Efficient, single-axial-mode operation of a monolithic $MgO:LiNbO_3$ optical parametric oscillator

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A monolithic doubly resonant optical parametric oscillator (OPO) fabricated from $MgO:LiNbO_3$ was pumped by a cw, frequency-doubled, diode-laser-pumped Nd:YAG laser. The threshold for cw operation was 12 mW, and pump depletions of up to 78% were observed two times above threshold. The total OPO output power was 8.15 mW, with a conversion efficiency for the incident pump of 34% and combined conversion efficiency for the 1064-nm laser light of 14%. The OPO 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.

Optical parametric oscillators[1] (OPO's) are currently enjoying a revival of interest. New materials and improved pump sources are enabling OPO's to live up to their decades-old promise of providing efficient, narrow-band, widely tunable sources of light. In the cw long-pulse regime OPO's have been demonstrated in lithium niobate ($LiNbO_3$) as narrow-linewidth sources using the singly resonant configuration[2] and in $LiNbO_3$ waveguide devices with low thresholds.[3] A single-mode injection-seeded pump source was used in a demonstration of a pulsed narrow-bandwidth $LiNbO_3$ OPO for high-resolution spectral measurements near 3.4 μm.[4] Barium metaborate (BaB_2O_4) has been used in OPO's with an injection-seeded laser pump source for improved linewidth and stability[5] and to extend pulsed OPO operation to ultraviolet wavelengths.[6] Improved infrared nonlinear materials such as silver gallium selenide ($AgGaSe_2$) have been used for broadly tunable mid-infrared OPO's.[7] OPO's are also widely used in studies on squeezed states of light.[8–10] We report here on the stable cw single-mode operation of a doubly resonant OPO pumped by a frequency-doubled, diode-laser-pumped Nd:YAG laser.

Early efforts at running doubly resonant OPO's were plagued by instabilities. As the doubly resonant OPO is overconstrained by the requirements of energy conservation, phase matching, and simultaneous resonance of signal and idler waves,[11,12] perturbations on the pump frequency or OPO cavity length can cause large power fluctuations and mode hopping of the OPO. However, because OPO's are of great potential importance as spectroscopic sources, as sources for injection seeding or locking, and for quantum optics, we have worked to overcome the problems of doubly resonant OPO's by using frequency-stable, single-mode, diode-laser-pumped solid-state lasers. The high efficiency, compactness, and exceptional frequency stability of these laser pumps have led to excellent stability and efficiency for OPO operation. The monolithic cavity design of the OPO also contributes to the device performance, making possible an OPO with a low threshold that runs in a single-mode pair as discussed below.

Previously we demonstrated a pulsed doubly resonant OPO (DRO) of monolithic design fabricated from 5% magnesium-oxide-doped $LiNbO_3$ ($MgO:LiNbO_3$).[13] $MgO:LiNbO_3$ was chosen because of its low loss at 1064 nm, noncritical phase matching, and reduced photorefractive effect. The 400-nsec pulse lengths of the pump light were too short for the DRO to reach steady-state operation. In spite of excellent pump depletion, energy conversion efficiencies were relatively low owing to the long buildup time that extended across much of the pump pulse. The pulsed DRO appeared to run in a single-mode pair over much of its range but would drift from mode to mode as the pump power and crystal temperature fluctuated.

To achieve cw operation we fabricated a monolithic OPO resonator of $MgO:LiNbO_3$ with reduced output coupling, and thus lowered the threshold. Two spherical surfaces of 10-mm radius of curvature were polished on the ends of the 12.5-mm-long crystal along with a total-internal-reflection face perpendicular to the z axis to provide a ring resonant path. Metal electrodes were deposited on the two surfaces perpendicular to the y axis to allow electric-field tuning. The ring geometry was used to obtain maximum conversion and to avoid feedback problems.[14] Dielectric mirrors were deposited directly onto the ends of the crystal, with the specification that the output coupler be 0.5% transmitting and the other end be highly reflecting at 1064 nm and highly transmitting at 532 nm. The double-resonance condition for the signal and idler was satisfied by operating near degeneracy. The pump light was not resonated in this DRO.

The finesse of the DRO resonator was measured using the 1064-nm Nd:YAG laser. An electric field was applied across the crystal y axis, and the r_{22} electro-optic and d_{21} piezoelectric coefficients were used to scan the optical cavity length. The finesse at 1064 nm was measured to be 960, with a voltage of 1506 V required to scan the 5.1-GHz free spectral range. This finesse implies a cold cavity loss of 0.58%. The crystal

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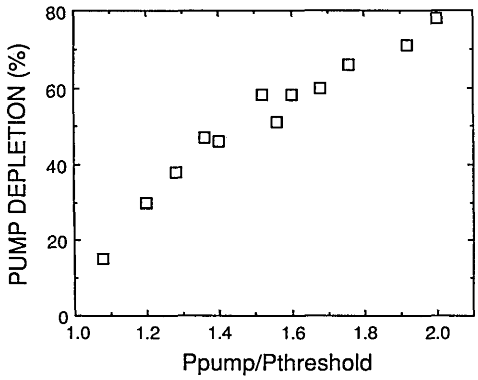

Fig. 1. Pump depletion of the cw DRO versus the number of times above threshold (pump power divided by threshold power).

bulk losses are expected to be of the order of 0.4%.[15] The high-reflector (pump) end of the crystal had a transmittance at 532 nm of 87%.

The DRO was pumped with the resonantly enhanced second harmonic of the cw diode-laser-pumped Nd:YAG laser.[15] The second-harmonic power was approximately 24 mW in a single mode for 57 mW of 1064-nm light incident upon the crystal. Pump light at 532 nm was mode matched into the DRO with a single lens.

For total cavity losses of 0.58%, the calculated threshold[1,16] of the DRO is 3.2 mW of incident pump power at 532 nm, assuming perfect spatial mode coupling of the pump into the OPO resonator. The threshold was measured experimentally to be 12 mW. The discrepancy can be accounted for by noting the extreme sensitivity of the DRO threshold to cavity losses and to mode matching.

Pump depletion of the 532-nm pump radiation versus the number of times above threshold is shown in Fig. 1. These data were taken by scanning the crystal voltage with the DRO oscillating at a signal wavelength of 1035 nm and idler of 1096 nm and observing the point of maximum pump depletion. At two times above threshold the pump depletion was 78%. The DRO resonator is tightly focused ($w_0 = 27\ \mu\text{m}$), thus limiting the applicability of existing theories for pump depletion of Gaussian-intensity pump radiation. However, the pump-depletion data are in good agreement with the plane-wave, transient-regime theory of Bjorkholm.[14]

With no active feedback control, the DRO would run cw and almost always in a single-mode pair at a fixed temperature and voltage. In this context single mode refers to operation with a single signal and a single idler axial mode, or two unique frequencies. A dither-and-lock servo was used on the crystal voltage to lock the OPO to its maximum power point. For the DRO running at a 1043-nm signal and a 1085-nm idler, a total output power of 8.15 mW of signal and idler power was observed for approximately 24 mW of incident 532-nm pump light. The conversion efficiency is 34% for the incident pump and 39% for the transmitted pump. With 57.4 mW of 1064-nm light incident upon the doubling crystal, this represents a 14.2% conversion efficiency of the Nd:YAG laser light to tunable single-axial-mode power after two nonlinear processes, and a 1.6% conversion efficiency of the 500-mW diode laser used to pump the Nd:YAG laser. At an estimated 75% pump depletion, the conversion efficiency implies an output-coupler efficiency of 50%, which is somewhat higher than expected from the loss as deduced from the finesse measurement and the presumed bulk crystal losses. The stability of the OPO output power and servo locking was limited by that of the frequency-doubling system to operation of only a few minutes at a time.

The single-mode condition could be confirmed at a fixed voltage using a scanning confocal interferometer with a 300-MHz free spectral range. Figure 2 shows an interferometer scan of slightly more than one interferometer free spectral range. The stability of the transmission peaks suggested that the DRO frequency was stable to within a few megahertz (the resolution of the instrument) and potentially was much more stable. With the DRO servo locked to a particular axial-mode pair, the DRO signal frequency could track laser frequency tuning as much as 90 MHz without a mode hop. This tuning bandwidth was observed for a signal wavelength of 1043 nm and an idler wavelength of

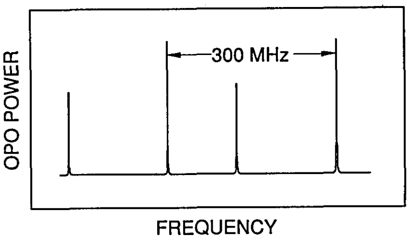

Fig. 2. Scanning interferometer trace of the DRO output light. The higher peaks are signal, the lower peaks are idler. The difference is attributed to the wavelength dependence of detector sensitivity.

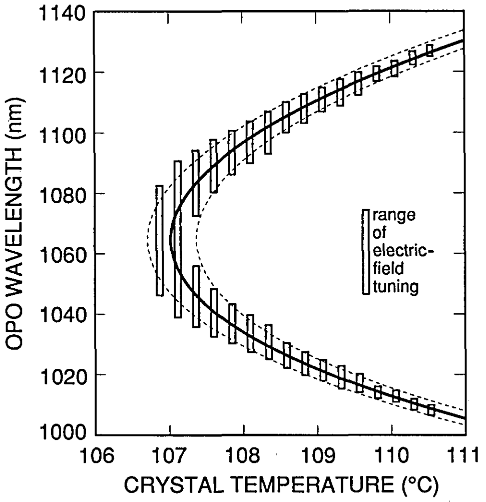

Fig. 3. Temperature tuning of the DRO showing signal and idler wavelengths. The bars represent the extent over which the DRO could be tuned at a fixed temperature by the applied electric field ($V_{\max} = 1100$ V). The solid curve shows the gain center as determined by the temperature-tuned phase-matching condition, and the dashed curves are drawn at plus and minus one cluster spacing away from the gain center.

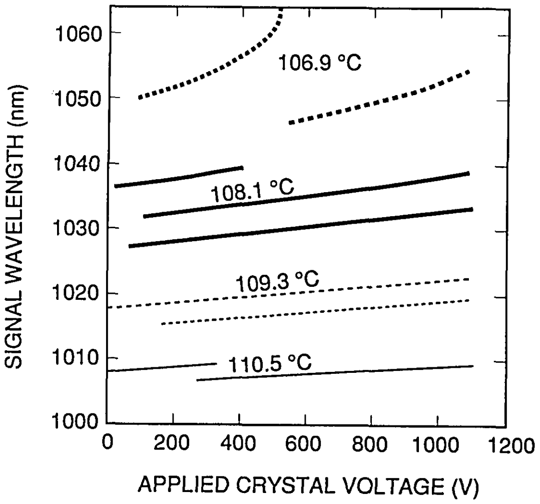

Fig. 4. Voltage tuning of the DRO showing the signal wavelengths only. At a fixed temperature several different clusters are able to oscillate.

1085 nm and is expected to be a strong function of operation relative to degeneracy.

Coarse tuning of the output wavelengths was accomplished by adjusting the crystal temperature, with fine control provided by the applied crystal voltage that controlled the cystal optical path length and birefringence. The DRO could be tuned from degeneracy with both signal and idler at 1064 nm to a signal wavelength of 1007 nm and a corresponding idler of 1129 nm. The temperature tuning range was limited by the bandwidth of the dielectric coatings. Figure 3 shows the wavelength temperature tuning dependence. The bars represent the extent that the voltage scan of 1100 V was able to tune the output at a fixed temperature and are not error bars. As the crystal voltage was scanned, the double-resonance condition would change and the DRO would hop axial modes. The mode hopping occurred along series of adjacent axial-mode pairs known as a clusters.[12,17] The solid curve in Figure 3 shows the gain center as determined by the temperature-tuned phase-matching condition, and the dashed curves are drawn at plus and minus one cluster spacing away from the gain center, which is also equal to the gain bandwidth.

At a fixed temperature two or even three clusters were able to oscillate in a small voltage range. Figure 4 shows the cluster tuning as a function of applied voltage with the curves parameterized by crystal temperature for four different temperatures. The clusters may have their signal wavelengths separated by as much as 17 nm near degeneracy and are separated by ≈3 nm for operation near the tuning limit. Near degeneracy a single cluster's signal wavelength could be scanned as much as 18.6 nm (or 5.0 THz) with the application of 924 V to the crystal. This gives a total wavelength scan for the cluster of 38 nm (or 10.0 THz) when the idler wavelength is included.

In conclusion, we have demonstrated stable, efficient, cw single-mode operation of a DRO pumped by a frequency-doubled, diode-laser-pumped Nd:YAG laser. The device was tuned from 1007 to 1129 nm and exhibited a 34% conversion efficiency from 532-nm pump light to signal and idler power. Pump depletions of 78% were observed. Detailed studies and modeling of the microscopic tuning behavior and OPO linewidths are being carried out. The possibility of DRO's with a signal-to-idler frequency ratio of 3:1 and cw singly resonant OPO's and the use of this class of OPO for production of sub-shot-noise correlation light beams are being explored.

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