Toward an optical synthesizer: a single-frequency parametric oscillator using periodically poled LiNbO$_3$

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We demonstrate single-frequency operation of a cw quasi-phase-matched singly resonant optical parametric oscillator (SRO). We obtained widely tunable output from 1.66 to 1.99 μm (signal) and from 2.29 to 2.96 μm (idler) by employing a periodically poled lithium niobate multigrating chip. Using a single-frequency miniature Nd:YAG ring laser as a pump source results in SRO output with high spectral purity and frequency stability (<10 MHz/min), which can be continuously tuned over 2 GHz without mode hops. We obtain a minimum SRO threshold of 260 mW by resonating the pump wave in the SRO cavity. © 1997 Optical Society of America

Bulk periodically poled lithium niobate (PPLN) has recently drawn enormous interest as a unique material for highly efficient quasi-phase-matched frequency conversion because of its much higher nonlinearity and potentially significantly broader tuning ranges than obtained with birefringent phase-matching techniques. Cw operation of singly resonant optical parametric oscillators (SRO’s) based on PPLN with output powers at the watt level and tuning over the 1.45–1.62/3.11–3.98-μm spectral range has been achieved. It was shown that single-axial-mode oscillation on the resonant signal wave is possible when one is pumping with a multiaxial-mode laser, whereas the nonresonant idler wave is also multiaxial mode. However, in this case the linewidth of the signal wave is essentially dictated by the bandwidth of the signal cavity, which usually is of the order of several megahertz, and the much more powerful idler wave is limited to the pump laser linewidth, typically several gigahertz for multimode lasers. Single-frequency operation of a quasi-phase-matched SRO was obtained with a single-frequency pump source, but wide tuning was not reported.

In this Letter we describe a SRO that both is widely tunable and has very high spectral purity, i.e., a narrow linewidth for the signal and the idler, as well as high absolute frequency stability. Our compact source, which is based on a diode-pumped miniature solid-state pump laser and PPLN, provides emission over a tuning range from 1.6 to 3 μm with signal and idler linewidths of <5 MHz and frequency instability of <10 MHz over minutes. Such a source that is capable of emitting any frequency within a wide spectral range and has high frequency stability and agility exhibits the essential features of an optical synthesizer.

A schematic of the setup that we use is shown in Fig. 1. Our pump source is a diode-pumped miniature Nd:YAG ring laser that delivers a single-frequency output power of 800 mW at 1064 nm, with a linewidth of 1 kHz and continuous tunability of 10 GHz. We used an optical isolator to prevent backreflection between the laser and the linear standing-wave SRO cavity. The SRO, which is resonant for the signal and the pump, is of the single-cavity type. It is configured as a semimonolithic linear standing-wave resonator containing a PPLN multigrating chip (Crystal Technology) and an external mirror separated by d = 16 mm from the chip. The PPLN crystal with dimensions of 19 mm × 11 mm × 0.5 mm has eight different gratings with periodicity lengths varying from 30 to 31.2 μm. One of the plane chip end faces is coated with a broadband dichroic mirror, providing reflectivities of 92% for the pump (1064 nm) and average values of 99.7% for the signal (1.66–2 μm) and 3% for the idler (2.3–3 μm). An antireflection coating with rest reflectivities of 0.3%, 0.8%, and 3% at the pump, signal, and idler wavelengths, respectively, is deposited upon the other chip face. The external mirror has a 25-mm radius of curvature and is mounted upon a piezoelectric transducer (piezo). The TEM$_{00}$ cavity mode has a waist of 29 μm, providing optimal nonlinear coupling for the given resonator geometry and crystal length. The pump was spatially mode matched to the fundamental resonator mode with an efficiency of 98%. The reflectivities of the external mirror at the pump, signal, and idler wavelengths are 99.7%, 99.8%, and 5%, respectively, on the curved surface, whereas the back face is uncoated. The total round-trip losses for the pump, signal, and idler are 0.5, 0.3%, and 3%, respectively.

![Fig. 1. Schematic of the experimental setup: The PPLN crystal is located in a temperature-stabilized oven (not shown). The pump and the signal waves are resonant, and the idler wave is strongly coupled out.](image-url)
signal, and idler waves are \( A_p = 10\% \), \( A_s = 2.5\% \), and \( A_i = 99.9\% \), respectively. The last value ensures singly resonant operation. For a SRO cavity that is highly transmitting, for the idler wave at both mirrors we estimate an internal threshold power of \( P_{th}^{int} = A_s/2E_{NL} = 8.6 \, \text{W} \), where the calculated single-pass nonlinearity \( E_{NL} \) is 1.45/kW, assuming an effective nonlinear coefficient \( d_{eff} = 15 \, \text{pm/V (1st-order quasi-phase matching)} \). A pump-power enhancement of 32 is deduced from a measured finesse of 63 and an incoupling of 65% for the pump wave below threshold.

We achieved robust stabilization of the pump wave by locking the cavity length on resonance with the laser frequency by use of a modified Pound–Drever technique. For this, we frequency modulated the pump wave by modulating the laser crystal piezoelectrically with a 10-MHz signal (50-mV peak-to-peak voltage). The pump wave reflected from the SRO cavity is detected with a sensitive InGaAs photodiode. We obtained an error signal by mixing the AC photodetector signal with the modulation frequency and by subsequent low-pass filtering. This error signal was fed back to the piezo, which shifted the external-cavity mirror by using a proportional integral servo controller. It is important to use the reflected light for stabilization, since the transmitted pump wave undergoes optical limiting above threshold and leads to an error signal that does not allow one to stabilize the reflected light at zero detuning. Since photodiodes with a cutoff wavelength of 1.8 µm were used for stabilization, the pump and the signal were properly separated by use of a calcite prism to avoid distortion of the error signal. The pump wave remained stably locked for more than 50 h with less than 2% power fluctuations. A minimum external threshold power of \( P_{th}^{ext} = 260 \, \text{mW} \) was found at a signal wavelength of 1.7 µm. This corresponds to an internal threshold power of 8.3 W, in excellent agreement with the above theoretical value.

The frequency stability of our SRO results from the single-cavity approach combined with a frequency-stable pump laser. In previous research, resonance enhancement was used only for reducing the SRO threshold. Here we point out that the cavity lock to the pump frequency also provides active stabilization of the SRO cavity length. The frequency stability \( \Delta \nu_s \) of the signal wave is then limited by the accuracy of the lock, the frequency stability \( \Delta \nu_p \) of the pump, and the temperature stability \( \Delta T \) of the nonlinear crystal. In our setup the last two parameters make the major contributions, resulting in

\[
\frac{\Delta \nu_s}{\nu_s} = \left( \frac{\partial n_e}{\partial T} \right)_{\nu_s} \cdot \frac{\partial n_e}{\partial T} _{\nu_p} \Delta T + \left[ n_e(\nu_p) + \frac{d}{L} \Delta \nu_p \right]
\]

where \( \Delta T \) denotes the temperature instability, \( n_e \) the extraordinary index of refraction, and \( L \) the length of the crystal. For our setup we calculate a value of \( \Delta \nu_s = 0.28 \text{MHz/mK} \Delta T + 0.5 \Delta \nu_p \). The crystal is actively temperature stabilized, with \( \Delta T = 2 \text{mK} \). Figure 2 shows the signal and the pump waves as observed with a confocal Fabry–Perot interferometer (FPI) and an InGaAs photodetector, indicating single-frequency operation of the SRO. The simultaneous measurement of the pump and the signal with a single FPI permits an estimate of the signal and the idler frequency stability, since the determination of a relative frequency drift between pump and signal is not affected by a drift of the FPI. We observed an upper limit of 10 MHz/min for the relative drift between the signal and the pump. With a typical value of \( \Delta \nu_p < 20 \text{ MHz over } 1 \text{ h} \) for the frequency instability of our laser, we can infer a frequency instability of \( <10 \text{ MHz/min} \) for the signal and the idler. Operation for more than 10 h without mode hops was obtained.

From the FPI spectrum we determined a signal linewidth of \(<5 \text{ MHz} \), also implying an idler linewidth of \(<5 \text{ MHz} \), which is resolution limited. Actual signal and idler linewidths are expected to be in the kilohertz range. We achieved continuous tuning of the signal frequency without mode hops over as much as 2 GHz by tuning the pump frequency through temperature control of the laser crystal. A wider tuning range requires synchronous control of pump frequency and chip temperature.

The wavelength spectrum of the signal and the idler emission was measured with a monochromator with a resolution of 0.1 nm. Figure 3 shows the observed signal and idler wavelengths as a function of crystal temperature. The data correspond to five different chip gratings (30.4, 30.6, 30.8, 30.95, and 31.1 µm), which provided phase matching within the bandwidth of the mirror coatings. Selection of a particular grating was achieved by translation of the PPLN chip through the resonator, as was done by Myers et al. No realignment of the cavity was necessary when the gratings were changed. Signal tuning over the entire range of 1.66 to 1.99 µm was found, corresponding to an idler tuning range of 2.29 to 2.96 µm. In addition, emission of red light with microwatt powers was observed in the 655–680-nm spectral region; this emission was caused by non-phase-matched sum-frequency mixing between the resonant signal and pump waves.

Figure 4 shows the total idler output power as a function of input pump power at a wavelength of 2.45 µm and a temperature of 150°C. The outcoupled signal power is roughly seven times smaller than for the idler, owing to its much lower output coupling.
Fig. 3. Tuning of the signal and the idler as a function of crystal temperature. Each set of data corresponds to one grating of the PPLN chip. The theoretical curves are calculated from published Sellmeier equations.\textsuperscript{11}

Fig. 4. Idler output power as a function of mode-matched input pump power.

The data (squares) were corrected for outcoupling losses through the external mirror ($T_i = 88\%$) and refer to the sum of the powers emitted through both sides of the cavity. The solid curve was calculated according to\textsuperscript{10}

$$P_{\text{out}}^i / P_{\text{in}}^p = \frac{v_i}{v_p} \frac{4T_p}{T_p + A_p} \left( \frac{P_{\text{ext}}^p}{P_{\text{in}}^p} - \frac{P_{\text{ext}}^i}{P_{\text{in}}^i} \right),$$

where $T_p$ and $A_p$ are the input coupling transmissivity and the residual round-trip power losses, respectively.

In conclusion, we have demonstrated an all-solid-state cw singly resonant parametric oscillator based on periodically poled lithium niobate. A minimum threshold of 260 mW was achieved by use of pump enhancement and a maximum conversion efficiency of 18\%. Single-frequency operation of both the signal and the idler with linewidths of $<5$ MHz and absolute frequency instabilities of less than 10 MHz over minutes without stabilization on an external reference cavity was shown. Continuous tuning of the signal and the idler waves as much as 2 GHz is possible by control of the laser frequency. The excellent spectral properties of the SRO output rely on using a single-frequency diode-pumped monolithic Nd:YAG laser with high frequency stability and active stabilization of the SRO cavity length on resonance with the pump-wave frequency. Signal and idler emission over ranges of 1.66–1.99 and 2.29–2.96 $\mu$m, respectively, were obtained. We believe that our SRO represents an important step in the development of narrow-linewidth broadly tunable all-solid-state laser sources and will permit novel applications in the field of high-resolution spectroscopy.

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*http://quantum-optics.physik.uni-konstanz.de

Note added in proof: We have recently extended the tuning range of the SRO to include the spectral regions 1.45–1.6 $\mu$m and have improved the conversion efficiency to 30\%.

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