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1.3 Watt Single-Frequency Nd:YLF/ppKTP Red Laser

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Abstract: Using a temperature-tuned ppKTP crystal, a record 1.3W single-frequency red laser at 661nm is achieved from intra-cavity second-harmonic generation of a Nd:YLiF$_4$ ring laser oscillating on the π-polarized transition (λ~1321nm).

OCIS codes: (140.3570) Lasers, single-mode; (190.2620) Frequency conversion

1. Introduction

All solid-state continuous-wave (cw) narrow-linewidth and tunable red lasers are convenient alternative sources to bulky and expensive dye-lasers for high-precision laser spectroscopy. In order to probe the narrow (Δν~1Hz) $^2S_{1/2}$– $^2D_{5/2}$ two-photon transition in atomic silver (λ=660.5nm), a watt-level single-frequency and finely tunable source is required, based on the frequency doubling of the π-polarized $^4F_{3/2}$ - $^4I_{13/2}$ transition of Nd^{3+} in yttrium lithium fluoride host (YLF) at λ~1321nm. Such a single-longitudinal mode (SLM) red laser can be conveniently achieved using a unidirectional ring cavity containing a suitable nonlinear crystal for second-harmonic generation (intra-cavity SHG). We have previously reported on a diode-pumped frequency-doubled Nd:YLF laser emitting on the σ-polarized $^4F_{3/2}$ - $^4I_{13/2}$ transition (λ~1314nm), yielding 0.92W of SLM red power at the calcium (Ca) inter-combination transition at 657nm [1]. Such a watt-level SLM power could only be achieved using a periodically-poled KTP (ppKTP) as the nonlinear frequency doubler. Due to the narrow spectral (quasi)-phase-matching bandwidth of ppKTP ($\Delta\lambda_{QPM}$=0.9nm FWHM for a 10mm long ppKTP, much smaller than the laser gain bandwidth $\Delta\lambda_{gain}$~ 4nm FW), strong second-order nonlinear cascading effects arose when the ppKTP was inserted in the laser cavity [1,2]. These intra-cavity $\chi^{(2)}$: $\chi^{(2)}$ processes led to spectral broadening of the fundamental laser emission, rendering single-frequency operation delicate to achieve unless perfect matching of the ppKTP spectral bandwidth with respect to the lasing wavelength, controlled by an intra-cavity etalon, is achieved. Such cascading effects are not observed when critically phase-matched LiB_3O_5 (LBO) or BiB_3O_6 (BiBO) possessing much larger spectral phase-matching bandwidths ($\Delta\lambda_{CPM}$=3.9nm and 47nm, respectively [2]) than the active medium gain bandwidth were employed. To achieve stable SLM operation of the σ-polarized Nd:YLF/ppKTP laser, a partially-coated thin etalon (R=40%) had to be inserted [1] to quench the undesired nonlinear cascading processes, limiting the maximum red power to less than 1W. In this work dealing with the π-polarized Nd:YLF laser, we have succeeded in upgrading the SLM red power to 1.3W by using a less spectrally-selective etalon (R=25%) while still managing to avoid the unwanted cascading effects. This power level constitutes to our knowledge the best performance ever reported for a single-frequency intra-cavity frequency-doubled 1.32µm laser. Furthermore, given the optimal SLM IR power extracted without SHG (P_ω=1.4 W with an output coupler T=2%), the overall SHG power efficiency of the set up is close to $\eta=(1.3W)_{660.5nm}/(1.4W)_{1321nm}$=93%, corresponding to 46% quantum efficiency.

2. Experimental ring laser setup

The experimental unidirectional ring laser setup, sketched in Fig.1, is similar to the one used for the σ-polarized Nd:YLF laser [1,2]. We use an asymmetric bow-tie resonator in order to accommodate the single-end longitudinal pumping scheme of the 10mm-long low-doped (0.8 at.%, corresponding to ~90% pump absorption at 806nm) Nd:YLF laser crystal, so as to overlap the bigger cavity waist (w_1~320µm at 1321nm) with the fiber-coupled pump diode waist (w_p~265µm at 806nm). A fused silica thin etalon (0.1mm thickness), with facet reflectivities of R=25%, is placed in the vicinity of the larger waist to minimize insertion loss. An optical diode consisting of a Brewster-cut TGG Faraday rotator rod combined with a zero-order half-wave plate ensures a robust unidirectional operation. All cavity mirrors are broadband HR-coated dichroic mirrors (R>99.8% in the range 1300-1350nm, with T~90% in the 650-810nm range). The near-IR power leaking through M3 is used for diagnostic purposes (wavelength measurement and spectral analysis by a confocal Fabry-Perot resonator with a FSR=750 MHz free spectral range). The ppKTP chip (dimension 5(W)x1(T)x10(L)mm^3, poling period Λ~16.55µm) is mounted on a temperature-controlled Peltier element and placed between the curved mirrors (ROC=-100mm), where the secondary cavity waist (w_2~50µm) is located. Typical pump threshold with the ppKTP inserted corresponds to an absorbed pump power of P_{abs}~3 W. The longitudinal mode spacing of the ring cavity is FSR=c/L_{cav}~ 420 MHz.

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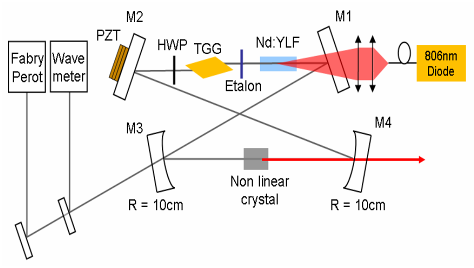


Fig.1: Diode end-pumped Nd:YLF/ppKTP ring laser setup.

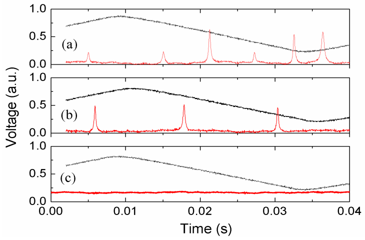
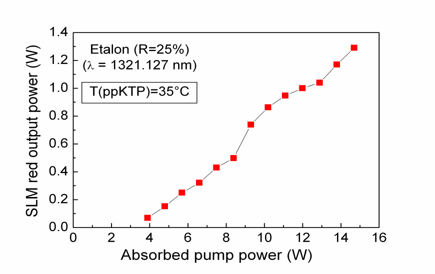


Fig.2: Confocal Fabry-Perot (CFP) spectra. For (c), the temporal IR output consists of a train of short pulses (f_{rep}~420MHz) on a background continuum (partial mode synchronization).



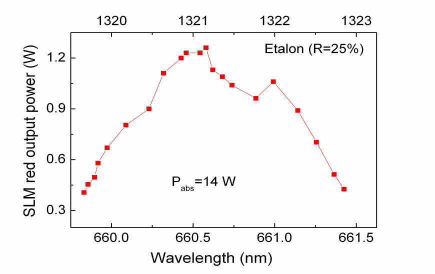


Fig.3 : Single-frequency cw red output power versus diode absorbed pump power. Maximum efficiency critically depends on the ppKTP phase-matching control and etalon adjustment.

Fig.4: Red power tuning curve. SLM tuning requires a perfect match between lasing wavelength and ppKTP spectral bandwidth controlled by temperature.

3. Experimental results

Without nonlinear crystal and etalon, the unidirectional laser typically oscillates on two longitudinal modes near the laser gain maximum as seen in Fig.2(a). From the near IR power (~50mW) leaking through M3 mirror, the intra-cavity power was estimated to be as large as ~100W. When angularly type-I phase-matched LBO or BiBO crystals (L=10mm) are inserted [2], the output spectrum (FH) always consists of a discrete line spectrum (bi-modal or SLM in the presence of the etalon), and optimization of the red output power for the SLM lasing wavelength is relatively straightforward via angular tilt of the nonlinear crystals followed by slight cavity re-alignment. However when the ppKTP crystal is inserted, a striking broad-band emission is systematically transmitted by the confocal FP analyzer (CFP) in the form of a background intensity continuum (bias) as shown in Fig.2(c). Simultaneously, the laser starts running bi-directional, whatever the rotation of the HWP controlling the efficiency of the optical diode. The lambda-meter can no longer display the central wavelength of this broadband emission. The two red output beams escaping from M3 and M4 are then generally weaker (~100-300mW) than the SLM unidirectional red output. This broadband emission is partially coherent since it is transmitted though the CFP (finesse~50). Recording the IR temporal waveform with a fast 10GHz bandwidth InGaAs detector actually reveals a train of short (<100ps) pulses at the laser FSR repetition rate superimposed on a small continuum background. This spectral broadening is attributed to second-order nonlinear cascading effects (sum-frequency and difference-frequency mixing between FH and SH longitudinal modes) responsible of self-phase-modulation and spectral broadening via an effective Kerr-lens effect ($n_2^{eff} \propto -1/\Delta k(\omega)L$), given the high circulating field intensity I_{cav} and the narrow ($\Delta\lambda_{QPM}$<1nm) spectral bandwidth of the quasi-phase matching. Genuine cw SLM operation can only – and tediously – be recovered after careful interplay of the intra-cavity etalon tilt (selecting the lasing wavelength) together with a delicate adjustment of the ppKTP temperature, so as to accurately match the SHG spectral bandwidth to the lasing wavelength until the CFP transmission displays the SLM fringe pattern of Fig.2(b). Unidirectional operation is then retrieved, followed by a much larger unidirectional cw red output (Figs. 3-4). Although this SLM retrieval procedure is quite tedious to achieve, once this SLM lasing is established the red laser can stay on the same longitudinal mode during more than one hour of operation with an extremely stable red power output (less than 1% decrease). Without etalon, or with a less spectrally selective uncoated one, the nonlinear cascading effects cannot be quenched and SLM operation can never be achieved. F. Camargo acknowledges a PhD scholarship grant from FAPESP (BR).

3. References

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