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Short Communication

Modelocked self-frequency doubling neodymium doped fiber laser

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Abstract. — We have demonstrated simultaneous lasing and self-frequency doubling of a neodymium and germanium doped silica fiber laser at $1.06\ \mu\text{m}$. The doubling action is provided by a self-organized phase matching grating in the fiber. The laser was modelocked using a linear external cavity which produced 600 ps pulses at $1.06\ \mu\text{m}$.

The phenomenon of second harmonic generation in germanium doped silica fibers has been studied extensively for several years [1-3]. A complete explanation of the microscopic physics behind the self-organized phase matching grating has remained elusive. Despite this fact, conversion efficiencies of 13% for Q-switched, modelocked pulses at $1.06\ \mu\text{m}$ have been reported [4] as well as conversion efficiencies of a few percent for cw modelocked pulses [5, 6]. In addition, self-frequency doubling fibers have been used to pump dye lasers [6, 7] as well as to replace conventional cavity elements in a mode-locked frequency doubling laser [8]. We report here on the first glass based self-frequency doubling laser system.

The laser system shown in figure 1 consists of 60 cm of silica fiber with less than 0.01% Nd^{3+} and 1-2% Ge dopant concentrations. The fiber made at Brown University, has a $7\ \mu\text{m}$ core diameter and a core cladding index difference of 0.01. This indicates that the fiber is multimode at both $1.06\ \mu\text{m}$ and $532\ \text{nm}$. The fiber was prepared for self-frequency doubling by seeded preparation [8]. In the seeding process the fundamental and the second harmonic signals are injected simultaneously into a glass based material, typically at intensities on the order of gigawatts per square centimeter. Although the process leading to the formation of a second order susceptibility and formation of a grating is not well understood, it is generally believed that the fundamental and the second harmonic need to be present simultaneously in order to create a second order susceptibility and to encode the proper momentum conserving spatial grating frequency [3, 8].

This seeding process was accomplished using a cw modelocked, and frequency doubled Nd:YAG laser. The intra-fiber powers used for preparation were 10 W at $1.06\ \mu\text{m}$ and 0.1 mW at $532\ \text{nm}$. The linearly polarized fundamental and second harmonic pulses were 100 ps and

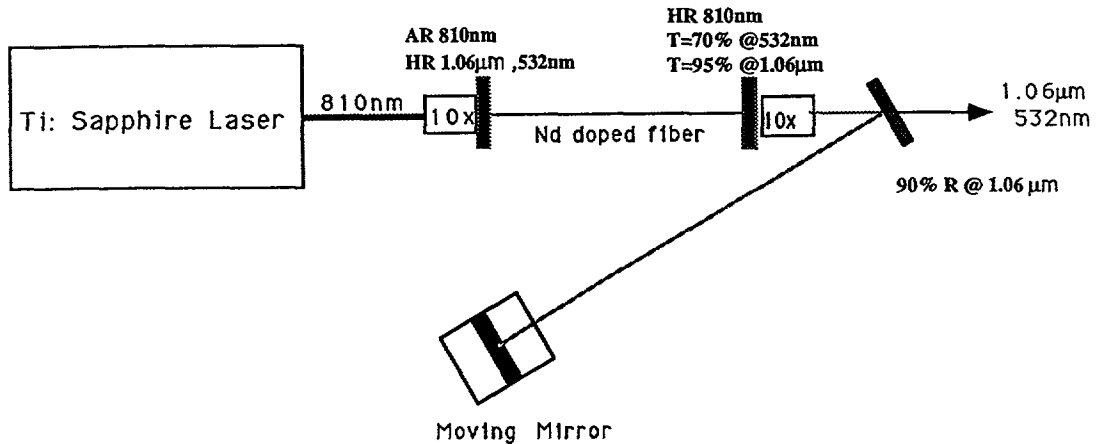


Fig. 1. — The experimental set-up for the self-frequency doubling fiber laser.

70 ps respectively, and had a repetition rate of 76 MHz. The seeded preparation took only 2 minutes. The prepared fiber exhibited a conversion efficiency of slightly under 1% when illuminated with the fundamental intensity it was prepared with.

The cavity consisted of the 60 cm of Nd doped fiber butt coupled to two dichroic mirrors. The length of the fiber was chosen to satisfy gain length product requirements, as only approximately 30 cm of prepared fiber is typically active as a doubler [9]. The input mirror was anti-reflection (AR) coated at 810 nm, and high reflection (HR) coated at 1.06 μm and 532 nm. The output coupler was 95% reflecting for the fundamental at 1.06 μm, greater than 70% transmitting for the second harmonic and highly reflecting for the pump at 810 nm. The output coupler was HR coated at the 810 nm in order to use a greater percentage of the available pump power by allowing for double pass absorption.

The fiber was pumped by a cw argon ion pumped Ti: Al₂O₃ laser tuned to 810 nm. The light was coupled into and out of the cavity using 10× microscope objectives. The dichroic mirrors were only 1 mm thick, thereby allowing efficient coupling on the input end and effective collimation on the output end. With 480 mW incident upon the input mirror and with approximately 90 mW of the pump power absorbed in a single pass, the maximum cw output of the fiber laser at 1.06 μm was 18 mW. Threshold for the laser occurred with less than 2 mW of pump power incident on the input coupler.

In order to increase the intra-fiber peak intensity and hence the conversion efficiency, the fiber laser was modelocked using a recently described linear external cavity technique [10]. This novel modelocking technique was chosen due to its simplicity and because it introduces no intracavity loss elements. The linear external cavity was formed using a 90% reflecting beamsplitter (at 1.06 μm) and a wideband reflecting mirror mounted to an 8 Ω audio speaker. The linear reciprocating motion of the wideband mirror was provided by driving the speaker with a function generator. Optimal results were obtained when the speaker was driven with a sawtooth wave at 80 Hz, with less than 0.25 mm displacements. With external cavity length approximately matched to that of the laser, the system produced fundamental pulses of ~ 600 ps at the cavity round trip time of 6.1 ns as shown in figure 2.

The entire modelocked output signal was filtered through two interference filters with 10 nm bandwidths centered at 532 nm, and measured using a phase sensitive detection system after

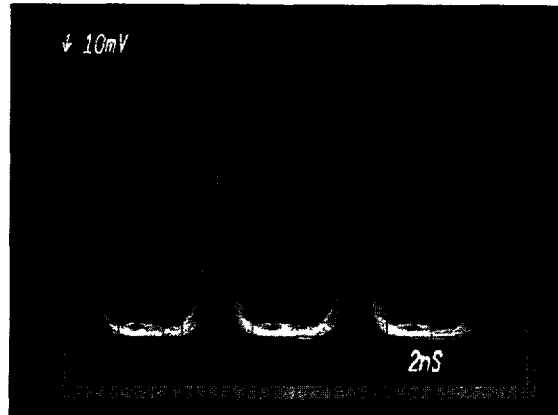


Fig. 2. — An oscilloscope picture of the modelocked pulse train at $1.06 \mu\text{m}$.

the 90% beam splitter. It was found that the log log plot of the fundamental *versus* the second harmonic had a slope of approximately 2, as expected for a second order nonlinear process. The second harmonic was faintly visible in room lights and had an average power of approximately $5 \mu\text{W}$, corresponding to an output conversion efficiency of $\sim 10^{-4}$. The $1.06 \mu\text{m}$ radiation and the second harmonic both appeared in the fundamental mode.

The small conversion efficiency of our system is due to the fact that the fundamental lasing intensity is small compared to the preparation intensity. Specifically, if we assume perfectly phase matched second harmonic generation, the conversion efficiency is a linear function of the fundamental reading intensity. The peak fundamental preparation and readout power was $\sim 1.4 \text{ kW}$ when the $\sim 1\%$ conversion efficiency was achieved. The fiber lasing peak power was approximately 182 mW , indicating that they should have been $\sim 1.3 \times 10^{-4}$ in good agreement with the experimentally obtained results. Other factors contributing to the small conversion efficiency include the fact that strong absorption features in the blue green region are typical in Nd:doped glass [11], however since the absorption coefficient at 532 nm is not known for this particular fiber, quantitative analysis is not possible. In addition, since only $\sim 30 \text{ cm}$ [9] is typically made SHG active in the preparation process, it is likely that only half the length of our fiber has a phase matching grating.

The real limit to the conversion efficiency of this type of system is the incomplete understanding of the second harmonic generation process in glass. Currently, the conversion efficiency for a glass based system is only practical for a high power pulsed laser where care has been taken to maximize the alignment between the lasing polarization and the frequency doubling grating polarization, and where modal overlap issues have been considered. Second harmonic generation in bulk glass [12] as well as microcrystallite doped glasses [13] has been recently observed. These discoveries open the door to application of this phenomenon in microcrystallite and Nd doped glass laser rods. Also, recent work [14] involving poling of heated silica has led to a second order susceptibility near the surface of the sample that is approximately two tenths of the $\chi_{22}^{(2)}$ of LiNbO_3 indicating that dramatic improvements in conversion efficiency of glass based systems are possible. Finally, although no degradation in the conversion efficiency due to multi-photon erasure processes or other effects [15] was noted, nor was any secondary grating formation [16] observed at the small intra-fiber intensities used in this experiment. At higher

powers these effects are expected to play a role in the performance of this type of system.

In conclusion, we have demonstrated a linear external cavity modelocked, self-frequency doubling Nd doped glass fiber laser with 600 ps fundamental pulses. As progress is made in the fundamental understanding of second harmonic generation in glass, self frequency doubling glass based lasers should be able to provide alternatives to noncentrosymmetric active crystalline materials such as Nd:YAB and Nd:YALO.

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