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Watt-Level Continuous-Wave Single-Frequency Mid-Infrared Optical Parametric Oscillator Based on MgO:PPLN at 3.68 μm

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Abstract: We report a continuous-wave single-frequency singly-resonant mid-infrared optical parametric oscillator (OPO). The OPO is based on 5 mol % MgO-doped periodically poled lithium niobate (MgO:PPLN) pumped by a continuous-wave single-frequency Nd:YVO_4 laser at 1064 nm. A four-mirror bow-tie ring cavity configuration is adopted. A low-finesse intracavity etalon is utilized to compress the linewidth of the resonant signal. A single-frequency idler output power higher than 1 W at 3.68 μm is obtained.

Keywords: mid-infrared; single-frequency; optical parametric oscillator (OPO); MgO:PPLN crystal; continuous-wave (CW)

1. Introduction

Tunable laser sources in the mid-infrared range are widely used in laser spectroscopy, atmospheric pollution monitoring, remote detection, and differential absorption lidar. In particular, continuous-wave (CW) single-frequency mid-infrared laser sources with broad wavelength tunability are more suitable for high-resolution spectral analysis [1–4] and atom physics [5]. Different techniques have been applied to obtain a mid-infrared laser source. Quantum cascade lasers have been proved to be a method to generate mid-infrared radiation and Razeghi et al. have done extensive work in this area [6,7]. A solid-state laser based on metal-ion-doped crystals can directly generate mid-infrared radiation; for example, research on a Fe:ZnSe laser has been reported [8,9]. An alternative method to reach the mid-infrared wavelength range is to utilize nonlinear frequency downconversion devices such as optical parametric oscillators (OPOs). OPOs with wide wavelength-tunability and a narrow linewidth have become a very important mid-infrared laser source. Compared with birefringent phase-matched (BPM) OPOs, quasi-phase-matched (QPM) OPOs can utilize the largest nonlinear optical tensor element of nonlinear crystals, and make the three interacting waves (pump ω_p, signal ω_s, and idler ω_i) collinearly propagate in nonlinear crystals so that the distance of nonlinear interaction is largely enhanced. Many QPM nonlinear materials such as periodically poled $LiTaO_3$ (PPLT), periodically poled $LiNbO_3$ (PPLN), periodically poled $KTiOPO_4$ (PPKTP), periodically poled $RbTiOAsO_4$ (PPRTA), periodically poled GaAs, and periodically poled GaP have been studied. Among these materials, PPLN is an excellent nonlinear crystal for QPM OPOs, having a relatively high nonlinear coefficient (d_{33} ~27.2 pm/V) with a wide transparent range (0.35–5 μm). Compared with PPLN, MgO-doped periodically poled lithium niobate (MgO:PPLN) has a much higher photorefractive damage threshold. Therefore, MgO:PPLN is widely used as a QPM nonlinear crystal in mid-infrared OPOs [10–15].

To obtain a narrow linewidth idler output from an OPO, a narrow linewidth pump laser source is necessary in the OPO system. In addition, additional wavelength-selective elements are generally utilized to suppress the linewidth of the oscillated signal in the OPO cavity. Peng et al. presented a narrow linewidth PPMgLN OPO, and the linewidth of the 2.98 μm idler was within 0.30–0.63 nm by theoretical analysis [16]. Henderson et al., demonstrated a singly-resonant CW OPO pumped by an all-fiber pump source, with a 3.17 μm idler linewidth of 1 MHz [17]. Vainio et al., demonstrated a singly-resonant CW OPO operating without mode hops for several hours due to the good thermal control of the MgO:PPLN crystal [18]. Reflecting volume Bragg gratings (VBGs) have been widely used in laser devices to obtain a narrow linewidth output. For example, Zeil et al., reported a singly-resonant CW OPO with optimum extraction efficiency, in which a single-longitudinal-mode signal output was obtained by employing a variable-reflectivity VBG as the output coupler of a ring cavity [19]. In addition, Xing et al., devised self-seeding dual etalon-coupled cavities in the OPO system pumped by a single-longitudinal-mode pulsed Yb-fiber laser. The linewidth of the oscillated signal was suppressed and the linewidth of the idler was efficiently narrowed [20].

In this paper, we report our experimental work on a CW single-frequency MgO:PPLN OPO pumped by a CW single-frequency Nd:YVO_4 laser at 1064 nm. We obtained a CW single-frequency 3.68 μm idler laser with an output power higher than 1 W. Wavelength tuning can be achieved through thermal control of the nonlinear crystal and use of the different grating periods.

2. Experimental Setup

The experimental configuration of the CW single-frequency MgO:PPLN OPO is shown schematically in Figure 1. The nonlinear medium used for the OPO is 5 mol % MgO-doped periodically poled lithium niobate (MgO:PPLN, HC Photonics) with a length of 50 mm and a laser aperture of 8 mm × 1 mm. The MgO:PPLN crystal contains seven domain grating periods from 28.5 μm to 31.5 μm with 0.5-μm increments. The crystal is antireflection-coated for the signal wavelength (R < 1%@1.4–1.7 μm), idler wavelength (R < 1%@3–4 μm), and pump wavelength (R < 1%@1.064 μm). The crystal is mounted in a temperature-controlled oven, in which the crystal temperature can be adjusted in the range of 25–200 °C with a temperature stability of ± 0.1 °C. A simple bow-tie ring cavity is used in the OPO system. The ring cavity consists of two identical curved cavity mirrors (M_1 and M_2) and two flat mirrors (M_3 and M_4), which are all made of CaF_2 and are antireflection-coated at the pump wavelength (T > 98%@1064 nm) and idler wavelength (T > 95%@3–5 μm), and have high reflectivity at the signal wavelength (R > 99.8%@1.4–1.7 μm). The OPO configuration gives a singly resonant OPO, which is resonant for the signal frequency. The two identical curved cavity mirrors (M_1 and M_2), enclosing the MgO:PPLN crystal, have a 75-mm radius of curvature and are separated by a distance of 120 mm. The nonlinear crystal is placed at the center between the two curved mirrors (M_1 and M_2). The other two flat cavity mirrors (M_3 and M_4) are separated by 35 mm. The total resonator length is about 325 mm.

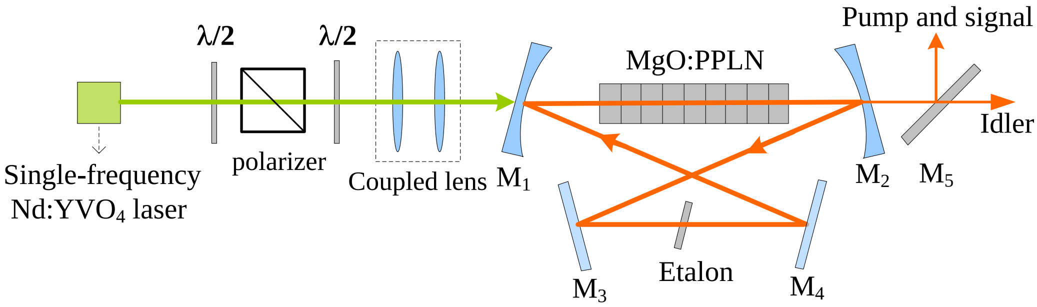


Figure 1. Configuration of the continuous-wave (CW) single-frequency MgO-doped periodically poled lithium niobate (MgO:PPLN) optical parametric oscillator (OPO).

The pump source is a continuous-wave single-frequency $Nd:YVO_4$ laser that produces over 10 W of radiation at 1064 nm. The $Nd:YVO_4$ laser has an excellent beam quality of M^2 ~1.1 and an output of linear polarization, which was described in Reference [21]. When the power is changed, the laser beam characteristics change significantly. In order to maintain a stable output, the $Nd:YVO_4$ laser is operated at maximum output power in this experiment. A combination of a half-wave plate and a polarizing beam splitter is used as a power attenuator to change the incident pump power. By using the second half-wave plate, the pump polarization is aligned along the crystallographic *z*-axis of the MgO:PPLN crystal to utilize the largest nonlinear coefficient d_{33}. The pump beam is mode-matched to the OPO cavity with a series of convex lenses, producing a $1/e^2$ waist radius of 60 μm at the center of the MgO:PPLN crystal. Its waist yields a focusing parameter ξ_p ~1.1. With the current OPO cavity, the signal beam waist at the center of the MgO:PPLN crystal is about 70 μm, resulting in optimum mode-matching to the pump (ξ_s ~ξ_p). To enhance the single-frequency operation of the OPO, an uncoated 0.5-mm-thick yttrium aluminium garnet (YAG) plate is used as an intracavity etalon with a free spectral range of 120 GHz. A 45° flat dichroic mirror M_5 is utilized as a filter to separate the idler from the output beams.

3. Experimental Results and Discussion

The wavelengths of the OPO signal and idler are recorded with a laser spectrum analyzer (EXFO WA-650) combined with a wavelength meter (EXFO WA-1500). When the pump beam passes through a 29.5 μm grating period of the MgO:PPLN crystal and the crystal temperature is controlled at 120.0 ± 0.1 °C, the idler wavelength is 3.68 μm (Figure 2) and the corresponding signal wavelength is 1.49 μm (Figure 3). The wavelengths of the pump (λ_p), signal (λ_s), and idler (λ_i) waves are in accord with the conservation of energy ($1/\lambda_p = 1/\lambda_s + 1/\lambda_i$).

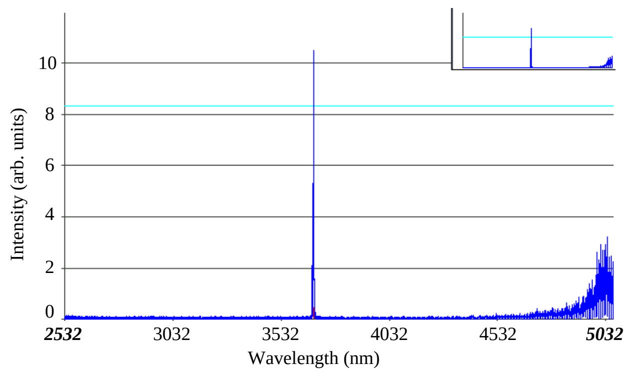


Figure 2. Idler wavelength of the MgO:PPLN OPO at temperature T = 120 °C for the grating period Λ = 29.5 μm.

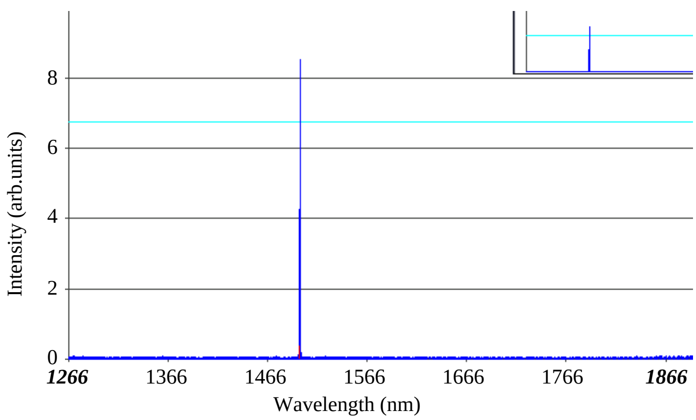
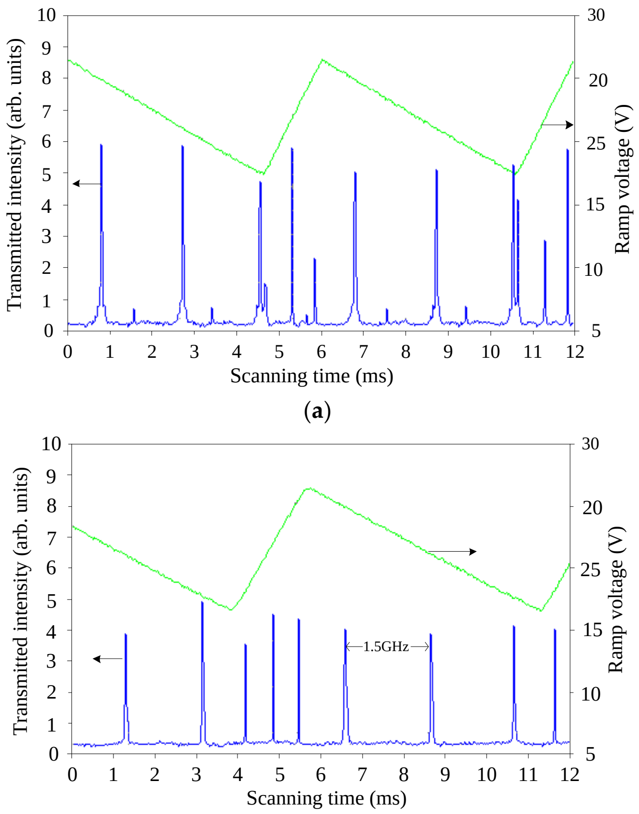


Figure 3. Signal wavelength of the MgO:PPLN OPO at temperature T = 120 °C for the grating period Λ = 29.5 μm.

To investigate its longitudinal mode structure, the signal spectral information is monitored by a 1.5 µm scanning confocal Fabry-Perot (F-P) interferometer, with a free spectral range of 1.5 GHz. As shown in Figure 4, the upper trace is the F-P ramp voltage and the lower trace is the voltage of the signal transmission through the F-P interferometer. Figure 4a shows the F-P spectrum of the signal from the MgO:PPLN OPO without the YAG etalon. To lock the cavity mode and reduce the spectral noise, an uncoated 0.5-mm-thick YAG plate is used as an intracavity etalon inserted in the cavity. By adjusting the angle of the etalon carefully, the signal spectral noise can be reduced. Figure 4b shows the F-P spectrum of the signal from the MgO:PPLN OPO with the YAG etalon. As can be seen, a single-frequency operation of the signal is presented in Figure 4b. According to the energy conservation condition $\omega_i + \omega_s = \omega_p$, the single-frequency operation of the idler from the MgO:PPLN OPO can be confirmed.



(**a**)

(**b**)

Figure 4. F-P spectrum of the signal from the MgO:PPLN OPO: (**a**) cavity without etalon; (**b**) cavity with an uncoated yttrium aluminium garnet (YAG) etalon.

The idler output power, as a function of the incident pump power, is measured by a power meter (Coherent PM2). Figure 5 shows the measured idler power versus incident pump power. When the YAG etalon is inserted in the four-mirror ring cavity, the oscillated threshold of the OPO is increased from 2 W to 5 W. Without the etalon in the OPO cavity, with a pump power of 10 W from the single-frequency $Nd:YVO_4$ laser, the 3.68 µm idler power is 1.3 W emitting from mirror M_2. With an intracavity etalon, the 3.68 µm idler power is 1.1 W, corresponding to an optical efficiency of 11%.

The idler beam quality is also measured as a function of the idler power. By making use of the knife-edge method, the idler beam radius as a function of the distance from mirror M_2 is achieved. By using a nonlinear fitting method, the beam quality factor M^2 can be obtained. For a single-frequency idler output power of 1 W at 3.68 µm, the values of M^2 are measured to be about 1.3 and 1.2 in the horizontal and vertical directions, respectively.

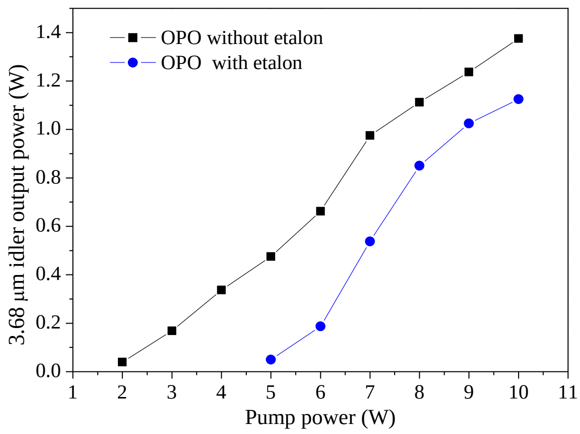


Figure 5. Output power of the 3.68 μm idler versus incident pump power.

We can tune the signal and idler wavelengths by changing the temperature of the MgO:PPLN crystal. According to the Sellmeier equations [22], the theoretical tuning curves for the seven available grating periods are shown in Figure 6. By shifting the MgO:PPLN crystal to keep the pump beam passing through the different grating periods, and changing the nonlinear crystal temperature between 20 °C and 200 °C, the OPO is able to generate idler wavelengths ranging from 2.9 to 4.1 μm.

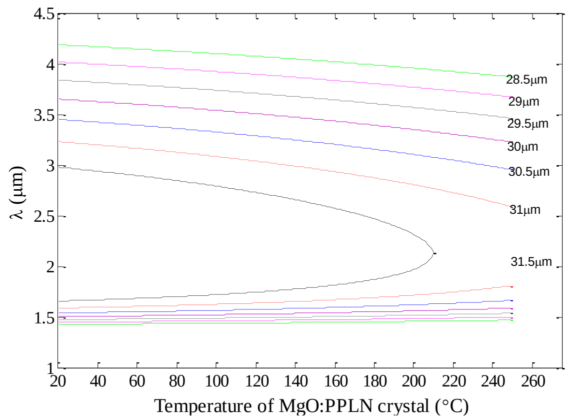


Figure 6. Theoretical tuning curves for eight periods of the MgO:PPLN crystal.

4. Conclusions

In conclusion, we have demonstrated a continuous-wave single-frequency mid-infrared MgO:PPLN OPO pumped by a continuous-wave single-frequency Nd:YVO_4 laser at 1064 nm. The symmetrical design of the system can easily achieve mode-matching. We used an uncoated 0.5-mm-thick YAG etalon to enhance the single-frequency operation of the MgO:PPLN OPO. With the etalon in the cavity, the OPO produced a single-frequency output of 1.1 W at 3.68 μm. By using different grating periods and adjusting the nonlinear crystal temperature between 20 °C and 200 °C, the idler wavelength of the OPO can be continuously tuned in the range of 2.9–4.1 μm.

Author Contributions: J.Z., P.C., and F.X. conceived and designed the experiment; J.T. and Y.L. performed the experiment; X.Z. and G.W. supervised the entire work; J.Z. and P.C. wrote the paper.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kovalchuk, E.V.; Dekorsy, D.; Lvovsky, A.I.; Braxmaier, C.; Mlynek, J.; Peters, A.; Schiller, S. High-resolution Doppler-free molecular spectroscopy with a continuous-wave optical parametric oscillator. *Opt. Lett.* **2001**, *26*, 1430–1432. [CrossRef] [PubMed]
2. Verbraak, H.; Ngai, A.K.Y.; Persijn, S.T.; Harren, F.J.M.; Linnartz, H. Mid-infrared continuous wave cavity ring down spectroscopy of molecular ions using an optical parametric oscillator. *Chem. Phys. Lett.* **2007**, *442*, 145–149. [CrossRef]
3. Zaske, S.; Lee, D.-H.; Becher, C. Green-pumped cw singly resonant optical parametric oscillator based on MgO:PPLN with frequency stabilization to an atomic resonance. *Appl. Phys. B* **2010**, *98*, 729–735. [CrossRef]
4. Ricciardi, I.; Tommasi, E.D.; Maddaloni, P.; Mosca, S.; Rocco, A.; Zondy, J.J.; Natale, P.D. A narrow-bandwidth, frequency-stabilized OPO for sub-Doppler molecular spectroscopy around 3 μm. *Proc. SPIE* **2012**, *8434*, 84341Z.
5. Mickelson, P.G.; Martinez de Escobar, Y.N.; Anzel, P.; De Salvo, B.J.; Nagel, S.B.; Traverso, A.J.; Yan, M.; Killian, T.C. Repumping and spectroscopy of laser-cooled Sr atoms using the $(5s5p)^3P_2$-$(5s4d)^3D_2$ transition. *J. Phys. B Mol. Opt. Phys.* **2009**, *42*, 235001. [CrossRef]
6. Bandyopadhyay, N.; Slivken, S.; Bai, Y.; Razeghi, M. High power, continuous wave, room temperature operation of λ~3.4 μm and λ~3.55 μm InP-based quantum cascade lasers. *Appl. Phys. Lett.* **2012**, *100*, 212104–212107. [CrossRef]
7. Razeghi, M. High-performance InP-based mid-IR quantum cascade lasers. *IEEE J. Sel. Top. Quantum Electron.* **2009**, *15*, 941–951. [CrossRef]
8. Jelínková, H.; Němec, M.; Šulc, J.; Miyagi, M.; Iwai, K.; Takaku, H.; Doroshenko, M.; Basiev, T.T.; Komar, V.K.; Gerasimenko, A.S. Transfer of Fe:ZnSe laser radiation by hollow waveguide. *Laser Phys. Lett.* **2011**, *8*, 613–616. [CrossRef]
9. Evans, J.W.; Berry, P.A.; Schepler, K.L. 840 mW continuous-wave Fe:ZnSe laser operating at 4140 nm. *Opt. Lett.* **2012**, *37*, 5021–5023. [CrossRef] [PubMed]
10. Murray, R.T.; Runcorn, T.H.; Guha, S.; Taylor, J.R. High average power parametric wavelength conversion at 3.31–3.48 μm in MgO:PPLN. *Opt. Express* **2017**, *25*, 6421–6430. [CrossRef] [PubMed]
11. Kemlin, V.; Jegouso, D.; Debray, J.; Segonds, P.; Boulanger, B.; Menaert, B.; Ishizuki, H.; Taira, T. Widely tunable optical parametric oscillator in a 5 mm thick 5% MgO:PPLN partial cylinder. *Opt. Lett.* **2013**, *38*, 860–862. [CrossRef] [PubMed]
12. Zhao, J.Q.; Yao, B.Q.; Zhang, X.L.; Li, L.; Ju, Y.L.; Wang, Y.Z. An efficient, compact intra-cavity continuous-wave mid-infrared SRO with a narrow line width. *Laser Phys. Lett.* **2013**, *10*, 045801. [CrossRef]
13. Wei, X.; Peng, Y.; Wang, W.; Chen, X.; Li, D. High-efficiency mid-infrared laser from synchronous optical parametric oscillation and amplification based on a single MgO:PPLN crystal. *Appl. Phys. B* **2011**, *104*, 597–601. [CrossRef]
14. Koch, P.; Ruebel, F.; Nittman, M.; Bauer, T.; Bartschke, J.; L'huillier, J.A. Narrow-band, tunable 2 μm optical parametric oscillator based on MgO:PPLN at degeneracy with a volume Bragg grating output coupler. *Appl. Phys. B* **2011**, *105*, 715–720. [CrossRef]
15. Das, R.; Kumar, S.C.; Samanta, G.K.; Ebrahim-Zadeh, M. Broadband, high-power, continuous-wave, mid-infrared source using extended phase-matching bandwidth in MgO:PPLN. *Opt. Lett.* **2009**, *34*, 3836–3838. [CrossRef] [PubMed]
16. Peng, Y.F.; Wei, X.B.; Xie, G.; Gao, J.R.; Li, D.M.; Wang, W.M. A high-power narrow-linewidth optical parametric oscillator based on PPMgLN. *Laser Phys.* **2013**, *23*, 055405. [CrossRef]
17. Henderson, A.; Stafford, R. Low threshold, singly-resonant CW OPO pumped by an all-fiber pump source. *Opt. Express* **2006**, *14*, 767–772. [CrossRef] [PubMed]
18. Vainio, M.; Peltola, J.; Persijn, S.; Harren, F.J.; Halonen, L. Singly resonant cw OPO with simple wavelength tuning. *Opt. Express* **2008**, *16*, 11141–11146. [CrossRef] [PubMed]
19. Zeil, P.; Thilmann, N.; Pasiskevicius, V.; Laurell, F. High-power, single-frequency, continuous-wave optical parametric oscillator employing a variable reflectivity volume Bragg grating. *Opt. Express* **2014**, *22*, 29907–29913. [CrossRef] [PubMed]

20. Xing, T.; Wang, L.; Hu, S.; Cheng, T.; Wu, X.; Jiang, H. Widely tunable and narrow-bandwidth pulsed mid-IR PPMgLN-OPO by self-seeding dual etalon-coupled cavities. *Opt. Express* **2017**, *25*, 31810–31815. [CrossRef] [PubMed]
21. Zhao, J.Q.; Wang, Y.Z.; Yao, B.Q.; Ju, Y.L. High efficiency, single-frequency continuous wave Nd:YVO_4/YVO_4 ring laser. *Laser Phys. Lett.* **2010**, *7*, 135–138. [CrossRef]
22. Gayer, O.; Sacks, Z.; Galun, E.; Arie, A. Temperature and Wavelength Dependent Refractive Index Equations for MgO-doped Congruent and Stoichiometric $LiNbO_3$. *Appl. Phys. B* **2008**, *91*, 343–348. [CrossRef]