seen in Figure 6c shows more than 40 dB extinction between the signal and forward ASE. Above the pump power of 8 W, the generation of stimulated Raman scattering (SRS) component at ~1020 nm is observed, which is about 20 dB below the signal power at 1064 nm. The SRS threshold is calculated as ~8 kW for 10 m length of such LMA fiber. The oscilloscope trace of the pulses obtained from the dual-stage amplifier (Figure 6b) shows the effect of gain saturation in the trailing portion of the pulse. The LMA fiber of the second stage is also coiled with about 10 cm diameter in a ‘Figure 8’ configuration to achieve single mode output beam with M² value of ~1.1.
5. Conclusion

As stated in the Introduction, the key objective of our work is the realization of a low duty cycle kW-level fiber laser source based on the master oscillator power amplifier (MOPA) configuration. Based on the design parameters obtained by simulations, a dual stage MOPA configuration is designed to achieve kW peak powers for 40 ns pulses with 25 kHz repetition rate. The LMA fiber used in second stage not only helps to overcome the non-linear effects such as SRS but also reduces the ASE power generation and pulse distortion due to gain saturation effect, while amplifying the signal power to the kiloWatt level.

A key challenge in the above design is the self pulsing generation along with amplified pulses. The buildup of ASE power in the signal OFF duration along with the spurious reflectivity present in the setup are found to be the main reasons for these self pulses. Based on the FDTD simulations performed, we concluded that to obtain higher power without self pulsing generation in the amplifier we need to reduce the length of Yb-DCF and increase the input signal power. The input power to the first amplifier stage was increased by using a pre-amplifier stage at the output of master oscillator. Due to the low level of ASE generation in the LMA fiber, no such self pulsing were observed till 10 W of pump power. To obtain a single mode output and to overcome mode shifting effect [14] the LMA fiber was coiled with 10 cm diameter in ‘Figure 8’ configuration. Using multiple stages of amplifier, we have sucessfully achieved peak power of 4.5 kW for 40 ns pulses with 25 kHz repetition rate.

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References:


