

Coherence properties of a doubly resonant monolithic optical parametric oscillator

C. D. Nabors,* S. T. Yang, T. Day, and R. L. Byer

Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305

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We describe a doubly resonant optical parametric oscillator (DRO) pumped with the second harmonic of a narrow-linewidth Nd:YAG laser. The linewidth of the DRO signal was less than 13 kHz, the DRO was shown to generate a phase-locked subharmonic of the pump at degeneracy, and the signal and the idler were shown to be mutually coherent with the pump and to be phase anticorrelated with each other away from degeneracy. The signal-idler heterodyne linewidth was 500 Hz, and pump phase modulation was shown to transfer to the DRO phase at degeneracy.

1. INTRODUCTION AND REVIEW

Doubly resonant optical parametric oscillators¹ (DRO's) are the only type of optical parametric oscillator to be routinely operated above threshold cw and thus have the greatest potential for narrow-linewidth coherent operation. Coherence studies of DRO's have been limited historically by the DRO's extreme sensitivity to cavity stability and pump fluctuations since they are overconstrained by the requirements of energy conservation, phase matching, and simultaneous resonance of signal and idler waves.² In pioneering research, Smith³ reviewed DRO operation and tuning theory and pumped a Ba₂NaNbO₃ DRO with a frequency-stabilized argon-ion laser to achieve single-mode operation for a few seconds at a time. More recently workers studying squeezed states have operated DRO's⁴ and triply resonant optical parametric oscillators⁵⁻⁷ (OPO's) above threshold but have not reported on the linewidths or other coherence properties. Triply resonant OPO's are even more highly constrained above threshold than are DRO's. Advances have also been made in the field of singly resonant OPO's,^{8,9} but here linewidths have been limited to greater than 30 MHz (Ref. 10) by the need for pulsed laser pump sources.

The basic operations of our monolithic doubly resonant OPO has been described in Refs. 11 and 12. To summarize, we reported on a DRO fabricated from MgO:LiNbO₃ pumped by a cw, frequency-doubled, diode-laser-pumped Nd:YAG laser.¹³ MgO:LiNbO₃ was chosen for its low loss, high nonlinearity, and noncritical phase matching. The monolithic crystal resonator design is shown in Fig. 1. Dielectric mirrors were deposited directly upon the spherically curved surfaces of the resonator, and a traveling-wave ring path was formed for the ordinary polarized signal and idler waves by the use of the total-internal-reflection surface. Pump light, which was polarized extraordinarily, was not resonant for the ring path because of bireflection at the crystal surfaces. The length of the crystal was 12.5 mm, and the radii of the mirrors were 10 mm, providing a 27- μ m focus inside the crystal at 1064 nm and a resonator free spectral range of 5.088 GHz. The crystal was heated in an oven to 107°C or greater to phase match the parametric interaction noncritically.

Threshold for cw operation was 12 mW, and pump deple-

tions of as much as 78% were observed at 2 times above threshold. The total DRO output power was 8.15 mW, with a conversion efficiency for the incident pump of 34% and a combined conversion efficiency for the 1064-nm laser light of 14%. The DRO was temperature tuned from 1007 to 1129 nm, operated on a single-axial-mode pair over most of the range, and could be electric-field tuned by as much as 38 nm near degeneracy.

In this paper we describe the coherence properties of the DRO, including its narrow linewidth and exceptional stability. The high performance of the device permitted the demonstration of pump-DRO phase locking at degeneracy, pump-DRO phase correlations, signal-idler heterodyne measurements, and pump-DRO phase transmodulation, which have not to our knowledge previously been observed.

2. PUMP SYSTEMS

The DRO was previously pumped with the resonantly doubled output of a diode-laser-pumped, single-frequency, cw Nd:YAG laser. Because of problems with residual photorefractive damage in the MgO:LiNbO₃ doubler and the need for greater power at the second-harmonic (532-nm) wavelength, we developed a multiwatt injection-locked Nd:YAG laser system capable of producing as much as 13 W of cw power at 1064 nm with an estimated linewidth of 5–10 kHz.¹⁴ Single-pass frequency doubling in a 2-cm piece of MgO:LiNbO₃ produced more than 120 mW of power at 532 nm for 10-W input at 1064 nm. As will be seen below, it is highly advantageous to use the second harmonic of a master laser as an OPO pump. The second-harmonic pump source is derived from the 1064-nm fundamental, which provides a local-oscillator frequency and phase reference that can be used in coherence measurements of degenerate and near-degenerate operation of the DRO.

3. DRO SIGNAL LINEWIDTH

Earlier¹² we estimated an upper bound of the DRO linewidth to be a few megahertz, based on scanning Fabry-Perot interferometer measurements. To determine the linewidth rigorously we performed a heterodyne beat-note measurement,

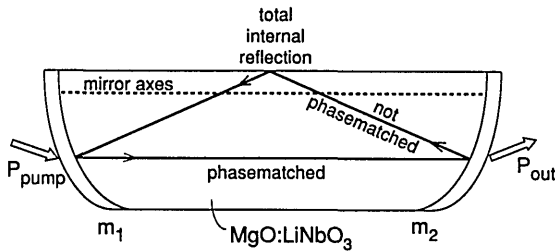


Fig. 1. Monolithic DRO crystal cavity design. Dielectric mirrors that are highly reflective for the signal and the idler and transmit the pump are deposited directly upon the curved ends of the MgO:LiNbO₃ resonator. m_1 , highly reflecting at 1064 nm, $T = 85\%$ at 532 nm. m_2 , $T = 0.5\%$ at 1064 nm.

using an independent Nd:GGG single-frequency nonplanar ring laser.¹⁵ The Nd:GGG laser oscillator has a wavelength of 1062.2 nm instead of the Nd:YAG wavelength of 1064.2 nm, and this enabled us to perform the beat-note measurement well away from degeneracy (by ~ 531 GHz, or 104 DRO free spectral ranges). The free-running linewidth of this type of monolithic ring laser has been measured by a number of workers¹⁶⁻¹⁸ to be of the order of 5–10 kHz for short-term jitter.

The experimental layout is shown in Fig. 2. The injection-locked Nd:YAG pump laser was frequency doubled, and the fundamental and the second harmonic were separated with a Pellin–Broca prism. The second-harmonic power was mode matched into the monolithic DRO cavity, and the output power (signal and idler) was combined with the Nd:GGG oscillator output on a beam splitter. One beam was then detected with a fast photodiode and analyzed with a Hewlett-Packard 8566B 22-GHz rf spectrum analyzer. The other beam was sent through an $f = 1$ m spectrometer with a charge-coupled-device camera focused on its image plane to monitor the coincidence of the DRO signal wavelength with the Nd:GGG laser line. The DRO was tuned with temperature to near degeneracy, and then the voltage was adjusted to fine-tune the signal frequency until a beat note was observed. The idler frequency was too far away (1 THz) to play a role in the heterodyne measurement. The DRO was free running and was not servo locked for this measurement.

A typical rf beat-note spectrum is shown in Fig. 3. The 3-dB full linewidth of the beat note was 13 kHz, limited by beat-note carrier jitter. The sidebands at 230 and 530 kHz are due to relaxation oscillation (amplitude) noise on the Nd:GGG and Nd:YAG laser systems, respectively. As both the doubled Nd:YAG laser pumping the DRO and the Nd:GGG laser have linewidths of the order of 5–10 kHz, we see that the operation of the DRO reproduces the linewidth of the pump laser system. This assertion is supported by the OPO self-beat-note experiment described in Section 5. We emphasize that this measurement, using two independent oscillators, yields the true linewidth, i.e., the convolution of both oscillators' linewidths, and has no implicit common-mode rejection as is present in many measurements of laser oscillator relative linewidths.

4. DEGENERATE OPERATION: PUMP-DRO PHASE LOCKING

It was previously predicted¹⁹⁻²¹ that the phase of an OPO operating with degenerate signal and idler waves would be

phase locked to the pump with either 0 or π relative phase.²² This has been elegantly demonstrated in degenerate squeezed-state experiments below threshold.⁵ To test the theory above threshold we ran the DRO at degeneracy and combined the DRO output beam with a 1064-nm reference beam from the Nd:YAG laser. This reference beam is phase correlated with the second harmonic used to pump the DRO. One of the combined beams was imaged onto a screen and observed with the charge-coupled-device camera. The other beam was sent through a scanning Fabry–Perot interferometer to monitor the axial mode structure of the DRO at degeneracy. The beam incident upon the Fabry–Perot interferometer was blocked during data taking to prevent potential feedback effects. Great care was taken to ensure that there was no injection locking of the degenerate OPO by stray light from the Nd:YAG laser by using a prism to separate the 1064-nm laser light from the green 532-nm pump beam. The pump light was passed through a highly reflecting mirror for the infrared ($T = 0.05\%$ at 1064 nm) and then through an aperture.

Figure 4 shows the stable fringes obtained by interfering the degenerate DRO with the Nd:YAG laser. The DRO

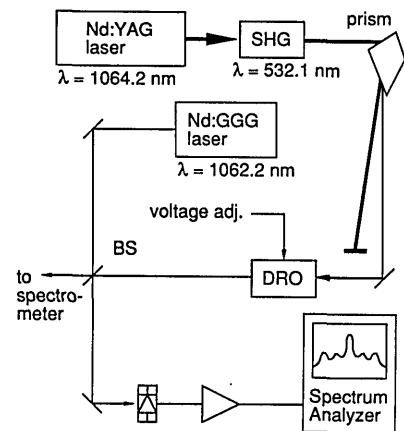


Fig. 2. Experimental layout showing the DRO pumped by the frequency-doubled injection-locked Nd:YAG laser for heterodyning with the Nd:GGG laser. SHG, second-harmonic generator; BS, beam splitter.

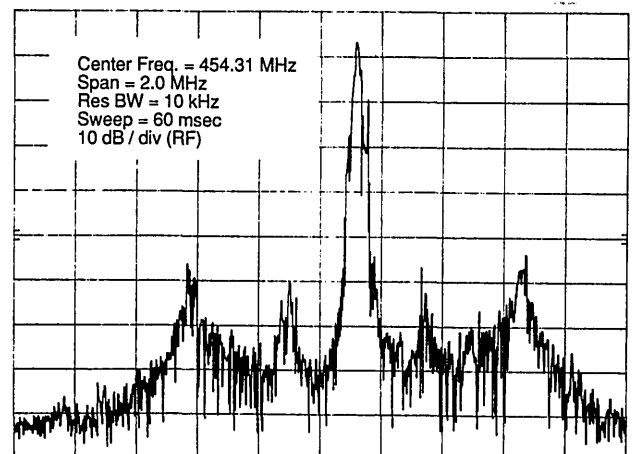


Fig. 3. Heterodyne rf beat-note spectrum of the independent DRO signal and Nd:GGG laser oscillators. The 3-dB full width of the central peak is 13 kHz.

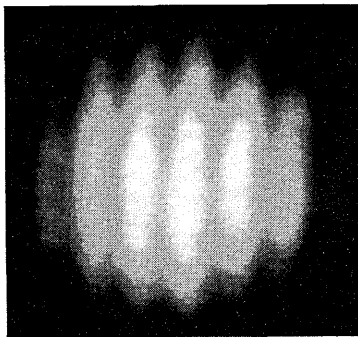


Fig. 4. Stable fringe pattern produced by interfering the degenerate DRO beam with a reference beam from the Nd:YAG laser.

would run at degeneracy for as long as 20 min at a time with no servo control and no applied tuning voltage.

When the pump was interrupted, the overall phase of the fringe pattern was observed to jump phase randomly by 0 or π . This is a good indication that no injection locking of the DRO from the laser was taking place. An attempt was made to observe the tunneling of the OPO phase between the 0 and π states,²³ which was unsuccessful owing to excess DRO relative amplitude noise during near-threshold operation. Both standing-wave and ring path DRO configurations were tested. Operation with the standing-wave geometry was less stable in frequency and amplitude than for the ring path, and the DRO was more susceptible to feedback effects.

The stable fringes show that the degenerate DRO is a true phase-locked subharmonic of the pump. We investigated the high-frequency phase fidelity by performing a heterodyne rf beat-note experiment with the reference laser beam frequency shifted by 45 MHz, using an acousto-optic modulator driven by a rf synthesizer. Figure 5 shows the rf beat-note spectrum. The asymmetry of the phase noise is due to amplitude noise on the DRO signal. Most of the noise in the subkilohertz band can be attributed to mechanical vibration of the mirrors in the interferometer, which limits the low-frequency sensitivity of the measurement.¹⁴ For reference, the phase-noise spectral density $S_\phi(f)$ at 5 kHz was determined from the plot to be 2×10^{-9} rad²/Hz.

5. NONDEGENERATE OPERATION: PUMP-DRO PHASE CORRELATIONS AND SIGNAL-IDLER HETERODYNE LINEWIDTH

Away from degeneracy the DRO signal and idler phases are no longer locked to the pump but diffuse randomly in such a way that the sum of their phases is either 0 or π .²⁴ (For simplicity we will assume that the overall phase is 0, with no loss of generality.) Diffusion of the relative phase is analogous to the phase diffusion seen in lasers that is responsible for the Schawlow-Townes linewidth. The phase sum was recently analyzed, using a quantum-mechanical Hamiltonian, and is a candidate squeezed-state observable.²⁵ We can write the relevant DRO electric fields as

$$\mathbf{E}_{\text{pump}} = E_{\text{pump}} \exp(2i\omega_L t), \quad (1)$$

$$\begin{aligned} \mathbf{E}_{\text{DRO}} = E_{\text{DRO}} & \{ \exp[i(\omega_L + \Delta)t + \phi(t)] \\ & + \exp[i(\omega_L - \Delta)t - \phi(t)] \}, \end{aligned} \quad (2)$$

where the first and second terms in Eq. (2) are the signal and

the idler fields, respectively, ω_L is the Nd:YAG laser frequency (equal to the degenerate DRO frequency), Δ is the DRO frequency displacement from degeneracy, and $\phi(t)$ is the relative DRO phase. We have assumed that the DRO is operating near enough to degeneracy that the output couplings (and thus the powers) of the signal and the idler are equal. We also introduce a local oscillator derived from the laser:

$$\mathbf{E}_L = E_L \exp[i(\omega_L t + \theta)], \quad (3)$$

where the phase θ can be adjusted experimentally. If we heterodyne the signal and the idler waves with the laser local oscillator, the voltage seen on the photodetector will be

$$V \sim E_{\text{DRO}}^2 \cos[2\Delta t + 2\phi(t)] + 2E_L E_{\text{DRO}} \cos(\theta) \cos[\Delta t + \phi(t)]. \quad (4)$$

The first term at frequency 2Δ represents the mixing of the signal and the idler, and the second term at frequency Δ the mixing of the signal and the idler each with the laser local oscillator. Relation (4) predicts that the beat-note amplitude of the signal at frequency Δ will depend on the phase of the local oscillator and vanish for $\theta = \pi/2, 3\pi/2$, etc. If the phases of the signal and the idler were not exactly anticorrelated with respect to the pump, the Δ beat note would not vanish. Additionally, relation (4) predicts that the linewidth of the beat note at 2Δ is four times as broad as that at Δ , assuming white frequency noise,²⁶ and twice as broad assuming a $1/f$ frequency noise spectral density, as is typical in most free-running laser systems.

In our experiments the DRO was operated one axial mode away from degeneracy so that $\Delta = 5.088$ GHz. The output of the DRO was mixed at a beam splitter with a local oscillator from the laser and then sent down a single-mode fiber to a Hewlett-Packard Model 71400A Lightwave Optical spectrum analyzer. Figure 6 shows the signal-idler beat-note spectrum at $2\Delta = 10.17$ GHz, taken with the local oscillator blocked. The vertical scale is 5 dB/division for optical power, which is the equivalent of 10 dB/division of rf power. The full width at half-maximum (3-dB rf) of the central peak is ≈ 500 Hz, with a resolution bandwidth of 300 Hz and

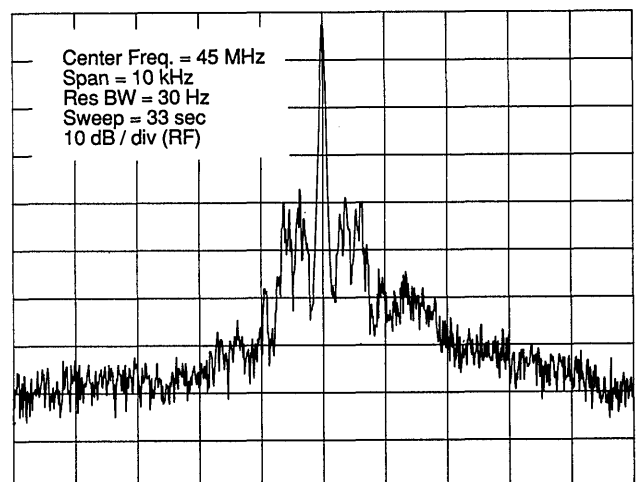


Fig. 5. Rf beat-note spectrum of the degenerate DRO heterodyned with a reference beam from the laser, which has been shifted 45 MHz with an acousto-optic modulator.

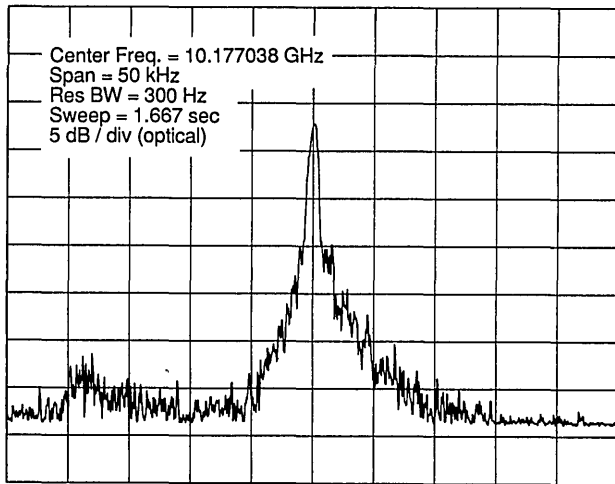


Fig. 6. Beat-note spectrum of the DRO signal with idler frequencies displaced one axial mode from degeneracy. The central peak has a width of 500 Hz, and there is a 1-Hz trace-to-trace jitter in its position.

a trace-to-trace jitter of ≈ 1 kHz for 1.67-sec sweeps. The jitter is approximately 1 part in 10^7 of the beat note and corresponds to fluctuations in the optical path length of $\delta(nL) \approx 6$ nm.

This observation substantiates the claim made in Section 3 that the off-degeneracy DRO does not add significant excess linewidth when pumped by a 5–10-kHz-linewidth laser. The asymmetry in the spectrum is again caused by amplitude noise, and the artifact at the left is possibly due to a small transverse mode effect. The beat-note linewidth of the signal at 5.088 GHz (not shown) is also ≈ 500 Hz, with a jitter similar to the 10.17-GHz note, and since this width is so close to the resolution bandwidth of the spectrum analyzer the relative linewidth prediction is problematic.

To confirm that the DRO signal and the idler were phase anticorrelated we varied the phase of the laser local oscillator, using a LiNbO₃ electro-optic phase modulator with $V_{2\pi} = 624$ V. A 1-kV/50-msec ramp voltage was applied to the phase modulator, and the spectrum analyzer was triggered at the start of the ramp and also swept at 50 msec. The spectrum analyzer center frequency was 5.088 GHz, and the span was 0 Hz, with a large enough resolution bandwidth (100 kHz) to pass most of the rf power. The horizontal axis of the spectrum analyzer trace is thus proportional to the local-oscillator phase, and with the vertical axis on a linear scale displaying rms volts we expect to see a wave proportional to $|\cos(\theta)|$, the rectification due to the spectrum analyzer's power detector law. Figure 7 shows the experimental trace with the independently determined calibration of the phase axis. The waveform is precisely as predicted, which verifies that the DRO signal and the idler phase are collectively coherent with the pump phases and anticorrelated with each other away from degeneracy.

6. PUMP-DRO PHASE TRANSMODULATION

There are a number of predictions of how an OPO should tune with a chirped or frequency-modulated pump.^{27,28} The OPO is interesting in this respect, as the tuning rate near degeneracy can be much larger than the pump tuning rate. We were unable to tune our pump rapidly but instead

phase modulated the pump and measured the effects on the DRO output frequency spectrum.

We assume that, like that of the pump, the DRO output is purely phase modulated and write the electric fields as

$$\mathbf{E}_{\text{pump}} = E_{\text{pump}} \exp\{i[2\omega_L t + \beta \sin(\omega_{\text{mod}} t)]\} \quad (5)$$

and

$$\mathbf{E}_{\text{DRO}} = E_{\text{DRO}} \exp\{i[\omega_L t + \delta \sin(\omega_{\text{mod}} t + \xi)]\}. \quad (6)$$

For small modulation depth, zero cavity detuning, and pump decay rate much greater than the DRO cavity decay rate we can use the degenerate OPO equations of motion²¹ to solve for δ and ξ to get

$$\delta = \frac{\beta}{2} \left[1 + \frac{1}{r} (\omega_{\text{mod}}/\omega_c)^2 \right]^{-1/2}, \quad (7)$$

$$\tan(\xi) = -\frac{\omega_{\text{mod}}}{\omega_c} r^{-1/2}, \quad (8)$$

where ω_c is the DRO cavity power bandwidth and r is the number of times above threshold for the DRO.

We detect the phase modulation by mixing the DRO with a frequency-shifted laser local oscillator

$$\mathbf{E}_{\text{LO}} = E_{\text{LO}} \exp[i(\omega_L + \omega_{\text{rf}})t] \quad (9)$$

to generate the rf voltage measured on a photodiode given by

$$V \sim \cos[\omega_{\text{rf}} t + \delta \sin(\omega_{\text{mod}} t + \xi)]. \quad (10)$$

We used a MgO:LiNbO₃ electro-optic phase modulator (heated to 130°C to avoid photorefraction) with $V_{2\pi} = 609$ V to modulate the 532-nm DRO pump at frequencies from 1 kHz to 20 MHz. The driving voltage on the electro-optic modulator was 20 V peak to peak, which corresponds to a modulation index on the pump of $\beta = 0.103$ rad.

For small modulation index and low modulation frequency the detected rf power in the sidebands at $\omega_{\text{rf}} \pm \omega_{\text{mod}}$ will decrease by $J_1(\delta)^2 \approx \beta^2/16$ relative to the carrier at ω_{rf} , or 4 times less (–6 dBc) than the modulation on the pump. For $\beta = 0.103$ rad the level is calculated to be –31.8 dBc, which is

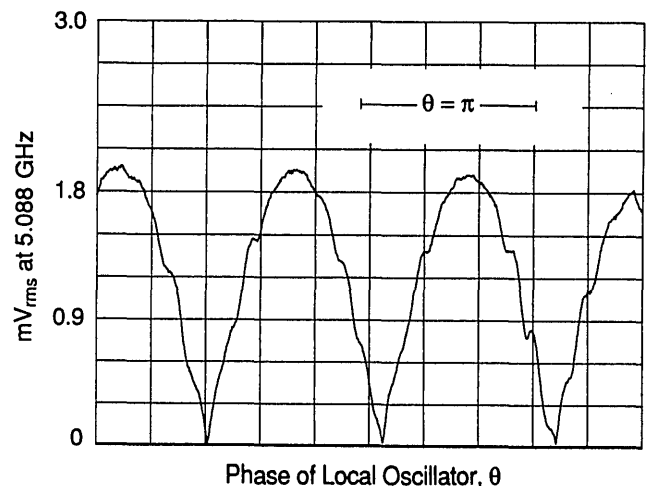


Fig. 7. Amplitude of local oscillator–DRO beat note at 5.088 GHz versus local-oscillator phase. The rectified cosine waveform is as expected from relation (4).

in excellent agreement with the experimental result of -31.1 dBc for low modulation frequencies. At higher frequencies the transmodulation is limited by the bandwidth of the DRO cavity and has the frequency response

$$\text{rel. sideband power} = \frac{\beta^2}{16} \left[1 + \frac{1}{r} (\omega_{\text{mod}}/\omega_c)^2 \right]^{-1}, \quad (11)$$

with a -3 -dB rolloff observed at frequency $\omega_{\text{mod}}/2\pi \approx 8$ MHz. We estimate that $r \approx 1.5$ for this experiment and obtain a measure of the total DRO cavity losses of 0.8% , in rough agreement with our earlier results.¹²

The MgO:LiNbO₃ phase modulator had residual amplitude and polarization modulation, which caused amplitude modulation on the DRO with modulation index 0.012 and contributed to the 1 - 3 -dB imbalance seen on the DRO phase sidebands. The DRO amplitude modulation alone is not enough to account for the imbalance, and the remainder may be due to cavity-detuning effects or to drift in the number of times above threshold of the DRO.

Away from degeneracy the signal and idler phases are anticorrelated with respect to the pump, and no transmodulation of the signal-idler is predicted. Rf sidebands are observed on the 10.17 -GHz signal-idler beat note at -40 dBc, but they can be accounted for by the DRO amplitude modulation alone and are not the result of phase modulation.

The good agreement between theory and experiment for the transfer of phase modulation from the pump to the DRO signal suggests that the theoretical model should also be valid for the more interesting case of a frequency-modulated or chirped pump.

7. DISCUSSION AND CONCLUSIONS

We have demonstrated a cw monolithic doubly resonant optical parametric oscillator with exceptionally high coherence. The linewidth was shown to be limited to that of the laser pumping it and was less than 13 kHz. The DRO operated reliably at degeneracy without any form of injection locking and was a phase locked subharmonic of the pump. Away from degeneracy, the signal and the idler were heterodyned, and a linewidth of 500 Hz was measured for short-time stability. The signal and the idler were also shown to be phase anticorrelated with respect to the pump away from degeneracy. Pump phase modulation was shown to transfer to the DRO at degeneracy with good agreement with theory, which may have applications for FM spectroscopy.

Future improvements to and applications of the DRO system will include pumping with frequency-stabilized sources such as locking the Nd:YAG pump and Nd:GGG lasers to the same reference cavity for relative stabilities of less than 3 Hz,²⁹ spectroscopy with the DRO as a tunable source, demonstration of a DRO with signal-to-idler frequency ratio of $3:1$, and further DRO tuning and modulation studies. The DRO output can be line-narrowed by locking to a high-finesse reference interferometer, or the self-beat-note between signal and idler at 10.17 GHz could be phase locked to a rf synthesizer to stabilize the DRO directly. We are currently investigating the cw DRO as a source with sub-shot-noise correlations of signal and idler amplitudes. When the quantum phase correlations are also considered,

the DRO is a direct example of the Einstein-Podolsky-Rosen paradox.^{25,30}

The phase locking of the DRO at degeneracy is a demonstration of a coherent $2:1$ optical frequency divider. This result is significant for metrology and spectroscopy, for which frequency chains are needed across a variety of spectral bands.³¹ The proposed $3:1$ DRO can also act as a $1.33:1$ and $4:1$ frequency divider for the pump frequency. The difficulty lies in detecting the point of exact $3:1$ signal:idler operation, which is not a problem at degeneracy. We propose several possible solutions. If the DRO pump is the second harmonic of some master laser, the laser (possibly offset by some rf) and the idler could be summed to yield a color near the signal. The sum frequency output will be coherent with the DRO signal wave only when the signal and idler frequencies are exactly in the ratio $3:1$. The sum of the laser and the idler could also be optically fed back to injection lock the signal phase, or the laser could be deeply phase modulated (modulation index $\approx \pi$) and mixed with both the signal and the idler. This would alternately sum the laser with the idler frequency to get signal and subtract the laser from the signal frequency to get idler as the laser phase is varied, and it would produce an AM output only when the exact $3:1$ condition were met. The phases of the signal and sum waves will not in general be coherent, as the OPO phase $\phi(t)$ is not canceled out, and some type of active phase-lock-loop servo will be required to implement these schemes.

If no master laser at half the pump frequency were available, the idler could be frequency tripled and compared with the signal, which is the technique required to lock an OPO to the $2:1$ operating point, where the idler can be frequency doubled and compared with the signal. The $2:1$ OPO will act as a $1.5:1$ and $3:1$ frequency divider for the pump frequency but would, however, be difficult to fabricate as a doubly resonant OPO by using conventional quarter-wave-stack dielectric mirrors. Higher-order phase-locked frequency dividers ($5:1$, $6:1$, ...) will be progressively harder to realize in practice as the summing or doubling steps become more numerous, and conventional frequency multiplying from below becomes more practical than parametrically dividing down from above.

What we have again learned experimentally is that monolithic resonator designs and excellent pump mode quality (spatial, temporal, and linewidth) are highly desirable for high-performance laser and nonlinear-optical devices. We fully expect that with improved frequency- and amplitude-stabilized pump sources the DRO performance will continue to improve.

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* Present address, MIT Lincoln Laboratory, 244 Wood Street, Lexington, Massachusetts 02173.

REFERENCES

- For reviews of OPO's see R. L. Byer, in *Treatise in Quantum Electronics*, H. Rabin and C. L. Tang, eds. (Academic, New York, 1973) pp. 587-702; R. G. Smith, in *Advances in Lasers*, A. K. Levine and A. J. DeMaria, eds. (Dekker, New York, 1976), Vol. 4; Yuan Xuan Fan and R. L. Byer, "Progress in optical parametric oscillators," in *New Lasers for Analytical and Industrial Chemistry*, A. Bernhardt, ed., Proc. Soc. Photo-Opt. Instrum. Eng. 461, 27-32 (1984).
- J. Falk, "Instabilities in the doubly resonant parametric oscillator: a theoretical analysis," *IEEE J. Quantum Electron.* **QE-7**, 230-235 (1971).
- R. G. Smith, "A study of factors affecting the performance of a continuously pumped doubly resonant optical parametric oscillator," *IEEE J. Quantum Electron.* **QE-9**, 530-541 (1973).
- A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, C. Fabre, and G. Camy, "Observation of quantum noise reduction on twin laser beams," *Phys. Rev. Lett.* **59**, 2555-2557 (1987).
- Ling-Ann Wu, Min Xiao, and H. J. Kimble, "Squeezed states of light from an optical parametric oscillator," *J. Opt. Soc. Am. B* **4**, 1465-1475 (1987).
- P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, "Squeezed-light-enhanced polarization interferometer," *Phys. Rev. Lett.* **59**, 2153-2156 (1987).
- S. F. Pereira, K.-C. Peng, and H. J. Kimble, "Squeezed state generation and QND detection by nondegenerate parametric down conversion," presented at the Sixth Rochester Conference on Coherence and Quantum Optics, Rochester, New York, June 26-28, 1989.
- W. J. Kozlovsky, E. K. Gustafson, R. C. Eckardt, and R. L. Byer, "Efficient monolithic MgO:LiNbO₃ singly resonant optical parametric oscillator," *Opt. Lett.* **13**, 1102-1104 (1988).
- T. K. Minton, S. A. Reid, H. L. Kim, and J. K. McDonald, "A scanning, single mode, LiNbO₃ optical parametric oscillator," *Opt. Commun.* **69**, 289-293 (1989).
- J. Pinard and J. F. Young, "Interferometric stabilization of an optical parametric oscillator," *Opt. Commun.* **4**, 425-427 (1972).
- W. J. Kozlovsky, C. D. Nabors, R. C. Eckardt, and R. L. Byer, "Monolithic MgO:LiNbO₃ doubly resonant optical parametric oscillator pumped by a frequency-doubled diode-laser pumped Nd:YAG laser," *Opt. Lett.* **14**, 66-68 (1989).
- C. D. Nabors, R. C. Eckardt, W. J. Kozlovsky, and R. L. Byer, "Efficient, single-axial-mode operation of a monolithic MgO:LiNbO₃ optical parametric oscillator," *Opt. Lett.* **14**, 1134-1136 (1989).
- W. J. Kozlovsky, C. D. Nabors, and R. L. Byer, "Efficient second harmonic generation of a diode-laser-pumped cw Nd:YAG laser using monolithic MgO:LiNbO₃ external resonant cavities," *IEEE J. Quantum Electron.* **24**, 913-919 (1988).
- C. D. Nabors, A. D. Farinas, T. Day, S. T. Yang, E. K. Gustafson, and R. L. Byer, "Injection locking of a 13-W cw Nd:YAG ring laser," *Opt. Lett.* **14**, 1189-1191 (1989).
- T. Day, A. C. Nilsson, M. M. Fejer, A. D. Farinas, E. K. Gustafson, C. D. Nabors, and R. L. Byer, "30-Hz linewidth diode-laser-pumped, Nd:GGG nonplanar ring oscillators by active frequency stabilisation," *Electron. Lett.* **25**, 810-812 (1989).
- T. J. Kane, A. C. Nilsson, and R. L. Byer, "Frequency stability and offset locking of a laser-diode-pumped Nd:YAG monolithic nonplanar ring oscillator," *Opt. Lett.* **12**, 175-177 (1987).
- S. P. Bush, A. Gungor, and C. C. Davis, "Studies of the coherence properties of a diode-pumped Nd:YAG ring laser," *Appl. Phys. Lett.* **53**, 646-647 (1988).
- K. J. Williams, A. Dandridge, A. D. Kersey, J. F. Weller, A. M. Yurek, and A. B. Tveten, "Interferometric measurement of low-frequency phase noise characteristics of diode laser-pumped Nd:YAG ring laser," *Electron. Lett.* **25**, 774-775 (1989).
- W. H. Louisell, *Coupled Mode and Parametric Electronics* (Wiley, New York, 1960).
- W. H. Louisell, A. Yariv, and A. E. Siegman, "Quantum fluctuations in parametric processes. I," *Phys. Rev.* **124**, 1646-1654 (1961).
- P. D. Drummond, K. J. McNeil, and D. F. Walls, "Non-equilibrium transitions in sub/second harmonic generation I. Semi-classical theory," *Opt. Acta* **27**, 321-335 (1980).
- Ling-An Wu and H. J. Kimble, "Interference effects in second-harmonic generation within an optical cavity," *J. Opt. Soc. Am. B* **2**, 697-703 (1985).
- P. D. Drummond and P. Kinsler, "Quantum tunneling and thermal activation in the parametric oscillator," *Phys. Rev. A* **40**, 4813-4816 (1989).
- R. Graham and H. Haken, "The quantum fluctuations of the optical parametric oscillator," *Z. Phys.* **210**, 276-302 (1968).
- M. D. Reid and P. D. Drummond, "Quantum correlations of phase in nondegenerate parametric oscillation," *Phys. Rev. Lett.* **60**, 2731-2733 (1988).
- D. S. Elliot, R. Roy, and S. J. Smith, "Extracavity laser bandshape and bandwidth modification," *Phys. Rev. A* **26**, 12-18 (1982).
- A. I. Kovrigin and R. L. Byer, "Stability factor for optical parametric oscillators," *IEEE J. Quantum Electron.* **QE-5**, 384-385 (1969).
- A. Piskarskas, A. Stabinis, and A. Yankauskas, "Parametric frequency modulation of picosecond light pulses in quadratically nonlinear crystals," *Sov. J. Quantum Electron.* **15**, 1179-1180 (1985).
- T. Day, E. K. Gustafson, and R. L. Byer, "Active frequency stabilization of a 1.062- μ m, Nd:GGG, diode-laser-pumped nonplanar ring oscillator to less than 3 Hz of relative linewidth," *Opt. Lett.* **15**, 221-223 (1990).
- A. Einstein, B. Podolsky, and N. Rosen, "Can quantum-mechanical description of physical reality be considered complete?" *Phys. Rev.* **47**, 777-780 (1935).
- D. H. McIntyre and T. W. Hänsch, "Novel optical frequency divider and synthesizer," in *Digest of 1988 OSA Annual Meeting* (Optical Society of America, Washington, D.C., 1988), p. 131.