

# Single-frequency continuous-wave optical parametric oscillator system with an ultrawide tuning range of 550 to 2830 nm

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We present a cw single-frequency laser source with what is to our knowledge the largest emission range ever demonstrated, from the green to the mid-IR range. It employs a cw optical parametric oscillator with subse-quent resonant frequency doubling. Typical output powers are 30–500 mW, with 160 mW at 580 nm. Mode-hop-free oscillation, high absolute frequency stability, 20-kHz-signal linewidth, and up to 38-GHz continuous tuning are demonstrated. Both PPLN and PPKTP are used as nonlinear materials, and their performance is compared. © 2002 Optical Society of America

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## 1. INTRODUCTION

The development of all-solid-state, continuous-wave (cw) light sources with emission covering the visible spectrum, as an alternative to dye lasers, is one of the major challenges in laser source development. Optical parametric oscillators (OPOs) are an especially promising approach toward this goal. In recent years the increased availability of novel nonlinear materials and high-power solid-state single-frequency pump sources has led to great advances in the development of cw OPOs. For emission wavelengths between 1.5 and 4  $\mu\text{m}$ , such devices are now relatively mature<sup>1–3</sup> and are starting to become commercially available. To reach shorter wavelengths, the first developments of single-frequency cw OPOs pumped by visible radiation have been initiated.<sup>4–9</sup>

Here we report a cw OPO system with an exceptionally large tuning range—from 550 to 2830 nm—which to our knowledge is the largest tuning range of any single-frequency source so far. The system also exhibits excellent spectral properties such as ultranarrow linewidth

and high absolute frequency stability. A novel feature is a large continuous frequency tuning range ( $>1\text{ cm}^{-1}$ ) without pump tuning.

## 2. SETUP

Figure 1 shows a schematic of the system consisting of a singly-resonant OPO<sup>10–12</sup> and a resonant frequency doubler for the idler wave. The singly-resonant OPO is pumped in a single pass by a commercial 10-W single-frequency solid-state laser at 532 nm (Coherent Verdi). The pump laser is nontunable and has a measured short-term linewidth of 20 kHz, 500 kHz jitter over 1 ms, and a low frequency drift  $<50\text{ MHz/h}$ .

As the nonlinear element for the OPO we use periodically poled, multigrating crystals from two different material families: periodically poled potassium titanyl phosphate (PPKTP) or, alternatively, periodically poled lithium niobate (PPLN). Two PPKTP crystals, 24 mm in length with apertures of  $19 \times 0.3$  and  $19 \times 0.5$  mm and a

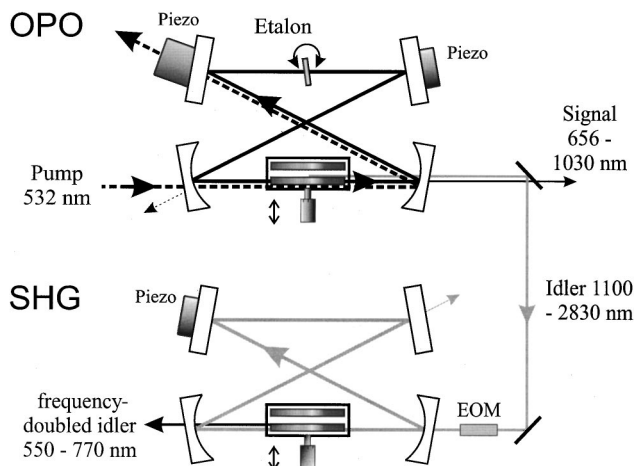


Fig. 1. OPO and second-harmonic-generation setup. EOM, electro-optic modulator. Pump laser, optical isolator, ovens, and lock electronics are not shown. The total area of the setup including pump laser and beam analysis is  $1.1 \text{ m}^2$ .

total of 19 different poling periods from  $8.96\text{--}12.194 \mu\text{m}$ , were fabricated at Tel Aviv University by the low-temperature poling method combined with the recently developed pyroelectric monitoring technique.<sup>13,14</sup> The PPLN multigrating crystal, 25 mm in length with an aperture of  $35 \times 0.5 \text{ mm}$  and 23 different poling periods from  $6.51\text{--}9.59 \mu\text{m}$ , was fabricated at the University of Kaiserslautern according to the method in Ref. 15. Hard-baked photoresist served as an insulator, and a LiCl solution was used for electrical contacting. The electrode width was  $1.3\text{--}2.3 \mu\text{m}$  in order to yield a uniform domain duty cycle of 50% for all periods. Coarse tuning of the OPO is performed by movement of different poling periods into the beam path with a translation stage while fine tuning is achieved by variation of the crystal temperature.

The OPO bow-tie ring cavity is formed from two concave (100-mm radius of curvature) and two flat mirrors and has a free spectral range of 680 MHz. It resonates the signal wave with a  $1/e^2$ -waist radius of  $48 \mu\text{m}$  (at  $\lambda = 800 \text{ nm}$ ) in the middle of the crystal (13% astigmatism). The cavity is designed to tolerate strong thermal lenses with a focal length as short as 4 mm, which reduces the waist to  $18 \mu\text{m}$  but changes the beam geometry outside the crystal only negligibly. This is a crucial aspect for controllable operation, as thermal lenses are expected to have focal lengths of only a few millimeters for this device.<sup>3</sup> All resonator mirrors are highly reflecting ( $>99.8\%$ ) for the signal and transmitting for the idler (three mirrors  $>95\%$ , one mirror  $>85\%$ ). Three mirrors are transmitting the pump (99%), and one is reflecting the pump (99%). A total idler round-trip loss of  $>99.998\%$  ensures singly resonant operation. An optical intracavity etalon [thickness 0.25 or 0.5 mm, free spectral range 400 or 200 GHz, signal reflectivity per surface varying from 20% to 60%] mounted on a galvoactuator (tilt angle  $\pm 4^\circ$ ) is used for additional control of the signal frequency.

To extend the emission range further into the visible, the idler output of the OPO is coupled into an external resonant-frequency doubler. Two PPLN crystals, also fabricated at the University of Kaiserslautern, are used

as nonlinear elements. They are 43 mm in length, with an aperture of  $47 \times 0.5 \text{ mm}$  and a total of 62 different poling periods from  $6.51\text{--}20.93 \mu\text{m}$ . Like the OPO, the frequency doubler is also configured as a bow-tie ring cavity with two plane and two concave (75 mm radius of curvature) mirrors. It has a free spectral range of 670 MHz and a nonastigmatic waist of  $50 \mu\text{m}$  (at  $\lambda = 1300 \text{ nm}$ ). The incoupling mirror has a transmission of 1.7%, while the other mirrors are highly reflecting for the idler ( $>99.9\%$ ) and transmitting for the doubled idler ( $>95\%$ ). The cavity length is locked to the idler wavelength by the Pound–Drever–Hall method and an electro-optic modulator for phase modulation at 12.7 MHz.

Further extension of the emission range toward the near-UV should be possible by frequency-doubling the signal, e.g., by using a second quasi-phase-matched crystal inside the OPO cavity.

### 3. EMISSION RANGE AND OUTPUT POWER

Figure 2 summarizes the emission range and output powers. The total emission range is covered by the frequency-doubled idler (550–770 nm, up to 70 mW), the signal (656–1035 nm, up to 60 mW), and the idler (1096–2830 nm, up to 800 mW). In addition, up to 1.25 mW of blue light is generated by non-phase-matched frequency doubling of the signal in the OPO crystal. Pump powers were between 0.8 and 3.3 W.

The output power is not limited by the available pump power. When the pump power is increased beyond an optimal value for the PPLN crystal, the output power saturates and the beam profile becomes increasingly distorted owing to thermal lenses and photorefractive effects. For PPKTP the limiting factor is the damage threshold of the crystals and the coatings. Above  $150^\circ\text{C}$ , part of the crystal input face was damaged at a pump power of 2.4 W.

Without the etalon, the emitted signal power is approximately twice as high for PPKTP as for PPLN, while idler power and emission range are comparable for both materials. The power conversion efficiency from pump to idler reaches up to 30% (69% quantum efficiency) for both materials, with a pump depletion of up to 93% (PPKTP) and an oscillation threshold varying from 290 mW at 830 nm to more than 2000 mW at the end of the emission range, depending on the etalon, crystal material, and temperature. For both materials the lowest threshold is approximately two times lower (!) than the theoretical value expected from Refs. 16–18 if thermal lensing effects are neglected. This deviation could be explained by the effect of thermal lenses that tighten the focusing relative to a Gaussian beam. When an etalon is introduced into the cavity, the additional losses ( $\sim 1\%$  depending on tilt angle) increase the threshold by a factor of 1.5 for PPLN. However, the same output power as without an etalon can be obtained by increasing the pump power accordingly. For PPKTP, in contrast, the etalon reduces the maximum obtainable output power and emission range substantially. This is because PPKTP has approximately two times lower losses and two times lower nonlinear gain compared with PPLN; thus the etalon losses are comparatively more important. The additional losses could not be

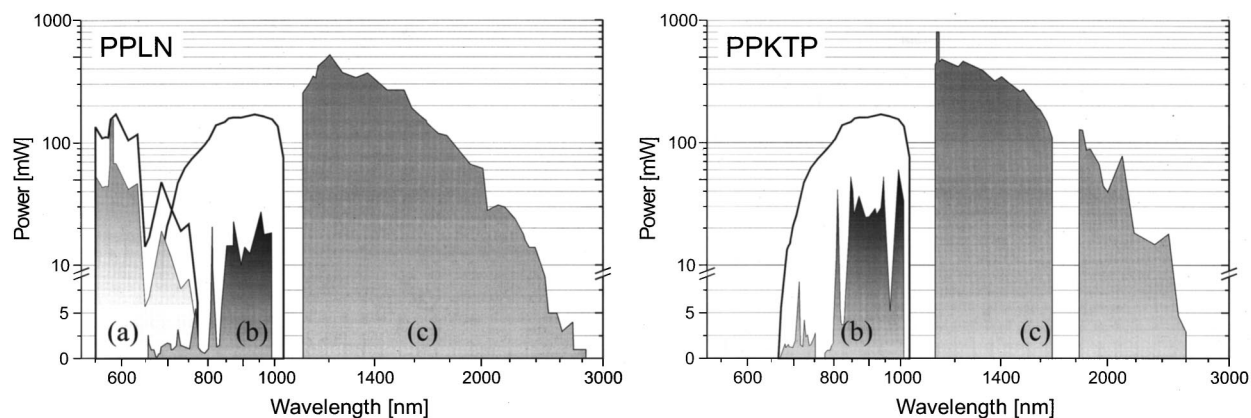


Fig. 2. (a) Frequency-doubled idler, (b) signal, and (c) idler power versus wavelength. Left, PPLN with and without etalon; right, PPKTP without etalon. Shaded areas, measured powers; curves, conservative estimates of the signal and doubled idler power expected for optimized outcoupling and incoupling mirrors.

compensated by an increase in the pump power because of the observed low damage threshold.

At approximately  $\lambda = 900$  nm the resonating signal power is of the order of 10 W (PPLN) and 20 W (PPKTP) with a cavity finesse of 150 and 300 (round-trip losses 4% and 2%), respectively. The signal is emitted as only a tiny leakage through the four highly reflecting resonator mirrors, and nearly all of the generated signal power (which can be inferred from the emitted idler power) is dissipated in the nonlinear crystal. It should therefore be possible to obtain significantly higher signal output power by using an output coupler with higher transmission for the signal. If it were, for example, set at 1.3% (for the PPLN crystal) or 0.7% (PPKTP), then one fourth of the generated signal power could be extracted from the resonator without affecting the overall OPO performance substantially. The expected signal power is more than 100 mW over most of the signal range. The signal power is indicated by curves (b) in Fig. 2. We note that  $\approx 100$  mW of signal radiation (measured for PPLN at 900 nm) is already extracted from the cavity by reflection off the etalon. Using an even higher outcoupling transmission for the signal might further increase the signal power. It would also reduce the thermal load on the crystal (dominated by signal absorption), possibly permitting the use of higher pump power and thus increasing the emitted idler power.

PPLN shows strong photorefractive effects. To reduce them, the crystal has to be operated above 140 °C and shows best efficiency above 200 °C. PPKTP works only below 150 °C and is best between room temperature and 80 °C. Above 150 °C part of the crystal input face was damaged. It could not be determined whether to attribute the damage to the crystals or the coatings. We expect that the performance of quasi-phase-matched devices will improve substantially when periodically poled, stoichiometric LiTaO<sub>3</sub> and gray-track-resistant PPKTP become available.

The idler output of the PPLN OPO can be coupled into the frequency-doubling cavity with a mode-matching efficiency of up to 87%, which proves the near diffraction-limited mode quality of the idler. For idler powers as indicated in Fig. 2, the second-harmonic-generation

efficiency varies between 23% at 560 nm and 2% at 770 nm. The doubling cavity, which was optimized for input powers of only 30 mW, shows 4%–5% linear losses and up to 10% conversion losses per round trip. The input coupler of 1.7% transmission thus does not establish an optimal impedance match, resulting in a coupling efficiency of only 25–50% (70% for low input powers up to 80 mW). By changing to a 15%-transmission input coupler for proper impedance matching, it should be possible to increase the output power to more than the 100 mW over most of the emission range (indicated by curves (c) in Fig. 2). The feasibility of this was demonstrated at 1160 nm, the only wavelength where an appropriate mirror was available. We thus obtained an output power of 160 mW at 580 nm from 420 mW of infrared light (at a pump power of 1.44 W).

#### 4. PHASE-MATCHING PROPERTIES

For both of the nonlinear materials employed, the wavelengths predicted by published Sellmeier equations deviate from the measured wavelengths by up to 30 nm. For PPLN the equation of Ref. 19 is more accurate than the equation of Ref. 20 for signal wavelengths above 760 nm and temperatures below 200 °C, while the opposite is the case below 760 nm and above 200 °C. The equation of Ref. 19 predicts the phase-matching temperatures of the frequency doubler correctly within 1 °C at 1100 nm and about 14 °C lower than those measured (corresponding to 2.4 nm) at 1540 nm. The equation of Ref. 20 shows larger deviations. For PPKTP the temperature-independent equation of Refs. 21 and 22 combined with the temperature derivatives of Ref. 23 is quite accurate at room temperature, as well as far from degeneracy after a 26 °C-temperature offset is introduced, while it deviates substantially above 120 °C and near degeneracy. The equations of Refs. 24 and 25 are less accurate.

#### 5. SPECTRAL PROPERTIES

The linewidth of the OPO was determined by a beat frequency measurement of the signal (PPLN, 0.5 mm etalon, 1.6 W pump power) against a monolithic Nd:YAG laser at

946 nm (InnoLight Mephisto). The free-running OPO shows a short-term linewidth of 20 kHz over 50  $\mu$ s with 300 kHz jitter over 5 ms and 5 MHz over 1 s. Figure 3 shows the frequency change over a time of 5 ms. A fast Fourier transform of Fig. 3 shows jitter frequencies mainly up to 800 Hz, which can easily be compensated for with a piezo. A 20-kHz linewidth without jitter is observed (Fig. 4) when the OPO is frequency locked to the Nd:YAG laser with a low bandwidth. The idler frequency, which is the difference between the pump and the signal frequencies, is expected to have a similar linewidth, but with the larger jitter of the pump laser.

The signal and idler can be tuned continuously (without mode hops) by changing the cavity length with a piezo and synchronously tilting the etalon, controlled either by a feedforward circuit or a feedback loop. The error signal for the latter was obtained by dithering the etalon at 1.9 kHz with a 0.34-mrad amplitude. Note that pump-frequency tuning is not necessary. A maximum tuning range of 38 GHz was achieved for PPKTP with a 0.5-mm etalon, limited by the walk-off losses induced by the etalon tilt angle (Fig. 5). This tuning range is  $2 \times 10^6$  times the linewidth and over 20 times larger than was previously demonstrated with a nontunable pump.<sup>12</sup> For PPLN, where photorefractive effects cause memory effects and ripples in the gain profile leading to a distorted error signal, the continuous tuning range was limited to typically 5–16 GHz.

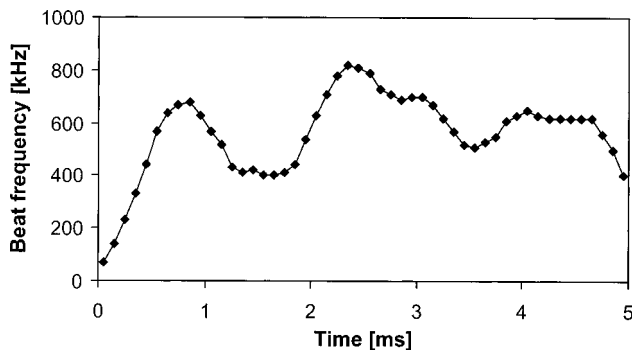


Fig. 3. Jitter of the free-running OPO. Each point corresponds to a 100- $\mu$ s frequency measurement.

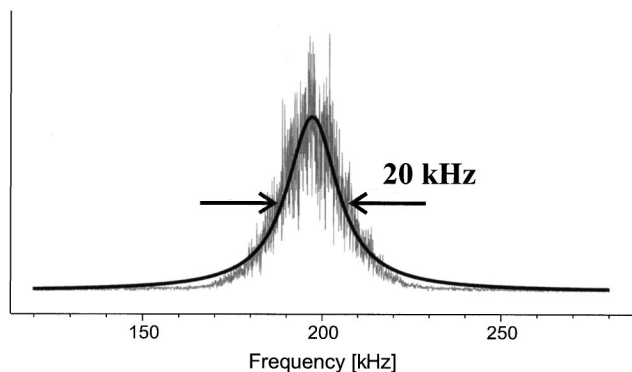


Fig. 4. Spectrum of the beat signal between the OPO signal wave and a 946-nm Nd:YAG laser. The OPO cavity is locked to the laser with a bandwidth of 4 kHz. The sampling time is 50 ms.

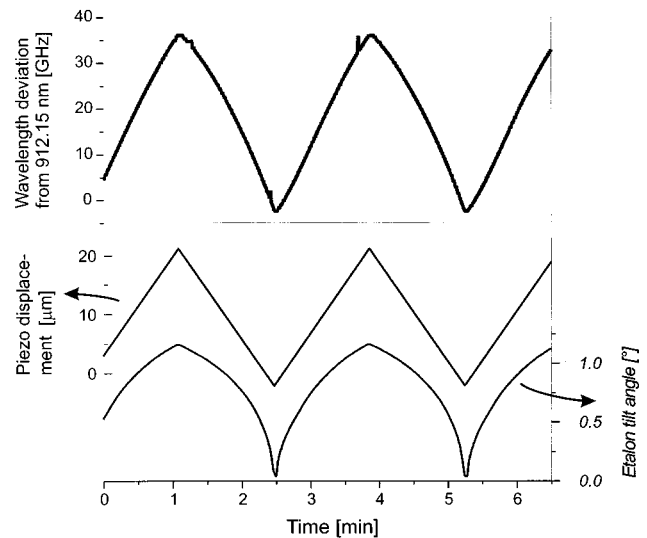


Fig. 5. Continuous tuning of the PPKTP OPO with fixed pump wavelength by changing the cavity length and using closed-loop control of etalon tilt; measured with a high-resolution wavemeter. Occasional spikes in the upper curve are most likely due to wavemeter malfunction.

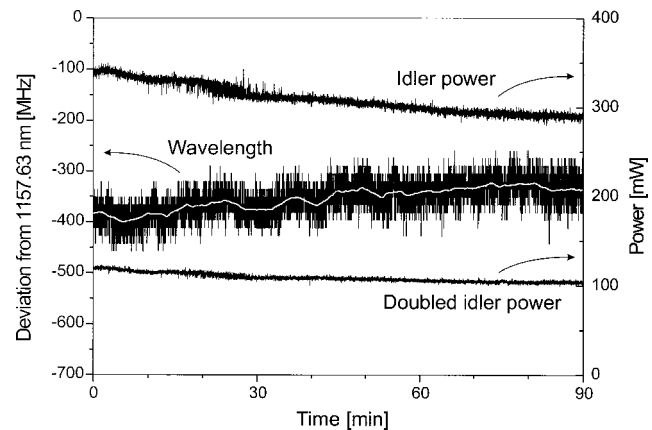


Fig. 6. Frequency measured with a high-resolution wavemeter and power stability of the PPLN OPO with 0.5-mm etalon and 1.6 W of pump power. The OPO cavity length is locked to the pump laser frequency. Also shown is the output power of the frequency doubler.

An even larger tuning range should be possible with optimized control electronics, different actuators for changing cavity length, and piezoelectrically tuned, air-spaced etalon used to eliminate walk-off losses. To achieve more than a 300-GHz tuning range, the gain profile of the OPO would have to be shifted in wavelength synchronously with the transmission profile of the etalon, e.g., by changing the crystal temperature.

A high long-term frequency stability can be achieved by locking the OPO cavity length to the pump laser to compensate for thermal drifts. An appropriate error signal can be obtained from the interference signal imprinted on the residual pump wave that is reflected by the incoupling mirror. Owing to the low pump frequency drift, the signal and idler frequencies are then stable with a drift  $<50$  MHz/h (Fig. 6). The free-running OPO, in contrast, typically shows a mode hop by one free spectral range (680



MHz) every 10 min owing to thermal drift of the cavity. The output power of the PPLN OPO decreases by  $\sim 10\%$  per hour. After at most 4 h of operation on the same frequency with the PPLN crystal, the OPO turns off completely. It recovers after the crystal is moved or the pump is turned off for several hours. We assume photo-refractive effects to be responsible for this odd behavior. The longest period of mode-hop-free operation obtained for the PPKTP crystal was 20 min with the cavity locked to the pump laser. At present it is not understood what is limiting this time.

## 6. USABILITY

Using the OPO system is comparatively easy. It is possible to turn it on and access any desired wavelength within  $\pm 400$  GHz in a few minutes and within less than 1 GHz in a few hours. We operated the OPO with the same PPLN crystal for more than six months without any decrease in efficiency. To demonstrate its reliability and flexibility, we used it to perform Doppler-free spectroscopy of molecular iodine at 580 nm,<sup>26</sup> a spectral region where OPOs could offer a more convenient alternative to dye lasers as tunable laser sources.

## 7. SUMMARY

We have developed a novel cw, single-frequency source with high output power and the widest spectral coverage reported so far. Excellent spectral and tuning characteristics are obtained by use of a commercially available, fixed-frequency pump laser. We expect this device to be a versatile light source for a very wide range of applications, including spectroscopy and characterization of optical components, e.g., for telecom applications.

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