120 W, linearly-polarized single-mode Yb-doped fiber laser and 60 W green by SHG

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ABSTRACT

We report a 120 W, linearly polarized, single-mode Yb-doped fiber laser operating at 10 MHz pulse repetition rate. To produce narrow linewidth and high peak power, a fiber oscillator power amplifier (FOPA) configuration is used. With an Yb-doped large mode area (LMA) fiber, the FOPA has generated up to 2.4 kW peak power and less than 20 pm linewidth without the onset of nonlinear effects at 5 ns pulse duration. 120 W average output power corresponding to a slope efficiency of 71% with respect to the launched power has been generated. The beam quality is 1.1 times diffraction-limited and the polarization extinction ratio is better than 95%. No linewidth broadening beyond the 20 pm instrumental resolution or nonlinear effects are observed at 120 W output power. The diffraction-limited beam quality from the FOPA allows us to use LBO crystals to achieve efficient second harmonic generation (SHG) without "gray tracking" problems. The frequency doubling of 110 W FOPA output has generated 60 W, near-diffraction-limited, linearly polarized green output. With two LBO crystals at noncritical phase-matching, a maximum of 54.5% doubling efficiency has been demonstrated. The overall electrical efficiency to green output is 10%.

Keywords: lasers, Yb, Pulsed, High power, Green laser, SHG

INTRODUCTION

High average power, high brightness, linearly polarized lasers at both visible and near infrared wavelengths are of great interest for scientific, industrial, medical and defense applications. Green lasers producing several hundred Watts have been demonstrated based on Q-switched DPSS lasers, but their beam quality is at least 10 times diffraction-limited due to thermal lensing effects in the DPSS lasers [1, 2]. To date, Yb-doped fiber lasers have demonstrated diffraction-limited beam quality at kilowatts [3] as the beam quality is determined by fiber structure, instead of thermal lensing effects as in DPSS lasers. Combining the high efficiency, compact size and high brightness of fiber lasers with second harmonic generation (SHG) is an attractive alternative that will enable many applications.

Recently, some progress has been made using the SHG of fiber laser sources to generate high power green [4]. Usually KTP or periodically poled KTP (PPKTP) is used because these nonlinear crystals require relatively low pulse energies or average powers to obtain efficient conversion. To date, a 6 W average power green laser has been demonstrated using the combination of a laser-diode-seeded Yb fiber amplifier and quasi phase-matched second harmonic generation in PPKTP [5.] Unfortunately, the beam quality was not reported and it was also found that the efficiency rolled over at higher average power due to local heating in the PPKTP crystal. Creation of color centers or gray tracks in KTP have also been reported for high power CW and Q-switched lasers [6~9]. Therefore using PPKTP or KTP to achieve high conversion efficiency for CW or low peak power fiber lasers will face many issues, such as beam quality degradation, power stability and crystal damage.

In this paper, we report a 60 W, 10 MHz, linearly polarized green laser based on a frequency-doubled fiber laser. To produce narrow linewidth and high peak power, a fiber oscillator power amplifier (FOPA) configuration is used. With an Yb-doped large mode area (LMA) fiber, the FOPA operating at high repetition rate with short pulse duration has generated up to 2.4 kW peak power without the onset of nonlinear effects. The diffraction-limited beam quality from the FOPA allows us to replace KTP or PPKTP with two LBO crystals to increase interaction length in order to achieve efficient SHG without gray tracking problems.

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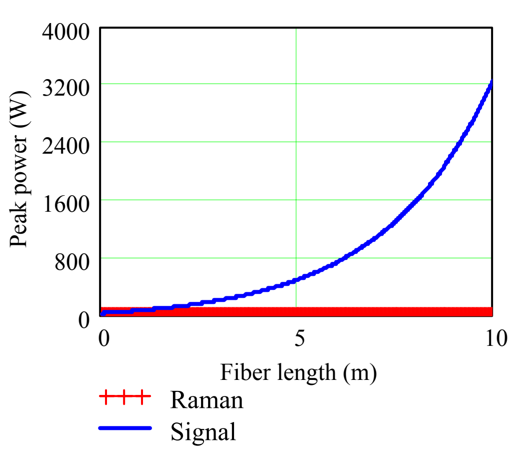
DESIGN CONSIDERATIONS

Table 1. Parameters for modeling SRS threshold

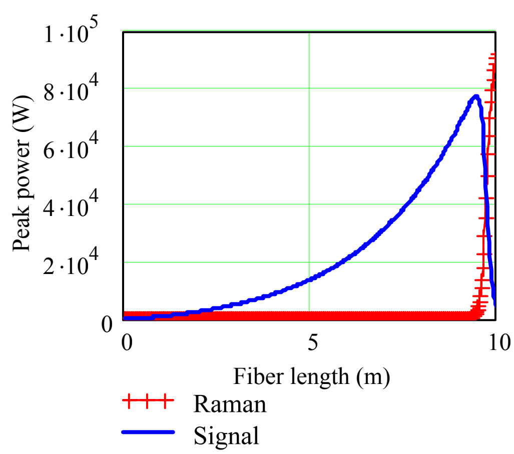
Pump wavelength	976 nm	Signal abs cross-section	3.10×10^{-27} m^2
Signal wavelength	1080 nm	Signal ems cross-section	4.20×10^{-25} m^2
Fiber length	10 m	Upper level life time	800 µs
Fiber mode-field dia	18 µm	Dopant concentration	6.94×10^{25} m^{-3}
Pump abs cross-section	1.99×10^{-24} m^2	Signal losses	0.02 dB/m
Pump ems cross-section	2.10×10^{-24} m^2	SRS gain coefficient	0.45×10^{-13} m/W

To achieve efficient SHG, the fundamental laser must have narrow-linewidth and high peak power. However, conventional Yb-doped high power fiber laser oscillators usually operate with broad linewidths due to broad gain bandwidth and the nature of inhomogeneous broadening of the rare-earth doped gain medium. For a conventional fiber laser oscillator without special linewidth control, the fiber laser linewidth can be up to several tens of nanometers. In addition, high power fiber lasers may also suffer from the onset of nonlinear effects, such as stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), four-wave mixing and self-phase modulation which will not only broaden laser linewidth but also affect laser stability [10].

Among the fiber nonlinear effects, SBS has the lowest threshold for a narrow linewidth system, but it can be avoided by simply reducing the pulse duration to well below 16 ns [11]. Once the SBS is suppressed, the maximum peak power of the fiber power amplifier is limited by either SRS or material damage. To design the power amplifier, a numerical model has been developed. The behavior of signal, forward and backward pumping as well as SRS are described by a set of differential equations. As the model includes both fiber gain and Raman gain, it is different from a SRS-only model or a fiber amplifier-only model. As a result, the impact of pump configuration on SRS effect can be seen. The model can handle co-propagation, counter-propagation and two-side pump schemes. The parameters used to calculate SRS thresholds and gains are listed below. As shown in Figure 1, for a 10 m long fiber with a core mode-field-diameter of 18 µm the SRS gain for a 3.2 kW peak power amplifier is only 5.26 dB while it is 142 dB for a 80 kW amplifier.



(a). 3.2 kW power amplifier, SRS gain =5.265dB



(b). 80 kW power amplifier, SRS gain=142dB

Figure 1. Calculated SRS distribution along the fiber length for (a) 3.2 kW and (b) 80 kW power amplifier.

The parameters are based on a telecommunication fiber that does not have Yb-dopant and may be different from our experiment fibers, but it should not make a significant difference in terms of SRS gain coefficient.

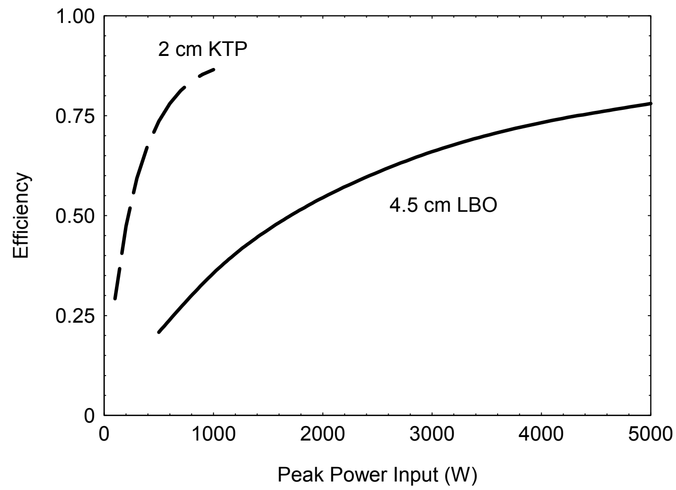


Figure 2. Calculated SHG efficiencies of KTP and LBO

Compared with a simplified estimate described in [11, 12], the rate-equation based model provides more accurate SRS threshold. With the simplified estimate, the SRS threshold is less than 5~8 kW while our model shows that it is about 60 kW. This is because the simplified estimate considers the signal distribution along the fiber as a constant, instead of an exponential distribution as in the real case shown in Figure 1.

Another issue that should be considered when designing a SHG system is the damage threshold of the crystal. LBO is one of the crystals that has similar damage threshold as optical glass. According to the specifications provided by manufacturer, LBO damage threshold is 18.9 GW/cm^2 for ns pulses, which is two times lower than fused silica. This means that the crystal is unlikely to be damaged if the beam diameter of the fundamental light is 50 µm. However the anti-reflection coatings on the crystal can significantly reduce damage threshold. Although the damage threshold from the manufacturer is 2GW/cm^2 for 15ns pulses at 10Hz, our preliminary experiments show that the crystal can be damaged at 100 MW/cm^2 level for a focused beam with a diameter of 100 µm. This may be caused by coating defects and contamination, or micro-scratches on the surface. Based on these results, we believe the peak power of the FOPA should be less than 3 kW.

Non-critical phase-matching (NCPM) of LBO provides no walk-off, very wide acceptance angle and maximum effective coefficient. It promotes LBO to work in its optimal condition. The SHG conversion efficiencies of more than 70% for pulse and 30% for cw Nd:YAG lasers have been obtained with good output stability and beam quality. The calculated conversion efficiency based on SNLO[13] is shown in Figure 2 where the beam diameter is 110 µm and the LBO length is 45 mm. With greater than 2 kW peak power from the FOPA, a 45 mm long LBO crystal can convert more than 50% of fundamental power into green output. The maximum power intensity within the crystal is approximately 21 MW/cm^2, which is much lower than the crystal damage threshold.

EXPERIMENT

1. 120 W linearly-polarized FOPA

The green laser based on frequency doubling of the FOPA consists of a CW fiber oscillator, an amplitude modulator, a fiber preamplifier, a fiber power amplifier and a second harmonic generator as shown schematically in Figure 3. The CW Yb-doped fiber oscillator with two fiber Bragg gratings generates very narrow linewidth at 1080 nm. The laser linewidth is measured to be less than 20 pm and the measured linewidth is limited by the resolution of the optical spectrum analyzer. The CW laser light is then modulated by an amplitude modulator which can vary pulse duration and repetition rate separately. The pulse duration of the seed source can be varied from hundreds of microseconds to nanoseconds, while the repetition rate can be varied from hundreds of kHz to hundreds of MHz. The average output power after the modulator is determined by the modulation duty factor. At 10 MHz repetition rate (100 ns repetition period) and 5 ns pulse duration, the duty factor of 0.05 produces approximately 1 mW average signal power. The signal is then amplified by a single mode Yb-doped fiber preamplifier. The maximum output power from the preamplifier is 200 mW and the maximum gain is 23 dB. Fiber isolators are used between the fiber oscillator, the preamplifier and the fiber power amplifier stages to protect each stage from back reflection which can affect performance of each stage. As the ratio of pulse duration and repetition period varies, the seed source provides a range of peak powers and the preamplifier has reached a peak power of tens of watts without the onset nonlinear effects.

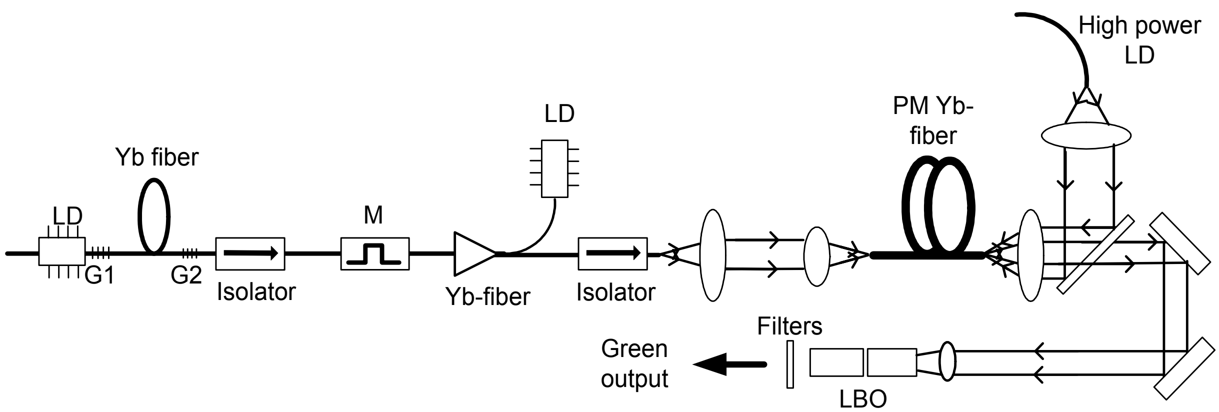


Figure 3. Experimental setup for achieving 60 W green based on frequency-doubling of the fiber oscillator power amplifier (FOPA). G1 and G2: fiber Bragg gratings; M: amplitude modulator.

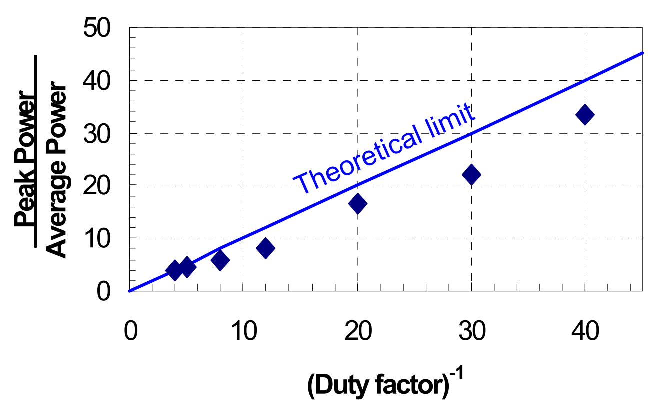


Figure 4. Ratio of peak to average power vs. duty factor.

To make sure the seed source operates properly over a wide range from 5 to 20 Mhz, the output pulse waveforms were measured with a photodetector and an oscilloscope. The ratio of peak to average power versus duty factor at different repetition rate is shown in Figure 4. During the experiment, the pulse duration is set to be 5 ns and pulse repetition rates varied from 40 Mhz to 5 Mhz corresponding to duty factors of 1/5 to 1/40. The ratio of peak power is measured to be in proportion to 1/duty factor. The lower the repletion rate, the higher the peak power from the seed source. The measured power ratio of peak to average is slightly lower than the theoretical limit due to ASE in the pre-amplifiers. Nevertheless, the peak power can be 30 times greater than the average power at pulse duration of 5 MHz.

The fiber power amplifier uses an Yb-doped polarization maintaining (PM) double-clad, LMA fiber with a fundamental mode-field-diameter of 18 µm and numerical aperture of 0.06. Compared with conventional single mode double-clad fibers, the LMA fiber provides higher absorption and larger mode field diameter thus reduces the fiber length and signal power intensities which are the key parameters for reducing the nonlinear effects. The fiber length is 10 m which

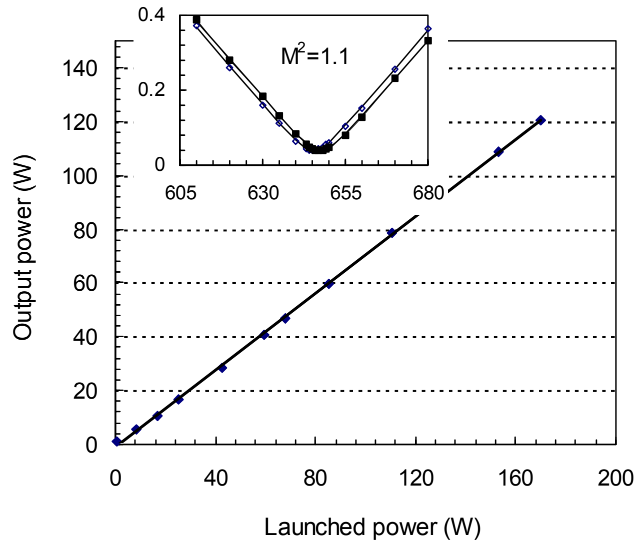


Figure 5. Output power of fiber power amplifier versus launched pump power. Inset: measured M^2 for both || and ⊥ polarizations at 110 W.

absorbs 98% of the pump power at 976 nm. The single mode, linearly polarized, pulsed signal from the preamplifier is launched into the LMA core with a set of special designed lenses which achieve mode-matching between the single mode fiber and the LMA fiber in order to selectively excite the fundamental mode. In order to achieve maximum polarization extinction ratio, the fiber stress-rod plane (or slow axis) is aligned parallel to the polarization of the seed light. The pump light is launched into the LMA fiber opposite from the pump end, as shown in Figure 3. The pump

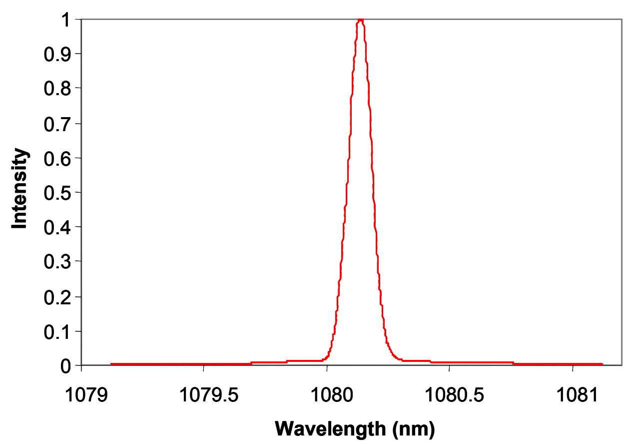


Figure 6. Measured spectrum of the output from the FOPA at 120 W.

wavelength is set to the strongest absorption peak near 976 nm to shorten the fiber thus minimizing possible nonlinear effects. The dielectric mirror for separating the pump light and the amplified signal provides >99% reflectance at 976 nm and <2% reflectance at 1080 nm. All lenses are AR coated for both pump and signal wavelengths in order to reduce undesired back reflection. The maximum power from the fiber coupled laser diode is 200 W and the coupling efficiency between the LD and the fiber is estimated to be 85%.

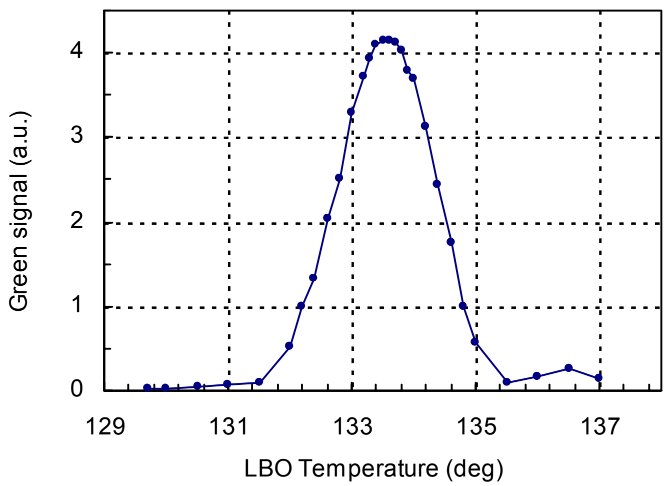


Figure 7. Dependence of green signal on LBO temperature.

At 10 MHz repetition rate and 5 ns pulse duration, the fiber power amplifier produced up to 120 W output power,

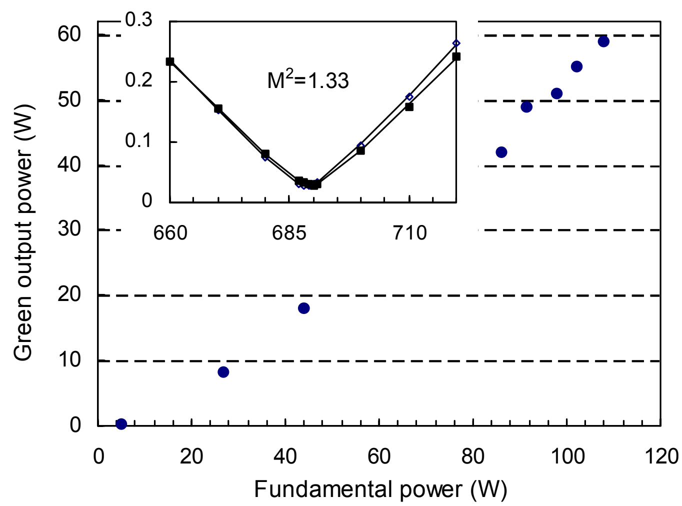


Figure 8. Green output power versus fundamental power. Inset: measured M2 of the green for both || and □ polarizations at 50 W.

corresponding to a slope efficiency of 71% with respect to the launched power as shown in Figure 5. The polarization extinction ratio is measured to be better than 95%. The beam quality is measured with the BeamScan (model BeamScan-XYGEPREC, Photon Inc) and it is 1.1 times diffraction-limited. As shown in Figure 6, no linewidth broadening beyond the 20 pm instrumental resolution or nonlinear effects are observed even at 120 W output power.

2. SHG of FOPA

As mentioned above, LBO is used as the frequency doubling crystal even though it has a relative low nonlinear coefficient compared to KTP and PPKTP. This is because multi-kilowatts peak power is sufficient for a long LBO or multiple crystals to achieve high efficiency without suffering from gray tracking. As the high quality long crystal is difficult to obtain and increasing the number of crystals will affect system complexity and may also induce unwanted phase shifts, a system with dual long crystals was chosen. The two AR-coated LBO crystals are 25 mm long and cut for noncritical phase-matching at the 1080 nm operating wavelength. Based on the manufacturer provided specifications and the experiments, the two crystals have very similar optical characteristics. The two crystals are mounted in two temperature controlled ovens with a crystal separation of 5 mm in order to keep the effective optical path as short as possible. The beam from the fiber power amplifier is focused by a 15 cm focal length lens and the beam waist is measured to be 56 μm (1/e2) with a high resolution BeamScan (resolution <4 μm). Following the crystals, two dielectric filters are used to separate green and fundamental beams. The green signal as a function of crystal temperature is measured at low power and is shown in Figure 7. The temperature tolerance for efficient phase-matching is approximately 2 ºC (FWHM). The green output versus fundamental power is shown in Figure 8. At 110 W fundamental power, up to 60 W green is produced, corresponding to maximum conversion efficiency 54.5%. The peak power of the fiber power amplifier at 110 W is estimated to be 2.2 kW. The beam quality of the green laser is measured to be 1.33 times diffraction-limited. Although all crystal temperatures are optimized at low power, they provide efficient frequency doubling at 60 W of green output power with no temperature adjustment.

In our experiment, the pulse duration is limited by the speed of the available modulator driver. The maximum modulation frequency of the modulator can be up to 10 GHz, replacing the modulator driver can easily reduce the pulse duration to 500 ps and increase the pulse repetition rate to 100 MHz. With the same peak power and configuration, we expect to demonstrate similar performance.

CONCLUSIONS

In conclusion, we have demonstrated a highly efficient, near-diffraction-limited, linearly polarized 60 W green laser based on the frequency doubling of a fiber laser. The overall electrical efficiency to green is 10%. We acknowledge useful discussions on frequency doubling with Mark Bowers and Dave Gerstenberger, and experimental assistance from Tracy Vatter and Paul Hoffman. This work is supported by the Air Force Research Lab under contract AFB F29601-98-D-0190-task order 8.

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