

High-Power Diode-Pumped Single-Frequency Nd:YLF and Nd:YVO₄ Lasers with Intra-cavity Second-Harmonic Generation to the Red Range

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Abstract—Single-frequency operation of diode-pumped Nd:YLiF₄ and Nd:YVO₄ continuous-wave (cw) ring lasers are investigated in the 1.31-1.34 μ m range, together with their intra-cavity second-harmonic generation to the red spectral range (0.65-0.67 μ m) using either BiB₃O₆ (BiBO), LiB₃O₅ (LBO) or periodically-poled KTiOPO₄ (ppKTP). Smooth single-longitudinal mode wavelength tuning over $\Delta\lambda\sim 3-4$ nm within the gain bandwidths could be achieved, with a watt-level output at gain centers in the near-IR and red range. Unlike with the birefringence phase-matched crystals, second-harmonic generation using ppKTP leads to various dynamical regimes, from narrow-band continuous-wave to broadband self mode-locked operation triggered by $\chi^{(2)}:\chi^{(2)}$ second-order Kerr-lens cascaded nonlinear interactions.

I. INTRODUCTION

Compact diode-pumped cw Nd:YLiF₄ (Nd:YLF) and Nd:YVO₄ sources lasing in the 1.3 μ m range (⁴F_{3/2}–⁴I_{13/2} transition) - with subsequent frequency doubling and quadrupling to the red/UV ranges - appear as convenient all-solid-state laser sources for high-resolution atomic spectroscopy of hydrogenic atoms [1]. The second-harmonic (SH) of the σ -polarized emission of Nd:YLF (peak wavelength at $\lambda_{2\omega}\sim 1314$ nm) matches perfectly the Ca (¹S₀–³P₁) inter-combination line at $\lambda_{2\omega}\sim 657.0$ nm, while the 2S-3S transition in hydrogen atom (H) can be probed by two-photon spectroscopy at 1312.6nm. When frequency quadrupled to the UV, single-frequency emission of Nd:YLF at 1312.64nm (lying at the edge of the σ -polarized emission) matches the D₂ cooling line of neutral Ag atoms (²S_{1/2}–²P_{3/2} at $\lambda_{4\omega}=328.16$ nm) [2]. Its π -polarized emission (peaking at $\lambda_{2\omega}\sim 1321$ nm), when tuned to 1322.4nm and frequency-doubled to 661.2nm, can be used to probe the narrow two-photon transition (²S_{1/2}–²D_{5/2}) of laser-cooled neutral Ag. Last but not least, the SH emission of Nd:YVO₄ at $\lambda_{2\omega}\sim 671$ nm can be used to cool neutral Li atoms for Bose-Einstein condensation experiments.

These DPSSL lasers can replace advantageously bulky and costly single-frequency dye-lasers, despite their limited gain bandwidths (typically a few nanometers). In the birefringent YLF host, the 1.3 μ m Nd³⁺ non-degenerate transitions have identical stimulated emission cross-sections $\sigma_{SE}=2\times 10^{-20}$ cm² [3], while in the vanadate host (YVO₄), the birefringent wavelength shift is negligible (both σ and π

wavelengths peak at ~ 1342 nm) with the π -polarized emission exhibiting larger cross-section than the σ -polarized one. Although the π emission cross-section of Nd:YVO₄ is ~ 5 times larger than in Nd:YLF, the 3 times shorter lifetime of the upper level in the vanadate host combined with its stronger thermal lensing (as compared with the fluoride host) makes the lasing efficiency in both laser media somewhat comparable.

In this paper we investigate the IR and red output performance of unidirectional, single-longitudinal mode (SLM), intra-cavity frequency-doubled Nd:YLF and Nd:YVO₄ ring lasers. Asymmetric bow-tie ring resonators (with broad-band coated mirrors for the 1200-1400nm range) are implemented to accommodate the fiber-coupled diode single-end longitudinal pumping scheme (Fig. 1), with the a -cut laser crystals (dimensions 3x3x10mm²) positioned at the larger waist of the resonator ($w_2\sim 320\mu$ m) coinciding with the 806-808nm diode pump waist location ($w_p\sim 260\mu$ m). For intracavity SHG, the pump and lasing mode overlap is carefully optimized by adjusting the distance D between the curved mirrors (ROC=-100mm), since a few millimeters variation of D can lead to $\pm 30\%$ change in the TEM₀₀ cavity waist w_2 without affecting the smaller waist w_1 ($\sim 47-50\mu$ m) between the curved mirrors where the nonlinear crystal is placed. Unidirectional operation is achieved with an optical diode consisting of a Brewster-cut TGG Faraday rotator rod and zero-order half-wave plate (HWP) proving the necessary polarization rotation compensation.

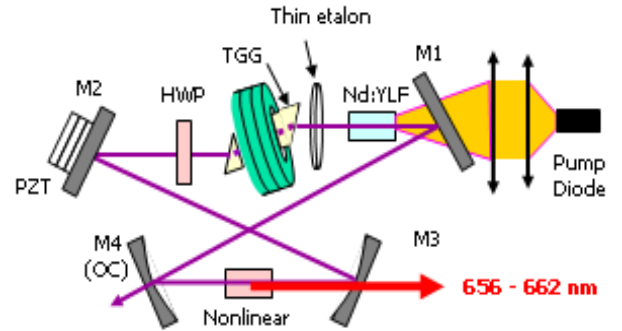


Fig. 1. Experimental ring laser setups. The IR output exits from M4 (output coupler) while the red output exits from M3 (T=90% in the red).

The use of a zero-order HWP was found crucial to maintain unidirectional operation when the laser was tuned within the 3-5nm gain bandwidths by use of a 100 μ m-thin fused silica etalon (partially coated with $R=25\%$ -40%). SLM operation is monitored by a scanning confocal Fabry-Pérot resonator (CFP), and the IR wavelength measured with a lambda-meter with ± 0.001 nm accuracy. The ring cavity is aligned with the help of a short plane-plane cavity enclosing the laser crystal, with the aid of the two output beams leaking from the plane HR mirrors. For the σ or π Nd:YLF setups we use either type-I critically phase-matched nonlinear crystals [BiBO with $(\theta, \phi)=(8.6^\circ, 0^\circ)$ or LBO with $(\theta, \phi)=(86.4^\circ, 0^\circ)$], or temperature-tuned quasi-phase-matched ppKTP crystals (QPM periods $\Lambda \sim 16.5$ -17 μ m), all with $L=10$ mm lengths. SHG of the Nd:YVO₄ setup makes uses of the same dual-band AR coated BiBO crystal, since the phase-matching angle for 1342nm SHG is $\theta=9^\circ$. Further details of the experimental setups can be found in [4-5].

II. EXPERIMENTAL RESULTS: POWER OUTPUTS

The highest nonlinear conversion to the red range was achieved with the Nd:YLF/ppKTP lasers operating on either the σ or π polarization. Fig. 2 displays the cw power performance of the σ -polarized laser setup versus the diode pump absorbed power. With a pump wavelength set at ~ 806 nm at the wing of the Nd³⁺ absorption manifold, the absorption of the 0.7% at.% Nd:YLF amounts to 90% independently of the pump polarization (which is the main reason why this pump wavelength was chosen instead of the 792nm strong peak absorption wavelength). The square symbols displays the IR output at gain center without any etalon or nonlinear crystal and using a $T=0.5\%$ output coupler (OC=M4). As can be seen in Fig. 3(a) showing the corresponding CFP output spectrum, the laser then spontaneously oscillates at gain center wavelength on 3 to 4 longitudinal modes (spaced by a laser free spectral range $FSR=c/L_{cav} \sim 470$ MHz).

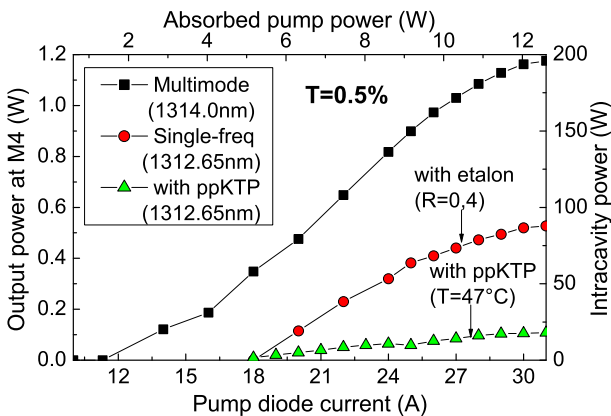


Fig. 2. IR output power of the σ -polarized Nd:YLF laser without ppKTP (square symbols without etalon and circle symbols with etalon) and with ppKTP phase-matched at the left side of the gain profile.

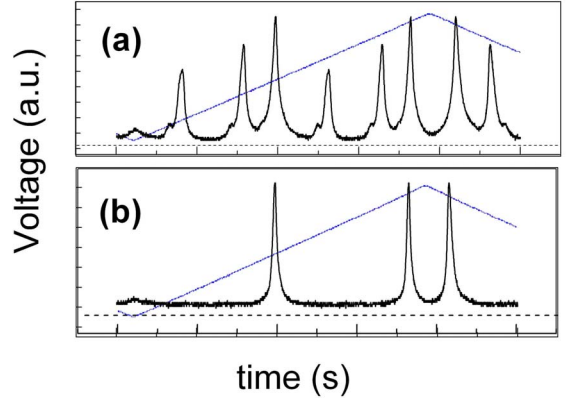


Fig. 3. Confocal Fabry-Pérot spectra: (a) without etalon, (b) with etalon (SLM operation).

Without the etalon loss, the measured intracavity power can be as high as 200W. At $P_{abs} > 10$ W an output power saturation (thermal roll-over) is observed, due to the effect of thermal lensing that dynamically modifies the transverse lasing mode (note that the thermal lens is negative in YLF due to a negative $dn/dT < 0$). Insertion of an etalon ($R=40\%$) leads to SLM operation (Fig. 3(b)). Tuning within the gain profile is achieved by etalon tilting, with simultaneous phase-matching optimization via the ppKTP temperature. At 1312.65nm (corresponding to the 4th subharmonic of Ag cooling wavelength) the output power drops to $P_o=0.5$ W. With the insertion of the highly nonlinear ppKTP sample ($d_{eff} \sim 8$ pm/V) the circulating SLM IR power drops from 90W to ~ 17 W (triangle symbols) as a consequence of the high nonlinear loss dominating the low passive anti-reflection coated ppKTP loss. This last assumption (low passive ppKTP loss) is corroborated by the identical pump threshold for the circle and triangle data. Furthermore, the red power is almost unchanged when the $T=0.5\%$ output coupler is replaced with a HR one ($T < 0.1\%$). At maximum $P_{abs}=13$ W, watt-level red output (0.92W) at gain center ($\lambda_{2\omega}=657$ nm, Ca inter-combination transition) is achieved for a ppKTP temperature of $T=63^\circ$ C. This power is reduced to ~ 0.4 W at 656.3nm (ppKTP temperature at $T=47^\circ$ C).

The SH conversion efficiency was slightly smaller when an angle-tuned BiBO crystal is used ($d_{eff} \sim 2.5$ pm/V), as in the case of the π -polarized laser. Tuning the SLM wavelength requires then small adjustment tilts of the crystal followed by fine realignment of the cavity (note that with the temperature-tuned ppKTP, no re-alignment is needed). Fig. 4 display the red power achieved with the Nd:YLF/BiBO π -polarized laser, when a HR ($R=99.8\%$) output coupler is used. At gain center ($\lambda_{\omega}=1321$ nm) SLM operation could sometimes be achieved without any etalon (filled circles in Fig. 4) due to the axial-mode suppression ensuing from the twice higher nonlinear loss experienced by sum-frequency mixing involving two longitudinal modes. However frequent mode-hops occur without the etalon. Etalon insertion leads to stable SLM operation at the expense of slightly higher loss (hollow circles).

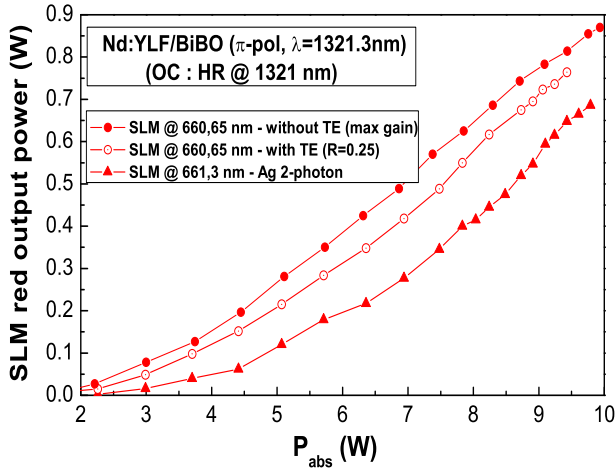


Fig. 4. Output red power of the π -polarized Nd:YLF/BiBO laser with a HR output coupler ($T<0.1\%$): without etalon (filled circles), with etalon ($R=50\%$) at gain center (hollow circles), with etalon tuned to Ag two-photon transition (triangles).

Typically 0.6-0.7W maximum SLM red power could be achieved with BiBO. Unlike with the ppKTP, the IR loss is no longer dominated by the nonlinear conversion loss (the circulating IR power depletes to ~ 50 W instead of ~ 17 W for ppKTP). Indeed replacing the HR coupler with a $T=0.5\%$ one leads to a reduction of the red power by a factor 2.

The same ring cavity as for the Nd:YLF π -polarized laser was used to test the performance of the Nd:YVO₄ laser. A straightforward replacement of the Nd:YLF crystal with a low-doped (0.15 at.%) Nd:YVO₄ crystal, with a pump diode wavelength tuned to 808nm corresponding to the peak absorption, leads to laser oscillation without further cavity re-alignment. The measured pump absorption of the vanadate crystal was identical (90%) to that of the 0.8 at.% Nd:YLF crystal. A dramatic thermal IR power roll-over was observed for $P_{abs}>12$ W as with the Nd:YLF crystals. We have tested the IR output performance using 3 different output couplers: $T=1\%$, 2% and 5% . Fig. 5 shows the IR performance when no etalon is inserted (unstable SLM or bi-mode operation at gain center) and without the BiBO crystal. The optimal IR coupling occurs for $T=2\%$, yielding up to

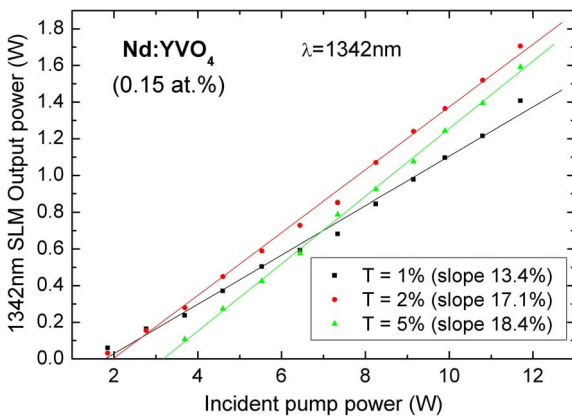


Fig. 5. IR power of the Nd:YVO₄ laser without etalon and nonlinear crystal.

$P_{\omega}=1.6$ W. Compared with Fig. 2, this output power is larger owing to the larger emission cross-section for Nd:YVO₄. Significant power is still achieved with $T=5\%$.

III. SINGLE-FREQUENCY WAVELENGTH TUNING

The widest and smoothest SLM tuning bandwidth is obtained using $e=100\mu\text{m}$ thin etalon with a partial reflective coatings of $R>20\%$, corresponding to a free-spectral range of $\text{FSR}=c/2ne=1\text{THz}$ ($\Delta\lambda\sim 5.8\text{nm}$). The use of a thicker etalon, e.g. $e=200\mu\text{m}$, yields smaller or erratic tuning bandwidths (sudden jumps to upper or lower wavelength side around the central wavelength). Such jumps may also occur for an uncoated etalon due to the lower etalon contrast. Etalon tilting provides smooth but discontinuous tuning by steps of $\sim 30\text{pm}$. Finer tuning steps of a few pm required by narrow atomic resonances (Doppler width < 5 GHz) can be achieved by using the lateral translation of wedged ($<0.2^\circ$) nonlinear crystal facet. Fig. 6 summarizes the SLM wavelength tuning features of the intra-cavity frequency-doubled Nd:YLF lasers. The highest power (0.92W) was achieved on the σ -transition with ppKTP, limited by the $R=40\%$ etalon loss. Our latest result with the π -polarized Nd:YLF/ppKTP laser yielded more than 1W of red power at 660.5nm, by employing a lower loss ($R=25\%$) etalon.

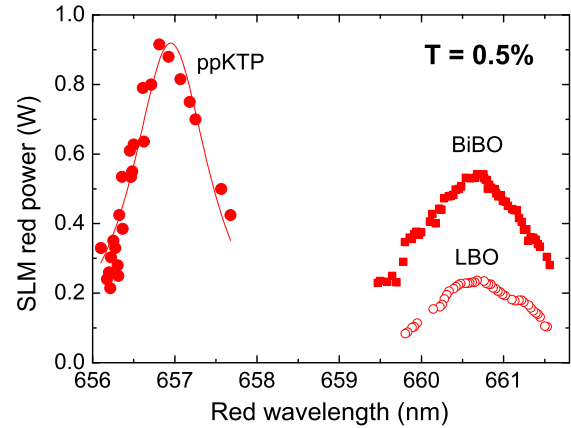


Fig. 6. SLM wavelength tuning of the red Nd:YLF lasers.

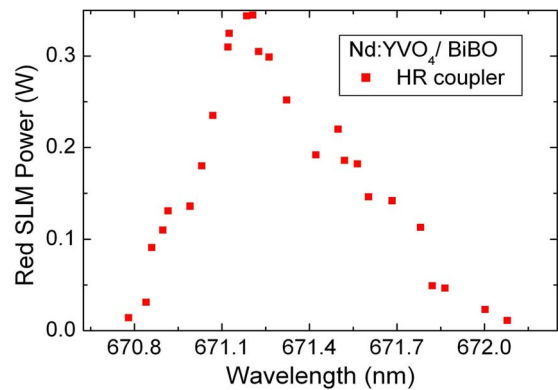


Fig. 7. SLM wavelength tuning of the red Nd:YVO₄ laser

Fig. 7 displays the red tuning feature of the Nd:YVO₄/BiBO laser. The lower output power compared with the BiBO curve in Fig. 6 is due to the increased $R=40\%$ reflectivity of the previous $R=25\%$ etalon at 1342nm.

IV. EVIDENCE OF SELF MODE-LOCKING REGIME

The use of ppKTP as an intra-cavity second-harmonic generator has scarcely been reported in cw intracavity frequency-doubled laser setups. Actually, the cw regime depicted in Fig. 2 or Fig. 6 requires the systematic use of an intra-cavity etalon as a spectrally selective element when ppKTP is used. When the etalon is removed, at high pump power ($P_{\text{abs}} > 8\text{W}$), the output of the CFP analyzer consists of a striking broadband phase-coherent continuum emission, as shown in Fig. 3(c) of reference [4]. Under these conditions, the laser runs bi-directional whatever the optical diode settings. An adiabatic transition to the line spectrum of Fig. 3(a) is then gradually retrieved when the pump power is reduced to below $P_{\text{abs}} < 6-8\text{W}$, meaning that the phenomenon is intensity-dependent. Given that a high-finesse Fabry-Pérot can transmit a broadband light if and only if it were phase-coherent, this is reminiscent of the spectral output of a Kerr-lens mode-locked laser. Occasionally, depending on the ppKTP temperature, the red light periodically flashes at a low repetition rate, reminding a simultaneous passive Q-switching. The corresponding average bidirectional red power was always lower than in true cw SLM operation, i.e. when the etalon is present and the ppKTP temperature is set at exact phase-matching. Recently, Holmgren *et al* reported on a Nd:GdVO₄ standing-wave laser that was passively mode-locked via $\chi^{(2)}:\chi^{(2)}$ cascaded second-order nonlinearities by a short ppKTP that was strongly temperature phase-mismatched on the focusing Kerr-lens nonlinearity side [6]. The self-starting pico-second mode-locking occurred near the thermal roll-over point of the cw laser. We believe that the broadband phase-coherent emission we have observed originates from the same cascaded Kerr-lens mode-locking phenomenon. To date, we could not yet check this assumption by direct temporal and spectral analysis of the IR emission using a fast oscilloscope and a suitable optical spectrum analyzer (unavailable to us). However, in addition to the peculiar CFP continuum transmission spectrum, we could infer from a fast Si photodiode intercepting the red output (and connected to a RF spectrum analyzer) that a stable and strong beatnote appears at $f \sim 470$ MHz, a frequency that matches exactly the free-spectral range of the laser cavity. This beatnote systematically disappeared under true cw SLM operation, meaning that the continuum output corresponded to a self-sustained pulsing temporal regime. Last but not least, the broadband emission also occurs even with the etalon inserted when the ppKTP is strongly phase-mismatched ($\Delta kL \leq -3\pi$) with respect to the lasing SLM wavelength [4]. On the contrary true cw SLM operation is retrieved when the temperature is set to perfect phase-matching ($\Delta kL \sim 0$).

We note that this peculiar behavior of the ring laser was never observed with neither BiBO nor LBO, but only with ppKTP which possesses much stronger second-order non-

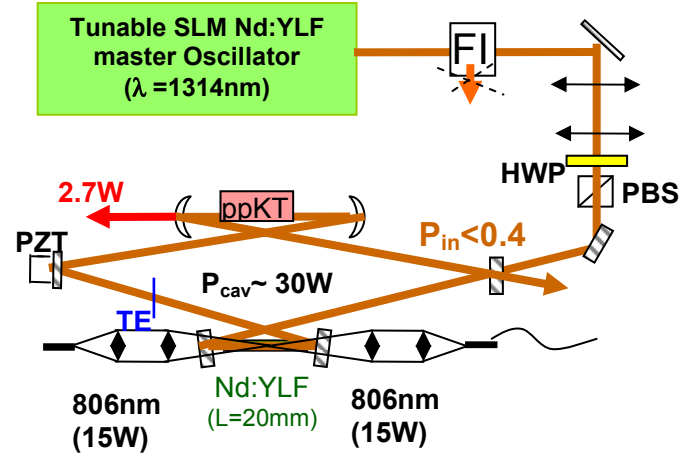


Fig. 8. Schematic for an injection-locked, dual-end pumped intra-cavity frequency-doubled slave ring oscillator.

linearity. We plan in the near future to characterize more in detail this regime of operation with suitable instrumentation devices.

V. CONCLUSIONS AND PROSPECTS

We have investigated in detail the cw single-frequency and tuning performance of single-end pumped 1.3 μm Nd:YLF and Nd:YVO₄ ring lasers both without and with intra-cavity SHG. The highest cw output power is achieved with ppKTP as the nonlinear converter, while birefringence phase matched BiBO or LBO are free from cascaded nonlinear effects. In all cases, thermal lensing in the laser crystal was found to be the limiting factor. We plan to upscale the cw red output power to multi-watt level by using a master-slave injection-locking scheme (Fig. 8).

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