

# Room-Temperature Stable Generation of 19 Watts of Single-Frequency 532-nm Radiation in a Periodically Poled Lithium Tantalate Crystal

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**Abstract**—We report on a system that produces 19 W of diffraction-limited radiation at 532 nm through single-pass frequency doubling of the output of a 1064-nm Yb<sup>3+</sup>-doped fiber MOPA in a periodically poled near-stoichiometric lithium tantalate (PPSLT) crystal. The output of the system was stable at the 19-W level for over one hour with no signs of photorefractive damage. The green power is believed to be limited by infrared-induced thermal dephasing in the PPSLT crystal.

**Index Terms**—Ferroelectric materials, nonlinear optics, optical fiber amplifier, periodically poled near-stoichiometric lithium tantalate (PPSLT), photorefractive effect, ytterbium.

HIGH-POWER visible light generation with good spatial beam quality is required in applications ranging from astronomy [1] to medicine [2] to laser displays [3]. Efficient direct generation of diffraction-limited visible light is difficult due to the absence of appropriate lasing materials. Nonlinear frequency conversion of infrared solid-state sources has successfully produced multiple watts of power in the blue [4], green [5], and yellow [6]. In recent years, the development of double-clad large-mode-area fibers has enabled the realization of 100-W-class diffraction-limited infrared sources with optical efficiencies well above 50% [7]. These sources allow for the possibility of high-power 10-W-class visible sources possessing excellent beam quality with overall optical efficiencies well over 10%.

However, high-damage threshold nonlinear optical crystals that use birefringent phase-matching (such as LBO) require peak powers in the IR of several kilowatts for efficient single-pass frequency conversion [5]. External resonant frequency doublers can increase the second harmonic generation (SHG) efficiency of continuous-wave (CW) or low-peak-power

pulsed sources in birefringently phase-matched crystals at the expense of considerable system complexity [8]. Intracavity SHG is not suitable for the master-oscillator-power-amplifier (MOPA) architecture, which is most commonly used for high-power single-frequency systems. Single-frequency linearly polarized fiber MOPAs can now exceed 100 W in output power [9].

Quasi-phase-matched nonlinear materials offer considerably higher conversion efficiencies than available birefringently phase-matched media. Periodically poled lithium niobate is widely used due to its high nonlinearity and its wide availability. However, the congruent composition that is commonly available for ferroelectrics (such as lithium niobate and lithium tantalate) suffers from photorefractive refractive damage (PRD) at even moderate levels of visible light [10].

In the past decade, considerable effort has been expended by several research groups on the development of ferroelectrics that have a near-stoichiometric composition, since stoichiometric crystals have lower defect densities [11]. The lower defect density increases the resistance of these materials to PRD and photochromic effects, such as green-induced infrared absorption (GRIIRA) [12].

The nonlinearity of these stoichiometric ferroelectrics are ideally suited for the 100-W and kW range powers that are readily available from fiber laser systems. The development of these stoichiometric nonlinear materials coupled with efficient fiber laser systems have led to the demonstration of efficient narrow-linewidth watt-class sources in the green and yellow [13], [14]. In this Letter, we describe a system that generates 18.8 W of CW diffraction-limited power at 532 nm in a single longitudinal mode through frequency doubling the output of a Yb<sup>3+</sup>-doped fiber MOPA in a periodically poled near-stoichiometric lithium tantalate (PPSLT) chip. To the best of our knowledge, this power represents the highest diffraction-limited power in the green (CW or average) that has been generated in a periodically poled material. It is also the highest CW power generated through nonlinear frequency conversion to the green in a single-pass configuration (QPM or birefringently phase matched).

The experimental setup is shown in Fig. 1. The seed to the fiber amplifier was a 2-W single-frequency 1064-nm Nd:YAG nonplanar ring oscillator (NPRO) with a measured FWHM linewidth of 10 kHz. The amplifier consisted of a commercial polarization-maintaining double-clad silica fiber from Nufern

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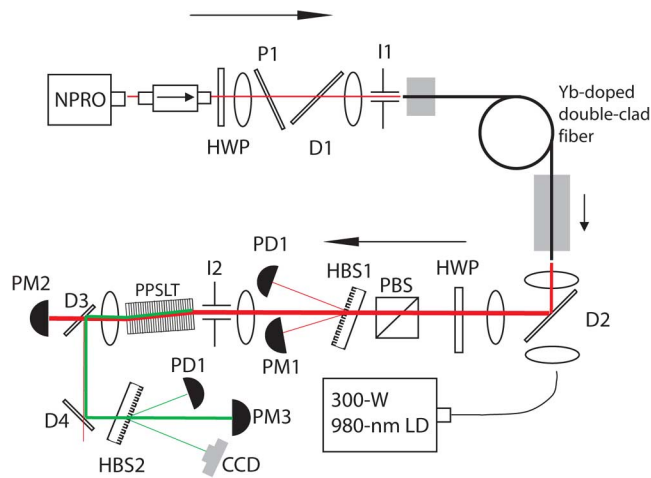


Fig. 1. Experimental setup for high-power green generation. NPRO: nonplanar ring oscillator; HWP: half-waveplate; P1: pickoff to measure onset of SBS; D1: 980 nm/1064 nm-dichroic that reflects 980 nm; D2: 980 nm/1064 nm dichroic that reflects 1064 nm; D3, D4: 532 nm/1064 nm dichroics that reflect 532 nm; I1, I2: high-power irises; PBS: polarizing beamsplitter; PD1, PD2: photodetectors; PM1, PM2, PM3: thermal power meters; HBS1: 1064 nm holographic beam sampler; HBS2: 532-nm holographic beam sampler; LD: laser diode; CCD: charge-coupled-device camera. The paths of the 1064-nm and 532-nm beams are shown. The 980-nm laser diode light path is omitted for clarity.

with a 20- $\mu\text{m}$ , 0.06-numerical aperture (NA) core, and a 400- $\mu\text{m}$ -diameter 0.44 NA inner cladding and a stress-induced birefringence in the core of  $3.7 \times 10^{-4}$ . The gain fiber was pumped in the backward direction with a 300-W fiber-coupled 975-nm laser diode stack. The pump power was coupled into the gain fiber's inner cladding with an efficiency of 83%. To minimize phase noise, active convective cooling of the gain fiber was avoided; instead, the gain fiber was cooled by coiling it against a threaded aluminum mandrel, which was in thermal contact with a water-cooled copper heat sink. The mandrel was machined to a 9.9-cm diameter to ensure that bending losses allow for only a single transverse mode to be guided in the fiber core with low loss. The effective cladding absorption of the fiber was measured to be 1.9 dB/m at 975 nm. The spectrum and power fluctuations of the 1064-nm output were simultaneously monitored through the holographic beam sampler (HBS) placed at the output of the amplifier (see Fig. 1). More detailed characterization of this fiber source, which is being developed for next-generation ground-based gravitational wave detectors, is reported elsewhere [15].

We modeled the performance of our fiber amplifier using a simulation program developed in our group to study rare-earth-doped fiber lasers and amplifiers [16]. Our simulations predicted that a fiber length of 7.4 meters would maximize the output power. However, to minimize the level of spontaneous Brillouin scattering, which can significantly increase the noise of the output light, we reduced the length of the fiber to 5.8 m. We determined that a high-damage threshold iris was needed to prevent the large amount of unabsorbed pump power from heating optics on the signal-input side of the fiber and affecting the input signal coupling. To this end, we fabricated a 1-mm thick copper iris with a 500- $\mu\text{m}$  aperture. In the future, we plan to splice the double-clad gain fiber at the signal input end to a single-clad fiber of the same geometry and apply high-refractive-index gel

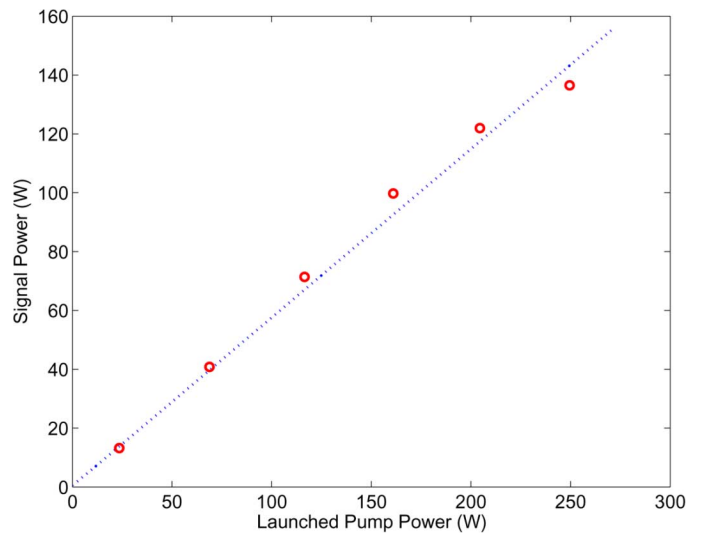


Fig. 2. Power curve of  $\text{Yb}^{3+}$ -doped fiber amplifier. Experimental data (circles) and simulation results (dotted line) are shown.

in a cooled housing to strip the unabsorbed pump power. Since this extra fiber length is added to the signal input end where the signal power is lowest, there should not be an appreciable increase in the spontaneous Brillouin-scattered power.

The measured output power curve of the fiber amplifier is shown in Fig. 2. The measured results agree well with our simulations. The small roll-off in efficiency at higher pump powers is due to the wavelength drift of the pump diodes. Our system is more sensitive to drift in the pump wavelength because of the short gain fiber length. The amplifier is able to produce a maximum output power of 136 W with an optical efficiency of 56% with respect to incident pump power. The polarization extinction ratio (PER) of the amplifier's output signal was above 15 dB at all power levels. We believe the PER could be slightly improved by using wavelength-stabilized 976-nm pump diodes, which would increase the stability of the absorption profile. This would result in a more stable fiber temperature profile and consequently higher PER, since we have found that temperature fluctuations can degrade the PER in these large-mode-area fiber systems. We determined that the full-width-half-maximum (FWHM) linewidth of the 1064-nm fiber-amplifier output over 1 second was below 50 kHz at the maximum power, which matches the linewidth of the seed. The spectrum and power fluctuations of the 1064-nm output are simultaneously monitored through the holographic beam sampler (HBS) placed at the output of the amplifier.

To frequency double the 1064-nm light, a 4-cm-long, 1-mm-thick PPSLT chip was used. Near-stoichiometry was achieved by taking the originally congruent-composition unpoled wafer and subjecting it to the vapor-transport-equilibration (VTE) process. After the VTE process, we periodically poled the chip. The details of the crystal fabrication and periodic poling processes were reported in detail by Hum *et al.* [11]. A low-temperature broadband anti-reflection (AR) coating with a center wavelength of approximately 800 nm was applied to both ends of the chip to maximize the generated green power. The PPSLT chip was placed in a home-made mount whose

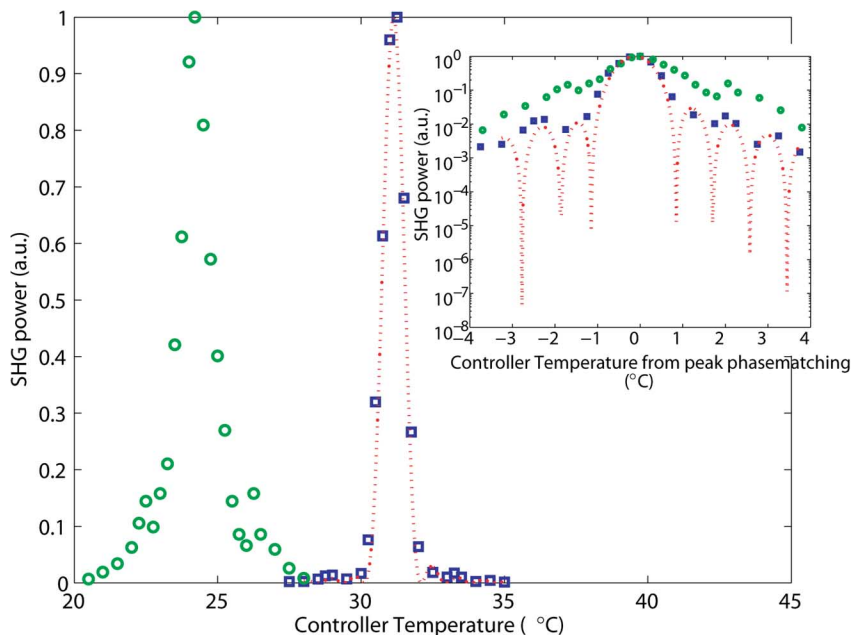


Fig. 3. Temperature tuning curves for the PPSLT chip. The low-power measurements (squares) and the theoretical tuning curve assuming no absorption (dotted line) for the given focusing conditions are shown. The measured tuning curve at the 19-W level is also shown (circles). Inset: Superimposed tuning curves at low-power (squares) and high-power (circles) on a logarithmic scale. The theoretical curve (dotted line) is also shown.

temperature was controlled with a thermo-electric cooler (TEC) and monitored with a thermistor. Care was taken to ensure that the mount was uniformly heated and thermally insulated from the environment.

Although a broadband AR coating to minimize reflections at wavelengths between 532 nm and 1064 nm was applied to the chip, the reflection at 1064-nm was measured to be approximately 2%. This reflection provided sufficient feedback to the amplifier to cause spiking in the 1064-nm output of the NPRO as the pump diode power was increased. This spiking damaged one of our earlier PPSLT samples. Since we did not have an isolator that could handle 100 W of incident IR power, we chose to mitigate this problem by slightly angling the PPSLT crystal in the horizontal direction and inserting an iris to prevent the reflected light from reaching the gain fiber. We experimentally determined the minimum allowable tilt angle by monitoring the fiber amplifier output with a fast photodiode to detect the onset of spiking. Since the width of the poled regions on the chip was only about 400  $\mu\text{m}$ , we had to increase the size of the waist in the crystal in the horizontal dimension to prevent the diffracting beam from sampling unpoled regions, which would result in decreased efficiency and distortions to the spatial mode of the generated green output. We focused the IR beam to waists with  $1/e^2$  diameters of 80  $\mu\text{m}$  and 110  $\mu\text{m}$  in the horizontal and vertical dimensions, respectively.

We measured a low-power, normalized conversion efficiency of 0.3%/(W  $\cdot$  cm) in our PPSLT chip, which is about 2.2 times lower than ideal given our focusing conditions. The discrepancy is most likely caused by a nonideal poling duty cycle [11]. To demonstrate that these PPSLT frequency doublers could be operated near room temperature without the onset of photorefractive damage, gratings with a poling period of 8.0  $\mu\text{m}$  designed to phasematch the 1064-nm frequency doubling process at 40°C

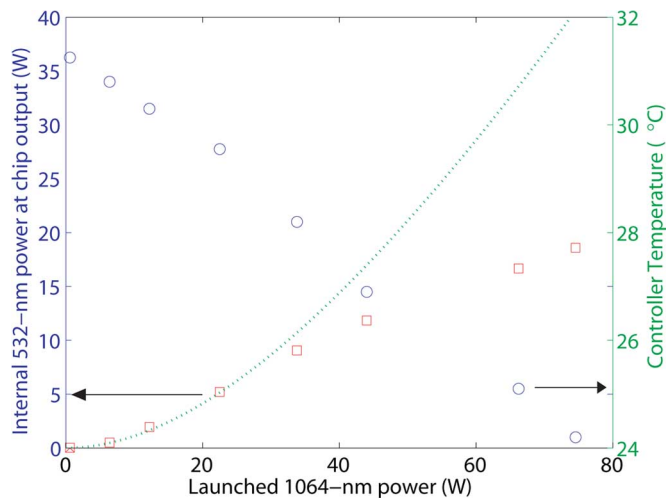


Fig. 4. Internal SHG power (squares) and optimum controller set-point temperature (circle) versus internal 1064-nm power. The dotted line is the extrapolated  $P \times \tanh^2$  curve from the measured low-power conversion efficiency.

phasematching were used. Low-temperature phasematching has the additional advantage that the thermal conductivity of SLT is higher at lower temperatures [17], so the temperature rise is reduced for a given amount of absorbed optical power. As a result of the tilt of the chip, the peak phasematching temperature was shifted downwards to 31.3°C. As shown in Fig. 3, the measured low-temperature tuning curve for the 4-cm device agrees well with theoretical predictions.

We increased the power from the fiber amplifier incident on the PPSLT chip in steps and monitored the generated green power as shown in Fig. 4. As the 1064-nm power was increased, the controller's temperature setpoint for the PPSLT chip was manually adjusted for maximum green power. The need for the

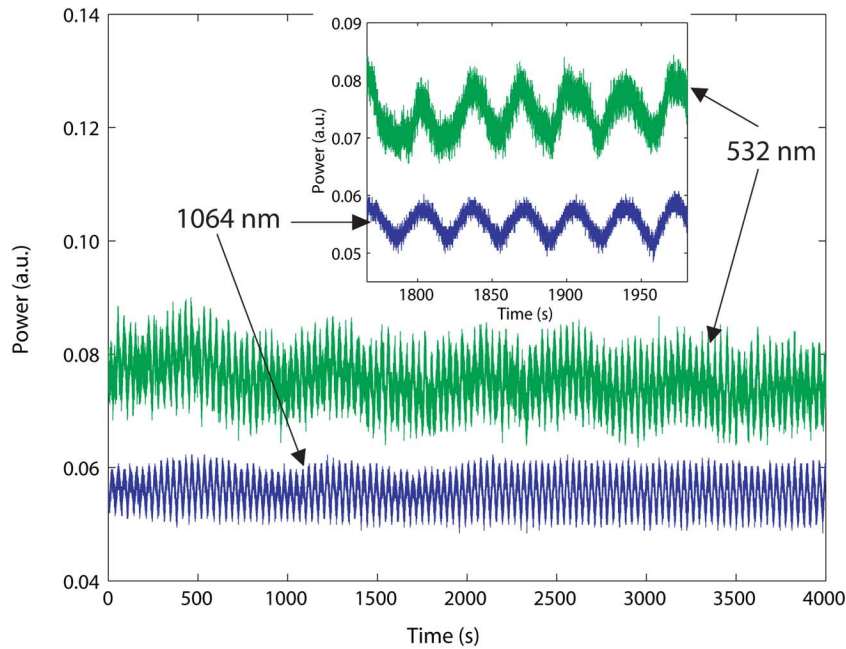


Fig. 5. 4000-second trace at the maximum green operating point (19 W) taken with with a fast photodiode. The IR power incident on the PPSLT chip is also shown. Inset: Zoomed-in trace of the green and IR demonstrating the 35-second-period oscillations in the IR and green due to fluctuations in the pump-diode wavelength.

adjustment is predominantly due to absorption of the incident IR in the PPSLT. We measure a maximum power of 18.3 W outside of the chip (corresponding to 18.8 W inside the chip) with a launched 1064-nm power of 75 W. This represents an overall optical efficiency of 16% with respect to incident diode pump power.

As the incident power was increased beyond 30 W, we found that the generated green power began to deviate from the theoretical  $\tanh^2$  curve. We think that this deviation may be due to thermal dephasing, a process by which the phasematching in the nonlinear medium is spoiled due to the uncompensated temperature dependence of the refractive index at the fundamental and second harmonic frequencies [18]. For efficient conversion under high nonlinear drive, the dephasing must be kept below  $\pi/10$  [19]. The thermal conductivity of the PPSLT crystal was measured in both the  $z$ -axis and in the direction normal to it [17]. Using the geometric mean of the values measured in the two axes of  $6.7 \text{ W}/(\text{m} \cdot \text{K})$ , and using measured values of  $0.1\%/ \text{cm}$  and  $5 \text{ cm}/\text{GW}$  for the PPSLT chip's linear and green-induced absorption at 1064 nm, we can calculate the thermal dephasing for a given incident power [20]. We determined that given our focusing conditions and measured normalized efficiency of our 4-cm-long PPSLT chip, the thermal dephasing reaches  $\pi/10$  when the 1064-nm launched power is 35 W, which matches well our measured results shown in Fig. 4.

At the maximum green power of 18.8 W, we measured the temperature tuning curve shown in Fig. 3. The broadening of the tuning curve at maximum power is clearly illustrated in the inset of Fig. 3, in which the low-power and high-power tuning curves have been superimposed on semilogarithmic axes.

The beam quality of the IR and green beams were each measured at both low and high powers. At low powers, the  $M^2$  of the IR beam was found to be 1.05 and 1.03 in the horizontal and vertical dimensions, respectively. At the maximum used power

of 75 W, the  $M^2$  of the 1064-nm beam was 1.04 and 1.05 in the horizontal and vertical dimensions, respectively. At low powers, the  $M^2$  of the 532-nm beam was 1.04 and 1.01 in the horizontal and vertical dimensions, respectively. At the maximum power of 18.8 W, the  $M^2$  of the green had deteriorated slightly to 1.19 and 1.05 in the horizontal and vertical dimensions, respectively, probably due to thermal focusing. Using a high-resolution OSA with 4-pm resolution, we were unable to observe any broadening in the green output as the power was increased.

Using a thermal power meter, we were unable to measure any decrease in the average output power in the green for over an hour. This steady output power value indicates that there was no appearance of photorefractive or photochromic damage. We also took a 4000-second trace with a fast photodiode to measure any fluctuations in the output power on faster time scales, as shown in Fig. 5 (due to the long path length of the light from the PPSLT chip to the photodiode and room temperature fluctuations, the beam slightly walked off the photodiode's small active area over the 4000 seconds, which explains the small decrease shown in the trace—the average value was re-attained upon translating the photodiode after the trace was taken). The measured peak-to-peak fluctuations in the green power were  $\pm 16\%$  over the 4000-second measurement period. Further examination of the photodiode data indicate that the fluctuations in the generated green power are due to fluctuations of the incident IR power (see inset of Fig. 5). We determined that the fluctuations in the IR power were due to a periodic wavelength drift of the stack of pump diodes. This wavelength drift had a large effect on the output power since our gain fiber was quite short and the  $\text{Yb}^{3+}$  absorption peak at 975 nm is quite narrow. The power fluctuations at both 1064 nm and 532 nm could be eliminated by using wavelength-stabilized pump diodes.

In conclusion, we have demonstrated 19 W of stable diffraction-limited single-frequency 532-nm radiation by frequency

doubling the output of a  $\text{Yb}^{3+}$ -doped silica fiber MOPA using a PPSLT crystal in a single pass. The overall optical efficiency of the system is 15%. Further improvements in efficiency can be achieved by improving periodic poling quality and/or by reducing of thermal dephasing effects. The latter may be achieved by using a shorter PPSLT crystal to increase the temperature acceptance bandwidth of the chip. Using the same  $\text{Yb}^{3+}$ -doped fiber amplifier, we expect to generate significantly more power at 532 nm with a 1.7-cm-long PPSLT crystal without further improvements in poling quality.

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