Single-frequency continuous-wave radiation from 0.77 to 1.73 μm generated by a green-pumped optical parametric oscillator with periodically poled $LiTaO_3$

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We describe a cw optical parametric oscillator (OPO) with multigrating periodically poled $LiTaO_3$. Pumped by a single-frequency 532-nm laser, the OPO emits single-frequency radiation at wavelengths from 0.77 to 1.73 μm with as much as 60 mW of output power. Mode-hop-free operation for as long as 50 min, a low frequency drift (<70 MHz/h), and as much as 700-MHz continuous frequency tuning of signal and idler are demonstrated.

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Continuous-wave optical parametric oscillators (OPO's) with single-frequency emission and wide tuning ranges (several hundreds of nanometers) in the mid IR have been a focus of interest in the past decade.[1–4] Single-frequency operation without mode hops, a wide emission range,[5] and first spectroscopic experiments have been reported.[2,5,6]

A stable, widely tunable single-frequency cw OPO pumped in the visible and emitting in the near IR has not yet been demonstrated. Early OPO's used birefringently phase-matched crystals.[7–9] Tsunekane *et al.*, using a doubly resonant LiB_3O_5 OPO pumped at 532 nm,[10] reported a 791–1620-nm emission range. Batchko *et al.* used a periodically poled crystal ($LiNbO_3$) in a 532-nm pumped cw OPO emitting in the range 917–1267 nm.[11] In neither device was stable single-frequency operation, which is crucial for precision applications such as spectroscopy, demonstrated.

In this Letter we describe a stable single-frequency OPO with what is to our knowledge the largest tuning range in the near IR demonstrated so far, from 0.77 to 1.73 μm. This range is achieved by use of multigrating periodically poled $LiTaO_3$, which has recently emerged as a nonlinear medium for frequency conversion of both short-wavelength and near-IR radiation[3,12,13] and is used here for the first time to our knowledge in a visible-pumped OPO. The OPO exhibits good power and frequency stability and is thus suited for precision applications.

We follow the concept of a singly resonant OPO with pump enhancement (PR-SRO).[1–3,8,14] Resonating the pump wave and locking the resonator length to the pump laser to a large extent transfer the frequency stability, narrow linewidth, and continuous tunability of the pump laser to both signal and idler. In addition, the threshold power is reduced, so commercially available lasers with excellent spectral characteristics can be used as pump sources. Mode-hop-free operation is achieved through the use of a frequency-stable laser and by accurate temperature control of the crystal.

A schematic of the setup is shown in Fig. 1. As a pump source we use a diode-pumped monolithic Nd:YAG ring laser with a single-frequency output power of 1.35 W at 1064.52 nm, a linewidth of approximately 1 kHz, and a typical frequency drift of 100 MHz/h. We can slowly tune the output frequency over an 8-GHz range by controlling the laser crystal's temperature. A Faraday isolator is used to prevent backreflection into the laser.

The laser is externally frequency doubled in a semimonolithic bulk MgO:$LiNbO_3$ resonator.[15] After the radiation has passed through another Faraday isolator and focusing optics, 450 mW of green light at 532.26 nm is available for pumping the PR-SRO.

The OPO is resonant for both signal and pump. It is configured as a semimonolithic linear standing-wave resonator that is formed by one mirror coated directly onto one flat end face of the nonlinear crystals and an external mirror mounted onto a piezo translator. The broadband dielectric mirror coated onto the outer end face of the crystals provides reflectivities of 99% for the pump (532 nm), >99.7% for the signal (670–1030 nm),

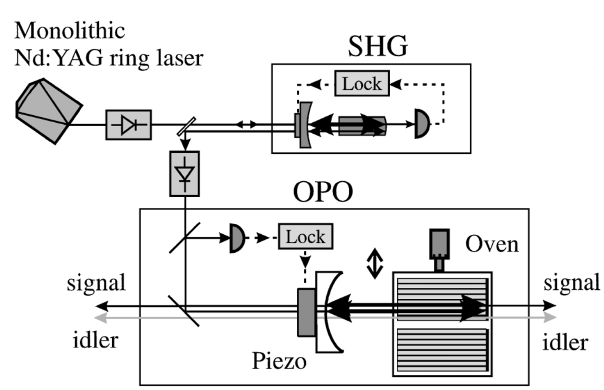

Fig. 1. Experimental setup. One resonator mirror is coated directly onto one end face of the crystals. Signal and idler are emitted on both sides of the resonator. SHG, second-harmonic generation.

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and <20% for the idler (1100–2600 nm). The inner end face is antireflection coated, with residual reflectivities of <0.5%, <0.5%, and <20% for pump, signal, and idler, respectively. The external mirror has a radius of curvature of 25 mm and provides reflectivities of 95.5%, >99.7%, and <20% for pump, signal, and idler, respectively. As nonlinear material we use two periodically poled $LiTaO_3$ multigrating crystals that were produced in Kaiserslautern. Each is 25 mm × 25 mm × 0.5 mm in size, with a total of 35 different poling periods from 7.3 to 10.7 μm. To reduce photorefractive effects we heat the crystals in a copper oven to temperatures of 160–240 °C with a temperature stability of 5 mK.

The OPO resonator is locked on resonance with the pump frequency by means of a Pound–Drever–Hall technique in which the crystal of the frequency doubler is electro-optically modulated at an OPO frequency of 14.5 MHz. A round-trip pump absorption $V_p \simeq 8\%$ in the crystal causes the crystal temperature and therefore the cavity optical length to change by approximately one free spectral range within 1 ms when the cavity length is to be locked. Despite these thermal effects, we have achieved a stable cavity lock by increasing the servo loop control bandwidth to 12 kHz and by actively compensating for the change in optical path length with a feed-forward system.

The external threshold of a PR-SRO is

$$P_{\text{th}} = \left(\frac{T_p + V_p}{T_p}\right)\frac{(T_p + V_p)(T_s + T_s)}{8E_{\text{sp}}}, \qquad (1)$$

where T_p is the pump input mirror transmission, T_s is the signal outcoupling mirror transmission, V_p and V_s are the pump and signal round-trip losses, respectively, and E_{sp} is the effective single-pass nonlinearity.[14] We have measured $T_p = 4.5\%$ and $V_p \simeq 8\%$ and estimate that $T_s + V_s \simeq 1.5\%$. With $d_{33} = -14$ pm/V for $LiTaO_3$,[12] and a focal waist of 37 μm on the flat end face of the crystal, a nonlinearity E_{sp} that varies from 1.1%/W near degeneracy to 0.6%/W at $\lambda_s = 0.7\ \mu$m is calculated, leading to an estimated external threshold of 59–111 mW.

Figure 2 shows the emission range where oscillation is reached on different poling periods and temperatures while the cavity length is scanned. The range extends from 0.70 to 2.20 μm. The output wavelengths coincide within 6 nm with those calculated from a published Sellmeier equation[12] if one allows for a −8-K offset of the temperature measurement. Emission also occurs near degeneracy, where the cavity is resonant for both signal and idler.

At nine discrete wavelengths the OPO crystal provides quasi phase matching in second, third, fourth, or fifth order for second-harmonic generation of the signal producing several-milliwatt peak power of blue light between 365 and 474 nm in scanned operation. At 12 wavelengths the sum-frequency generation of signal and pump is quasi phase matched in fifth to ninth order, producing UV light from 310 to 341 nm. The phase-matching temperatures for these processes coincide with the expected ones within 3 K, confirming the published Sellmeier equation.

On nine gratings with poling periods from 7.6 to 8.4 μm we obtained a stable OPO cavity lock. In cw operation the threshold was found to increase relative to scanned operation, which resulted in a reduced emission range from 768 to 978 nm for the signal and from 1167 to 1733 nm for the idler. The external oscillation threshold P_{th} varied from ~100 mW near degeneracy to 350 mW at the edges of the emission range. Figure 3 shows the output power at a pump power of 450 mW. The maximum idler output power corresponds to an internal photon conversion efficiency of 70% with respect to the actual incoupled power (50% of incident power). The maximum total power conversion efficiency of pump to signal plus idler is 22%. Threshold and efficiencies agree within a factor of 2 with the estimated values when the 85% mode matching of the pump is taken into account. Over the whole emission range, blue light from 384 to 489 nm at a level of microwatts was generated by non-phase-matched second-harmonic generation of the signal.

The OPO runs stably for extended periods of time, as shown in Fig. 4. The longest time without mode hops was 52 min. As long as there are no mode hops the frequency drift is less than 70 MHz/h (Fig. 4, inset),

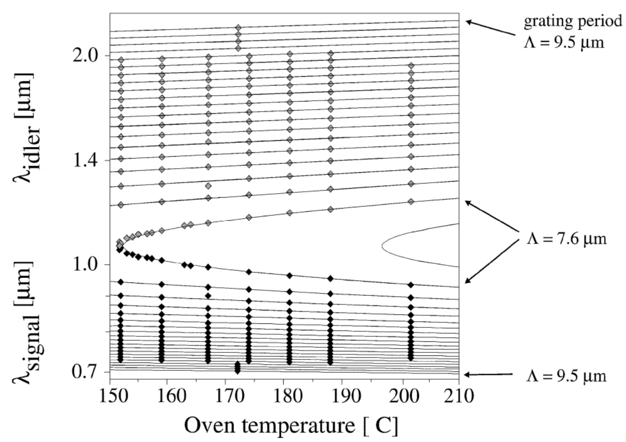

Fig. 2. OPO output wavelengths as a function of poling period and of oven temperature: squares, data shifted by −8 K; curves, theory.

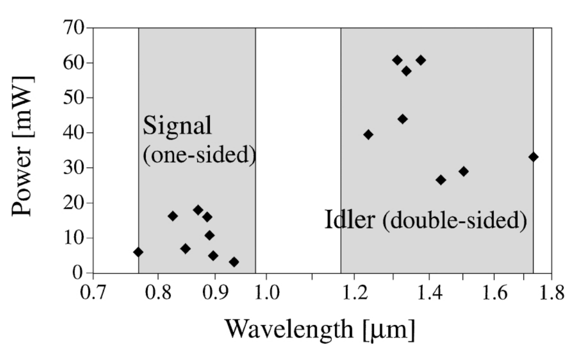

Fig. 3. Emission range (shaded regions) and output power of the PR-OPO in stable operation. The signal power refers to the output on the crystal side; the idler power is emitted in equal parts on both sides of the cavity.

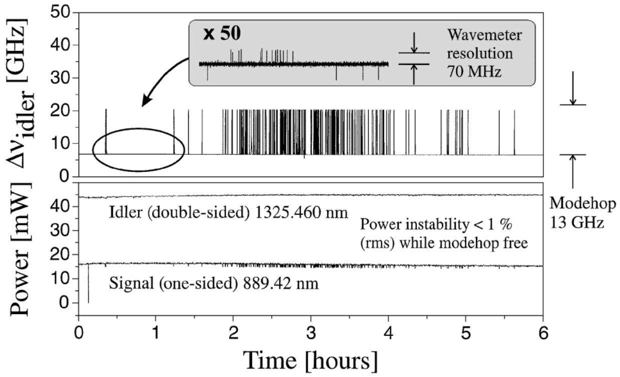

Fig. 4. Long-term measurement of idler frequency, measured with a high-resolution wavemeter, and output powers. A slow drift in pump wavelength or crystal temperature causes the signal frequency to jump between two cavity modes spaced six free spectral ranges apart, with corresponding idler frequency change.

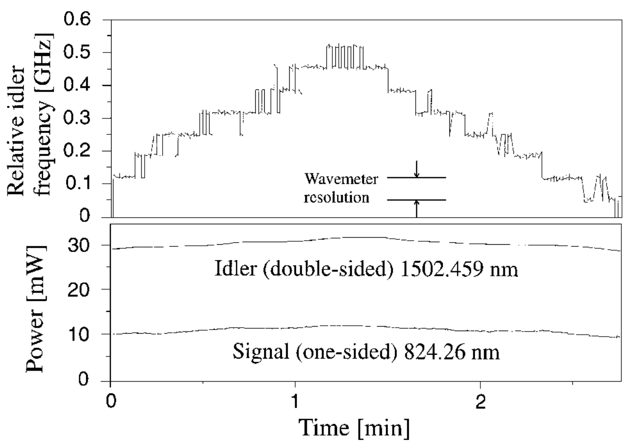

Fig. 5. Idler frequency tuning by tuning of the pump frequency by 1.1 GHz, and output powers.

which is an upper limit because of the finite resolution of the wavemeter employed. The rms fluctuations of the signal and idler power are below 1%. The figure shows that, on a mode hop, the idler frequency changes by 13 GHz, which corresponds to six free spectral ranges of the OPO and implies the opposite change in the signal frequency. This large jump is probably due to the presence of a parasitic etalon between the antireflection-coated crystal end face and the external mirror.

One can tune signal and idler frequency continuously by tuning the pump frequency. The tuning coefficients are $d\nu_{s/i}/d\nu_p \approx \nu_{s/i}/\nu_p$. The largest continuous tuning range that we measured was 400 MHz for the idler, corresponding to 700 MHz for the signal (see Fig. 5). A significantly larger tuning range will require simultaneous control of crystal temperature and pump wavelength. Output linewidths of a similar PR-SRO were measured to be below 160 kHz, limited by the finesse of the Fabry–Perot interferometer employed.[16]

In conclusion, we have shown that periodically poled $LiTaO_3$ can be used for downconversion of visible light, despite significant absorption. We have demonstrated a single-frequency optical parametric oscillator with pump enhancement with an unprecedented emission range of 0.77–1.73 μm with a gap near 1.06 μm. Signal plus idler powers of as much as 80 mW, mode-hop-free operation for extended periods of time, good power stability, high absolute frequency stability, and narrow linewidth make this type of light source attractive for many applications in metrology and spectroscopy. Future directions opened up by this research include efficient, widely tunable internal or external frequency conversion of signal, idler, and pump to extend the emission range into the visible.

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