A.1 High Pulse Energy Yb:YAG MOPA and Non-Linear Frequency Conversion Module for Remote Sensing Applications

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Efficient energy storage and extraction from a solid state laser is important for pulsed laser applications such as laser remote sensing of stratospheric ozone or tropospheric wind velocities. We present a design for an all solid state master oscillator, power amplifier (MOPA) laser system based on laser diode (LD) pumped Yb:YAG slab laser technology. The Yb:YAG MOPA system is designed to generate a one micro-second ($\Delta \tau = 1 \mu s$) 1 J macro-pulse at a 10 Hz repetition rate. The Yb:YAG MOPA can operate with 1 MHz transform limited linewidth. Demonstration of 100 mJ pulse output is a critical first step toward the demonstration of a 1 J pulse Yb:YAG MOPA. In a prior study for BMDO, we have shown that a 10 J pulse meets the demands of an all solid state laser illuminator that achieves S/N = 10, with a target resolution of 20 cm at distances up to 4000 km [1]. Our research program also sets the stage for the development of such a system.

The beauty of the MOPA architecture is that it offers soft failure mode and allows scaling by implementing power-amplifiers in the chain. However, for efficient energy extraction in each power amplifier the fluence at the input must be at least equal to the Yb:YAG saturation fluence ($J_{sat} = 9.6$ J/cm$^2$). Because the optical damage fluence for 10 ns Q-switched pulses is less than 9.6 J/cm$^2$, it is not possible to extract the stored energy from Yb:YAG amplifiers efficiently without causing optical damage. However, since the optical damage fluence for a 1 micro-second macro-pulse is 100 J/cm$^2$, it is possible to extract the stored energy efficiently without optical damage by using microsecond duration pulses.

The gain coefficient ($g_0l$) in most practical solid state amplifiers is limited to 3 because of the onset of parasitic oscillations. Depending on the specifics of the amplifier design, the smaller gain cross-section of Yb:YAG allows us to store ~ 10 times more energy per unit volume then Nd:YAG. Thus, by careful choice of pulse duration in the amplifier it is possible to saturate and extract efficiently a significant fraction of the stored energy without optical damage to the Yb:YAG crystal.

To meet the application requirements, we have designed a MOPA laser system, a traditional technique for scaling laser systems to high powers, while maintaining good beam quality and coherence. The laser system consists of a master-oscillator, pre-amplifiers, and a 100 mJ multi-pass amplifier. The Yb:YAG amplifiers are designed with the zig-zag slab [2] geometry. The MOPA configuration provides the ability to tailor the pulse width, beam divergence, and spectral width of the output pulses with low power components prior to the power amplifier. The scaling to high output pulse energy is determined by the power amplifier design. The MOPA system design enables the system to operate with longer pulse lengths, achieve good coherence control, with better power and timing stability, and operational reliability than conventional Q-switched based laser systems.
High Pulse Energy Yb:YAG Laser Design Specifications

Yb:YAG micro-chip Master Oscillator Module

At the heart of a coherent MOPA system is a highly coherent cw master oscillator based on the work of Taira[3]. The output of the 1 W cw master-oscillator is shaped into 1 µs pulses at a 10 Hz repetition rate with the aid of an acousto-optic modulator. These macro-pulses are then amplified in a pre-amplifier and a 100 mJ slab amplifier.

Pre-Amplifier Module and 100 mJ slab amplifier module

Pre-amplifier slabs 1 and 2 are double-passed as shown in Figure 1, where the 1 micro-Joule macro-pulses shaped by the acousto-modulator are amplified to the 7 mJ level. The end-pumped slab dimensions are 0.4 mm x 0.4 mm x 11 mm. Each slab is pumped with 120 W of cw power with cw fiber-coupled LDs, modulated at 10 Hz with a 1% duty cycle (i.e. 0.120 J per pulse, pump energy).

The average pump power is 1.2 W. The small signal gain, $g_0$, in each slab is conservatively set at 2.25. As a consequence, the macro-pulse output of the first slab is 87 µJ pulse, and the pulse output of the second slab is 7 mJ.

In the next stage of amplification, the 7 mJ pulses are amplified to the 100 mJ level in an edge pumped multi-pass, slab amplifier of dimensions width = 5.3 mm, length = 2.4 mm and thickness = 0.89 mm. The 30J/cm³ energy storage density of Yb:YAG permits very small volumes and thus excellent thermal control and average power scaling as discussed earlier. The design of the 6 bounce, double-pass, edge-pumped Yb:YAG power amplifier is based on the design of a cw fiber-coupled LD pumped Yb:YAG laser [2].

Our studies have shown that high brightness LD pumping permits efficient operation of a quasi-three level laser systems such as Yb:YAG with millisecond upper level storage times. The edge pumping innovation allows the realization of a compact, conduction cooled, reliable, laser engine that will permit operation at pulse energy levels that will meet the requirements for global remote wind sensing and stratospheric ozone concentration measurement applications. Edge-pumped slab lasers inherently allow energy to be stored and extracted in a variety of pulse formats depending on the application. By careful engineering it is possible to extract both high pulse energies and high average power from an edge-pumped slab laser system.
On a practical note, parasitic oscillations can limit the gain achievable in a slab lasers and amplifiers and therefore limit the stored energy. We propose to suppress parasitic oscillations in each amplification stage of the MOPA system by choosing the aspect ratio (i.e. width to thickness ratio) of the slab carefully and polishing the edge faces with a wedge angle. This approach has been demonstrated to be effective in the first edge-pumped Yb:YAG slab laser oscillator assembled by Rutherford [3].

Another key to improved energy extraction with reduced thermal distortion in MOPA laser systems is the use of super-gaussian spatial profile pulses. Propagation of super-gaussian pulses through saturated amplifiers results in better extraction of the stored energy because the incoming beam more uniformly fills the slab and utilizes a greater fraction of the inverted population. Mansell has developed micro-miniature optical device that convert a gaussian intensity profile beam into a super-gaussian profile beam and we propose to use these devices in the Yb:YAG system.

**Nonlinear Frequency Conversion**

The proposed high pulse energy 1.03 µm Yb:YAG MOPA system has many applications in remote sensing if the output can be converted to the longer infrared wavelengths. We are investigating frequency conversion using optical parametric amplifiers (OPAs) based on both waveguide and bulk periodically poled lithium niobate (PPLN). The goal is to down-convert to the telecommunications bands to take advantage of the tunable laser oscillators in the C and L band region. This band also allows the use of fiber pre-amplifiers, quantum noise limited detectors, and fiber based components for coherent detection of signals. Frequency conversion to the visible and to the ultraviolet is possible by harmonic and sum generation steps. As illustrated in Figure 2, the key is to utilize the advantages of the Yb:YAG system for energy storage and extraction followed by efficient frequency conversion to meet the various remote sensing application needs.

![Figure 2: Schematic of non-linear frequency conversion approach for remote sensing applications](image)

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