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Dye laser pumped, continuous-wave KTP optical parametric oscillators

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Abstract. We report on dye-laser-pumped, continuous-wave (CW) $KTiOPO_4$ (KTP) optical parametric oscillators (OPOs) with pump and idler resonant cavities. With a linear two-mirror cavity the pump power at threshold was 70 mW. The single-frequency signal and idler output wavelengths were tuned in the range of 1025 to 1040 nm and 1250 to 1380 nm by tuning the dye laser in the range of 565 to 588 nm. With a dual three-mirror cavity the threshold was 135 mW. Pumped by 500 mW of 578 nm radiation the 1040 nm single-frequency signal wave output power was 84 mW. Power and frequency stable operation with a spectral bandwidth of less than 9 MHz was obtained by piezo-electrically locking the length of the pump resonant cavity to the dye laser wavelength. Similar performance was achieved by placing the idler resonant OPO inside the resonator of the dye laser. With this system power stable and single-frequency operation was achieved with a spectral bandwidth of less than 11 MHz for the idler wave.

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Continuous-wave dye lasers are widely used for spectroscopic applications in the visible wavelength range. The strongest optical resonances of most molecules are, however, in the infrared (see, e.g., [1]). For extending the available wavelength range into the near and mid infrared it is therefore of interest to investigate the performance of continuous-wave (CW) optical parametric oscillators (OPOs) which are pumped by a dye laser. The properties of standard CW dye lasers are, in fact, highly suitable for the operation of low threshold and widely tunable OPOs. With intracavity etalons single-frequency TEM_{00} mode operation with a spectral bandwidth of a few MHz is routinely obtained. Using different dyes, output powers exceeding 100 mW are generated in the whole range of 380 to 900 nm.

Of particular interest is the investigation of dye laser pumped CW OPOs which are based on type II noncritical phase matching (NCPM) in the nonlinear crystal $KTiOPO_4$ (KTP). NCPM is of advantage, because there is no walk-off of the different waves in the crystal, which decreases the OPO threshold. Furthermore, KTP offers a reasonably high effective nonlinearity of 3–5 pm/V, an excellent optical quality, as well as a good commercial availability. The temperature dependence of the generated signal and idler wavelengths for a fixed pumped wavelength is small ($\mathrm{d}\lambda_s/\mathrm{d}T = -0.13$ nm/K on the signal wave, when pumped at 580 nm and $\mathrm{d}\lambda_s/\mathrm{d}T = -0.08$ nm/K, when pumped at 810 nm), which makes a careful stabilization of the crystal temperature obsolete. Still, a wide tunability of a NCPM OPO can be achieved with a widely tunable pump source. In KTP NCPM is possible over the whole visible wavelength range, where most dye lasers work. Such tuning of a CW OPO through tuning of its pump source has so far been demonstrated for various Ti:sapphire laser pumped systems, e.g. with LiB_3O_5 [2], KTP [3] and RTA [4] crystals. With pump wavelengths from 380 nm to 900 nm, a NCPM KTP OPO should generate a signal and idler output which covers the whole range from 540 nm to 3280 nm.

In addition to this large tuning range, the high spatial and spectral quality of the dye laser output radiation is well suited for a pump resonant OPO, where only one wave (signal or idler) is resonated in addition. The advantage of a pump enhanced OPO is its low pump power at threshold, which is lower than that of a singly resonant OPO by one or two orders of magnitude [5]. Triply resonant OPOs, where the pump, signal and idler waves are resonated, offer threshold pump powers which are even lower. Such OPOs are, however, far more susceptible to mode-hops and power instabilities caused by small perturbations of the cavity length or pump frequency [6].

The first aim of the investigations reported in this paper is the power and frequency stable operation of dye laser pumped CW OPOs with cavities, which are resonant only for the pump and the idler wave. The second aim is to demonstrate stable OPO operation with dye laser intracavity pumping, where the OPO is placed inside the resonator of a commercially available dye laser.

1 Experimental setup

The experimental setup is shown in Fig. 1. The pump laser for the OPO was a TEM_{00} unidirectional continuous-wave rhodamine 6G dye ring laser (Spectra Physics, model 581B) pumped by an argon ion laser (Spectra Physics, model 2040). With a resonator-internal birefringent filter, a Faraday rotator and two solid state etalons the dye laser generated a TEM_{00} single-frequency output power of up to 700 mW, which was tunable in the wavelength range of 563 to 643 nm. The typical spectral bandwidth as measured with a scanning Fabry Perot interferometer was 8 MHz. The laser output is passed through a 30 dB Faraday isolator (Gsänger, model FR620). The laser power which pumps the OPO could be gradually attenuated from a maximum value of 550 mW to 10 mW by rotating a half-wave plate placed between the laser and the isolator. The pump beam was focused into the OPO cavity with a spherical lens ($f = 40$ mm) to a beam radius of approximately 20 μm, which was measured with a two-dimensional beam profiler with 5 μm resolution (Mercantek Beamscope).

The OPO was operated with two different types of cavities. The first one was a simple linear cavity, where both, the pump and the idler wave, were resonated between the same mirrors (two-mirror-cavity). As the intracavity losses are low, this configuration should exhibit a low pump power at threshold and a high overall output power. However, with a two-mirror-cavity, continuous tunability over a wide range, which is an important motivation for the development of CW OPOs, cannot be achieved. A solution to this problem is a dual cavity configuration where an intracavity beamsplitter separates the resonated waves, such that the cavity lengths of both waves can be controlled independently [7].

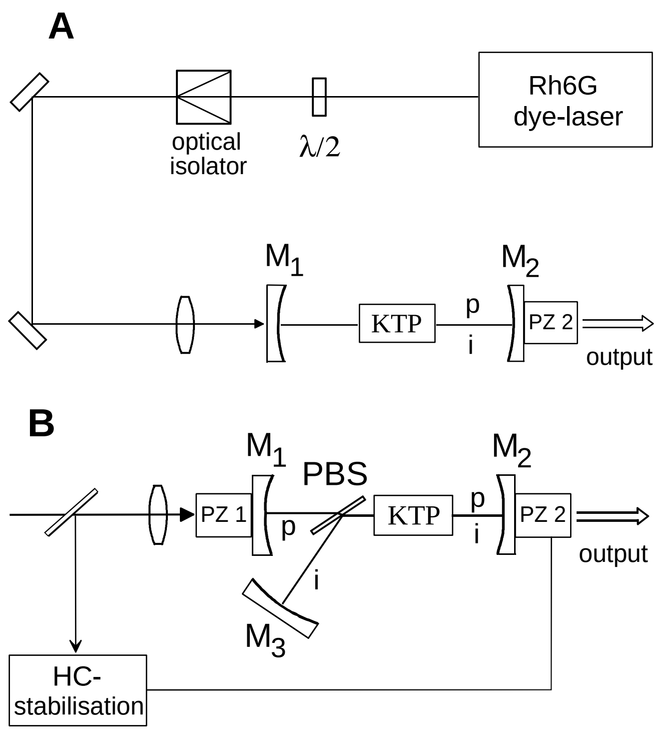

Fig. 1a,b. Experimental setup of the dye laser pumped CW KTP-OPO with a linear two-mirror cavity (**a**) or a dual three-mirror cavity (**b**)

The linear OPO cavity consisted of the mirrors M_1 and M_2 with a radius of curvature (ROC) of 25 mm in a near-spherical configuration (see Fig. 1a). The cavity was resonant for the pump and idler wave. The front mirror M_1 was broadband highly reflective for the idler wave (transmission $T_{I,1} < 0.2\%$ @ 1.3 μm) and of low reflectivity for the signal wave ($T_{S,1} > 90\%$ @ 1.03 μm). To investigate and optimize the pump impedance matching (i.e., matching the transmission of the pump input mirror to equal the sum of all other roundtrip losses) the OPO was operated with different input mirrors M_1 with transmissions of $T_{P,1} = 0.3\%$, 0.6%, 1.3%, and 2.4% for 580 nm. The output mirror M_2 was broadband highly reflective for the pump and idler wave with transmissions of $T_{P,2} < 0.2\%$ and $T_{I,2} < 0.2\%$, respectively, and of low reflectivity for the signal wave ($T_{S,2} > 90\%$).

The configuration of the second cavity was a dual three-mirror resonator, also resonant for the pump and idler wave (see Fig. 1b). An intracavity polarizing beam splitter (positioned at Brewster's angle of 56° for the p-polarized pump radiation) separated the s-polarized idler wave which was then resonated on the additional mirror M_3 (ROC = 50 mm). The surface of the 1.5 mm thick suprasil beam splitter which faces the crystal was antireflection coated for the pump wave ($T_P > 99\%$) and was highly reflective for the idler wave ($T_I < 0.5\%$). The transmission for the signal wave was 90%. The input mirror M_1 (ROC = 30 mm) transmitted the idler wave ($T_{I,1} = 80\%$) and reflected the signal wave ($T_{S,1} < 0.2\%$ @ 1030 nm) to provide a double pass of the signal wave through the crystal. For optimum impedance matching the OPO was operated with different input mirrors M_1 with transmissions $T_{P,1} = 1\%, 2\%, 3\%$ and 4% @ 580 nm. The mirror M_3 was highly reflective for the idler wave ($T_{I,3} < 0.2\%$) and transmitted the pump ($T_{P,3} > 95\%$) and signal wave ($T_{S,3} > 85\%$). The mirror M_2 had the same spectral specifications as mirror M_2 of the two-mirror cavity.

The 12 mm long KTP crystal used in both cavity configurations was *x*-cut for type II noncritical phase matching (e → eo, $\Theta = 90°$, $\phi = 0°$). Both facets ($5 \times 5\,mm^2$) were broadband antireflection coated for the pump and idler wave ($T_P > 99.7\%$, $T_I > 99.6\%$). The residual reflectivity at the signal wavelength was approximately 8%. To determine the crystal losses at the pump wavelength we measured the input coupling efficiency for different input mirror transmissions. The resulting loss was 1.6% in single pass, including the losses at the facets. The single pass losses of 17% for the non-resonant signal wave (1030 nm) and 0.5% for the idler wave (1340 nm) were measured with a spectrometer and include the surface losses.

The center of the crystal was placed at the position of the waist of the TEM_{00} cavity mode. The resonator length was varied in order to match the mode size of the pump cavity to the 20 μm radius of the pump focus.

In order to tune the two-mirror cavity into resonance with the pump radiation, the cavity length was scanned by changing the position of M_2 with a linear voltage ramp on the piezo-electric actuator PZ2. In the dual-cavity OPO the length of the pump resonator was scanned with PZ2 or with a ring shaped piezo crystal PZ1 attached to M_1. For both cavity configurations, the pump, signal, and idler waves transmitted through M_2 were separated with spectral filters and monitored with fast silicon and germanium photodiodes.

The pump light reflected by the OPO cavity and emitted through the side port of the isolator was measured by a fast silicon photodiode. With the dual cavity OPO, we measured a small fraction (4%) of the reflected pump light by using a glass plate S (with one AR-coated facet), which was placed in the incident pump beam (see Fig. 1b). To stabilize the length of the pump resonant cavity we used the Hänsch-Couillaud (HC) stabilization technique [8].

2 Experimental results

The wavelength of the dye laser and that of the OPO output were measured with a grating monochromator with a resolution of 0.2 nm for the pump and signal waves, and 0.4 nm for the idler wave. With the two-mirror resonator as well as with the dual cavity, the OPO generated a near-infrared signal and idler radiation in the wavelength range of 1025 to 1042 nm and 1250 to 1380 nm, respectively. This wavelength tuning was achieved by tuning the dye laser in the range of 565 to 588 nm (see Fig. 2). The measured signal wavelengths agree within 6 nm with those predicted by the Sellmeier equations based on the coefficients given in [5].

While scanning the cavity length the power of the signal wave and that of the transmitted pump were recorded simultaneously with a dual-trace sampling oscilloscope (Hameg HM205). A typical recording of the measured power is shown in Fig. 3 for the two-mirror OPO. Before the onset of OPO emission (at $t = 100\,\mu$s) the recorded pump light shows a Lorentzian-shaped increase of the intracavity pump power. At $t = 100\,\mu$s the OPO starts to oscillate and to emit signal radiation with a fast-rising slope. Simultaneously the intracavity pump power shows a fast decrease to a constant power level. This power level is the pump power at threshold and indicates steady-state operation of the OPO [9]. Below threshold the transmitted pump power (and thus the electrical signal of the photodiode placed behind M_2) is proportional to the pump power incident on the cavity.

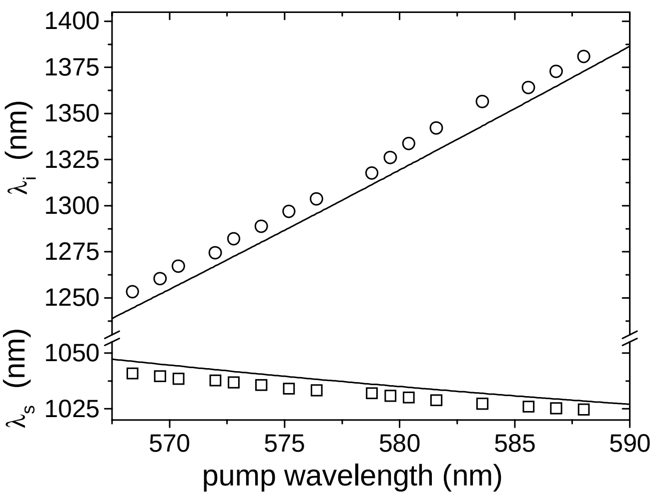

Fig. 2. Wavelengths λ_i and λ_s of the OPO signal and idler wave in dependence on the wavelength of the dye laser pump radiation. The *solid lines* represent the wavelengths calculated from the Sellmeier equations

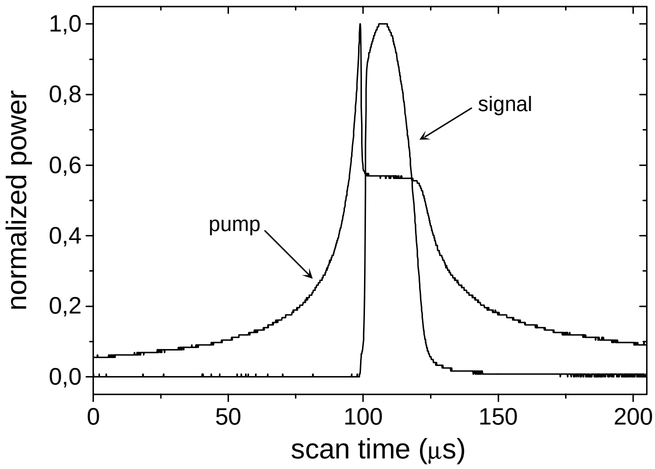

Fig. 3. Power of the signal wave and of the pump wave transmitted by the cavity of the KTP-OPO while scanning the length of the cavity

The calibrated photodiode signal was used to measure the pump power at threshold while scanning the cavity length of the two-mirror and the dual cavity OPO.

The dependence of the pump power at threshold on the dye laser wavelength, measured for the two-mirror and the dual cavity OPO, is shown in Fig. 4. For the two-mirror cavity, an input coupler with $T_{P,1} = 2.5\%$ provided (at a pump wavelength of 580 nm) best impedance matching with a high coupling efficiency of up to 90%, and a low threshold of 70 mW. For the dual-cavity the optimum mirror transmission was $T_{P,1} = 4\%$, which provided a pump coupling efficiency of 65% and a minimum threshold (at 566 nm) of 135 mW. For both cavities, the increase of the threshold for pump wavelengths exceeding 580 nm is caused by the reduced reflectivity of the mirror coatings at the corresponding idler wavelengths. For pump wavelengths below 565 nm the power of the Rh6G dye laser is below the pump power at threshold.

Pumped by 380 mW of 578 nm radiation, the two-mirror OPO generated a signal output measured at M_2 of 47 mW.

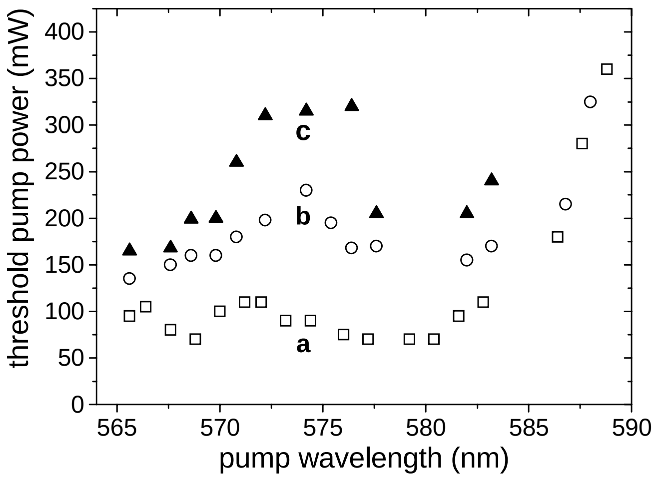

Fig. 4. Pump power at threshold in dependence of the pump wavelength measured for the OPO with the two-mirror cavity (a) and the dual three-mirror cavity (b), both while scanning the cavity length of the pump resonant cavity, and for the dual three-mirror cavity OPO while locking the pump cavity to the pump wavelength (c)

Because almost the same amount of output power is emitted through M_1, the total signal output exceeds 90 mW, which corresponds to a conversion efficiency of 25%. The dual cavity OPO generated a maximum signal wave output of 84 mW (measured behind M_2) when pumped by 500 mW of 578 nm dye laser radiation. For this OPO almost all of the signal wave is emitted through M_2 because of the high reflectivity of M_1.

For power- and frequency-stable operation of the dual cavity OPO, the length of the pump resonant cavity was locked to the pump wavelength by the HC stabilization. The pump power at threshold measured as a function of the pump wavelength is also shown in Fig. 4. The lowest threshold observed under these operating conditions was 165 mW at a pump wavelength of 566 nm. The variation of the threshold with the pump wavelength is very similar to the one measured while scanning the cavity length. As seen from Fig. 4, the threshold powers measured for continuous operation are, however, higher than those determined for scanned operation. We expect that the difference (which depends on the pump wavelength and amounts to 15%–80%) is caused by thermal lensing due to absorption of pump radiation in the KTP crystal. The amount of pump power absorbed in the crystal increases with the threshold power, so that thermal lensing becomes more significant.

With a pump power of 405 mW at 578 nm, the OPO generated an output power of approximately 70 mW, which was stable over several minutes. A recording of the signal wave is shown in Fig. 5. As seen from this example, the power stability measured within a time interval of 50 s is better than 3%.

The spectrum of the signal wave was monitored using a confocal scanning Fabry–Perot interferometer (SFPI) with a free spectral range (FSR) of 2.5 GHz. We observed that the spectrum was single-frequency over time intervals of several seconds before a mode-hop of the resonant idler wave occured. The measured (resolution limited) spectral bandwidth (FWHM) was less than 9 MHz. The reason for the occurrence of mode-hops is probably the slow drift of the dye laser frequency, which causes a shift of the parametric gain profile. As the OPO oscillates on the idler cavity mode which is closest to the gain maximum, even a small shift of that maximum in the order of the free spectral range of the idler cavity may cause a mode-hop of the OPO. Therefore, using a commercial standard electronic locking technique for the dye laser in combination with a beam lock of the argon ion laser should suppress OPO mode hops considerably.

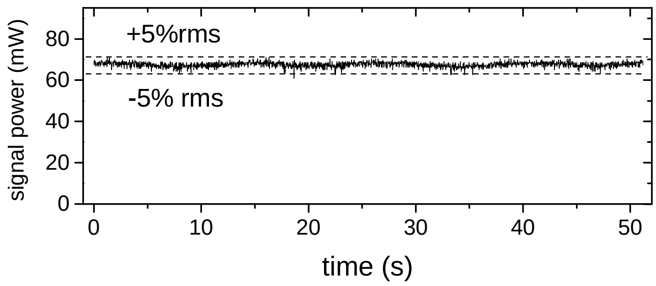

Fig. 5. Recording of the power of the signal wave of the dual cavity OPO with an electronically stabilized pump cavity

3 Intracavity OPO

An interesting alternative to an OPO with a pump resonant cavity is to place the OPO crystal inside the resonator of the pump laser. This was demonstrated for the first time by R.G. Smith et al. [11] with a near degenerate doubly resonant OPO which was intracavity to an argon ion laser. More recently, modern solid state lasers such as a diode pumped Nd:YAG laser [12] and a Ti:sapphire laser [13] were used for intracavity pumping of OPOs. The advantage is that the laser intracavity power is high enough to allow the realization of OPOs, where only the signal or the idler wave is resonated. A second advantage is that acoustically or thermally induced changes of the laser cavity may shift the laser frequency, but do not cause significant changes of the pump power within the nonlinear crystal.

The experimental setup of the idler resonant intracavity dye laser pumped KTP-OPO is shown in Fig. 6. An important goal was to demonstrate the feasibility of intracavity pumping of the OPO with a commercial dye laser, i.e. without modifications of the original laser design. Specifically, the OPO configuration had to match the given beam properties of the laser resonator and the given space inside the dye laser housing. For example, the residual back reflection of the pump from the linear OPO idler cavity overran the direction-discriminating effect of the Faraday rotator, so that unidirectional operation of the laser is not achieved. Therefore the Faraday rotator was removed in order reduce loss and thus provide more efficient bidirectional pumping of the OPO crystal. Although the OPO threshold was reached with both etalons inserted, they were removed as well, for the benefit of a constant pump power. This caused laser oscillation on several modes. The laser wavelength was tuned with the birefringent filter to 575 nm. The KTP crystal was placed in the laser cavity at the location of a secondary beam waist ($w_0 = 40\,\mu$m), which is originally provided by the manufacturer of the dye laser for intracavity frequency doubling.

To separate the generated idler radiation from the pump radiation, polarizing beam splitters were placed at Brewster's angle for the p-polarized pump beam at both sides of the crystal (see inset in Fig. 6). The reflectivity specifications of the beam splitters were the same as for the one

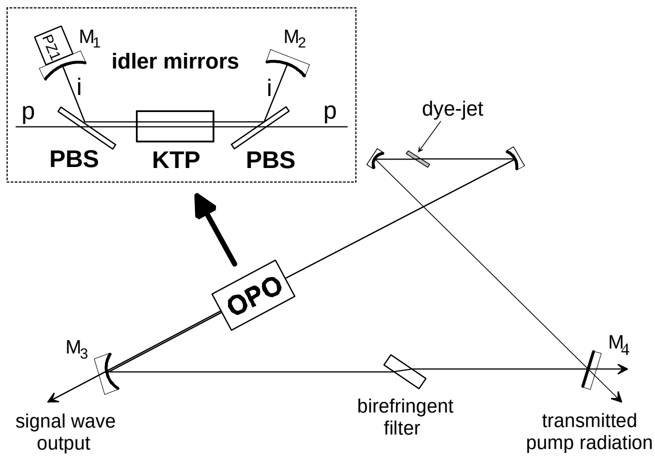

Fig. 6. Experimental setup of the idler resonant KTP-OPO pumped inside the resonator of the CW dye laser

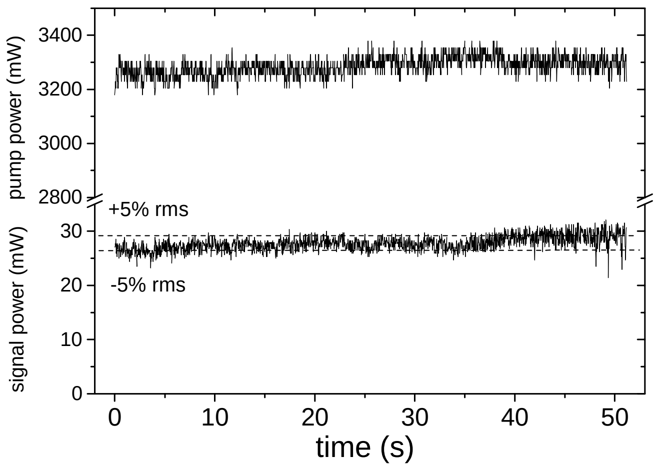

Fig. 7. Time recording of the signal wave output power of the intracavity KTP-OPO (*lower trace*). The *upper trace* is the simultaneously recorded intracavity dye laser power

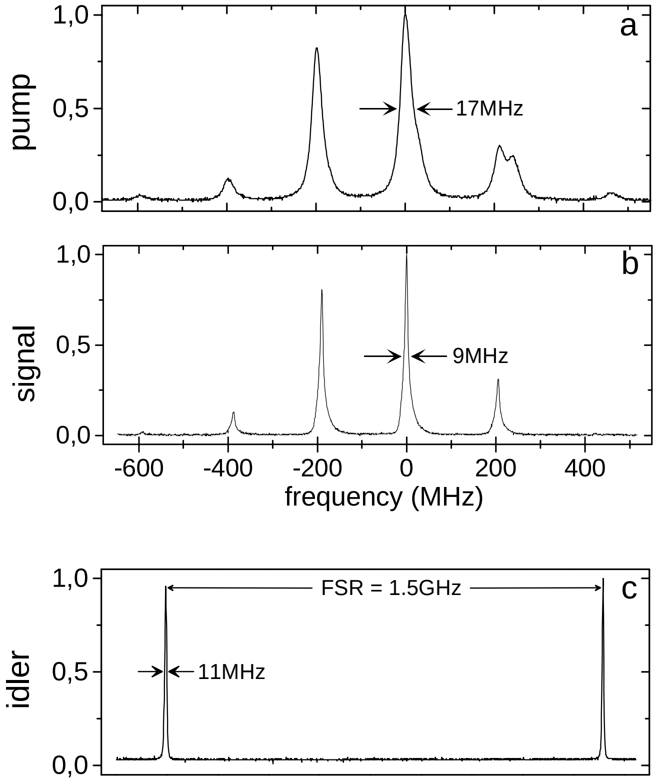

Fig. 8a–c. Spectra of the pump, signal and idler radiation of the intracavity OPO measured with confocal scanning Fabry–Perot interferometers. **a** Multimode pump spectrum of the dye laser. **b** Spectrum of the signal wave. **c** Single-frequency spectrum of the idler wave showing a spectral bandwidth of less than 11 MHz

used in the dual-cavity OPO. The idler resonant, 56 mm long, near-spherical OPO cavity is formed by the mirrors M_1 and M_2 (ROC = 25 mm). The mirrors were broadband highly reflective for the idler wave ($T < 0.2\%$ @ 1.32 μm) and highly reflective for the pump ($T < 0.3\%$ @ 575 nm). The residual reflectivity of each mirror at the signal wavelength was 10%.

The dye laser output power measured behind mirror M_4 (with a transmission of 1%) is proportional to the intracavity laser power. The laser spectrum was measured behind M_4 with a SFPI (with a FSR of 2.5 GHz). The signal wave output power was detected behind the laser mirror M_3 (with $T = 90\%$ for the signal wave). The signal spectrum was also measured behind M_3 using the same SFPI as for the pump. The spectrum of the idler wave was measured with a second SFPI with a FSR of 1.5 GHz using the small amount of idler radiation ($\sim$ 1 mW) transmitted by M_2.

The intracavity OPO reached its threshold at a laser internal pump power of approximately 2 W, which corresponds to an all-lines Ar^+-laser power of 4.5 W. The highest 1030 nm signal wave output of 28 mW was obtained with a dye laser internal pump power of 3.3 W, corresponding to an Ar^+-laser power of 6.5 W. The operation of the OPO showed good stability. Fig. 7 gives an example of a simultaneous time recording of the power of the signal wave and the intracavity pump radiation circulating in one direction. These recordings indicate that the power stability is better than 5% (rms) over 50 s.

The measured spectral properties of the intracavity pumped OPO are displayed in Fig. 8. The idler wave oscillates on a single longitudinal mode with a (resolution limited) spectral bandwidth of 11 MHz (Fig. 8c) for time periods of several seconds before a mode hop occurs. The pump consists typically of five longitudinal modes, which are separated by the 200 MHz free spectral range of the dye laser ring cavity (Fig. 8a). As a result of the multimode spectrum of the pump radiation it is expected that the spectrum of the nonresonant signal wave would consist of a set of modes spaced by 200 MHz, as well. This is confirmed by the measured spectrum of the signal wave displayed in Fig. 8b. The slight difference in the spectral shapes of the pump and signal radiation could be caused by a slight variation of the optical length of the laser cavity during the measurement.

4 Summary and conclusion

We demonstrated stable operation of pump and idler resonant CW KTP-OPOs pumped by a frequency tunable single mode CW dye laser.

By tuning the dye laser in the range of 565 to 588 nm, the wavelengths of the generated signal and idler radiation were tuned in the range of 1025 to 1040 nm and 1250 to 1380 nm, respectively. Operated with a linear two-mirror cavity, the lowest pump power at threshold was 70 mW and the signal output power exceeded 90 mW. For a three-mirror dual cavity the threshold was 134 mW, when the length of the pump resonant cavity was scanned through resonance. This dual cavity OPO generated a single frequency signal wave with a power of 84 mW, when pumped by 500 mW of 578 nm radiation. Electronically locking the length of the pump resonant cavity to the wavelength of the dye laser radiation provided power- and frequency-stable operation with a spectral bandwidth of less than 9 MHz. Power-stable operation of an OPO was also obtained without the electronic lock by pumping the OPO inside the resonator of the dye laser. The performance of this intracavity idler resonant OPO was similar to that of the pump and idler resonant OPO, i.e., power-stable and single-frequency operation for the idler wave with a spectral bandwidth of less than 11 MHz was observed.

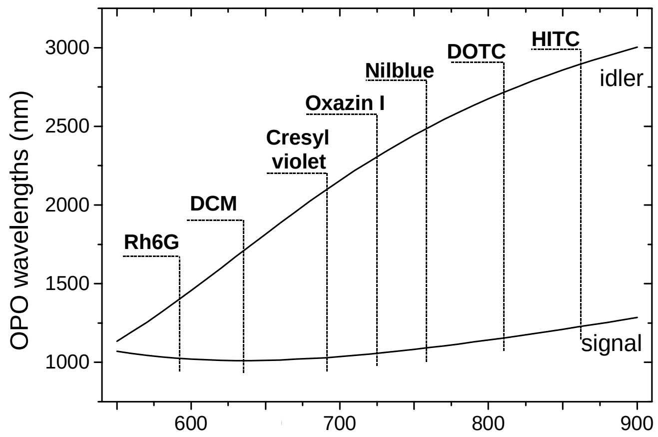

Fig. 9. Calculated wavelengths of the signal and idler waves of noncritically type-II phase matched KTP-OPOs pumped by a dye laser which is operated with different dye solutions

All three systems presented in this paper demonstrate that stable operation of dye laser pumped CW OPOs can be achieved. A comparison of their individual advantages certainly depends on the requirements of a special application. A linear cavity configuration offers a wide wavelength coverage at low thresholds and high output powers. Electronically locking the OPO cavity to a continuously tunable laser should provide a continuous tunability over a small range, which is suitable for specific spectroscopic applications [14]. However, a wide continuous tunability requires independent control over the cavity lengths of all resonated waves, which can be achieved by a dual-cavity configuration. In contrast to these systems the intracavity pumped dual-cavity OPO is attractive, because it requires no electronic locking. Furthermore, its design can be fitted to the given design of a commercially available dye laser. We note that the demonstrated results and in particular the tuning of the signal and idler waves are obtained by operating the dye laser only with one single dye solution (Rh6G). A much broader tuning range of the OPO is expected, of course, if other dyes are used. Fig. 9 shows the broad wavelength range of noncritically phase-matched KTP-OPOs accessable with various dyes pumped by Ar^{+}- and Kr^{+}-lasers. The corresponding wavelengths of the signal and idler waves extend over the whole spectrum from 1030 nm to more than 3 μm. In view of this wide tunability, dye laser pumped KTP-OPOs are promising devices for a significant extension of the wavelength range of tunable coherent radiation into the infrared, which is very useful e.g. for spectroscopic applications.

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