Optical injection locking of a singly resonant continuous-wave optical parametric oscillator

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We report on experimental realization of optical injection locking of a singly resonant continuous-wave optical parametric oscillator (OPO) based on a thermally induced waveguide in a magnesium-oxide doped periodically poled lithium niobate. An external cavity diode laser is used to control the frequency of the resonant signal output of the OPO at 795 nm. The key to successful injection locking was the improvement of the OPO spatial modes by a special operating condition with a thermally induced waveguide. The phase coherence of injection locking is confirmed by recording a high-contrast interference fringe between the injection laser and the OPO output. High-resolution measurement of the frequency spectrum of the nonresonant idler output by the delayed self-heterodyne technique shows that the spectral linewidth of the OPO is reduced from 4.5 to 0.4 MHz by injection locking. The full locking range is assumed to be less than 1.7 MHz.

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Phase locking of two independent laser oscillators through injection of weak light from one laser to another was demonstrated in 1966 [1] and is now established as a standard technique to precisely control and stabilize the optical frequency of laser oscillators [2–4]. However, to the best of our knowledge, optical injection locking of a continuous-wave (cw) optical parametric oscillator (OPO) by another independent laser is not reported yet. Similar to lasers, an all-optical technique such as injection locking is expected to provide a promising alternative for improving the frequency stability and tunability of cw OPOs [5]. Experimental demonstrations of all-optical frequency stabilization for a cw OPO so far have been limited to the self-injection locking that is phase locking through one of the output waves of the OPO itself within the cavity [6–10]. For pulsed OPOs, optical injection seeding is widely used for spectral narrowing, which is, however, not applicable to a cw OPO due to its different operating principle [2].

Based on our experiment with a singly resonant green-pumped cw OPO described in [11], we assumed that the main obstacle for optical injection locking of a cw OPO is the degradation of spatial mode matching between the OPO cavity mode and the injection laser mode due to thermal effects in the nonlinear crystal. In particular, we have confirmed that the thermal lensing effect induced by absorption of the pump laser power in the nonlinear crystal produces a strong distortion of the spatial mode of the resonant OPO output wave [11]. As a result, the OPO output beam had a multiple spatial mode and the effect of injection locking could not be observed.

In this Letter, we report on a successful demonstration of optical injection locking of a cw OPO by using an external cavity diode laser (ECDL) at 795 nm [12]. The key to successful injection locking was the self-guided operation of the OPO, which dramatically improves the spatial mode through formation of a thermally induced waveguide in the bulk magnesium-oxide doped periodically poled lithium niobate (MgO:PPLN) crystal [13]. As the spatial distortion by thermal lensing is now suppressed, the spatial mode matching between the OPO mode and the ECDL mode is improved, which results in the expected optical injection locking as the frequency of the ECDL is tuned into the linewidth of the OPO cavity. The phase coherence between the OPO and the ECDL by injection locking is confirmed by observing interference fringes and by measuring the spectral linewidth reduction.

Figure 1 schematically shows the experimental setup for optical injection locking of a cw OPO. The OPO is based on a 5 mol. % MgO:PPLN crystal placed in a standing-wave two-mirror cavity that is resonant only for the signal wave. The OPO is pumped at 532 nm, and the injection locking experiment is performed at the signal and idler wavelengths of 795 and 1608 nm, respectively, set for poling period and temperature of the crystal of 7.6 μm and 80.8°C, respectively. A detailed description of the OPO in the normal operating condition can be found in [11].

For injection locking, the output beam of the ECDL is coupled to the OPO cavity via a polarization-maintaining single-mode fiber (PM-SMF), in which the signal output beam of the OPO is also coupled from the opposite end.

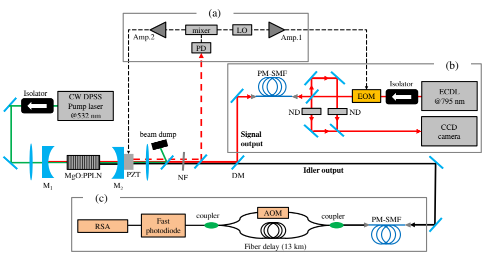

Fig. 1. (Color online) Experimental setup for injection locking of a cw OPO by an ECDL, including (a) the PDH setup for cavity length stabilization, (b) the setup for measuring the interference image between the ECDL beam and the OPO beam, and (c) the setup for measuring the spectral linewidth of the OPO idler output based on the self-heterodyne method. See text for details.

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Spatial mode matching between the ECDL beam and the OPO cavity is optimized by maximizing the coupling of both the OPO signal beam and the ECDL beam into the same PM-SMF. The length of the OPO cavity is locked to the frequency of the ECDL based on the Pound–Drever–Hall (PDH) technique [14] by using an electro-optic modulator driven at 100 MHz and a piezo transducer attached to the output mirror (M_2 in Fig. 1) of the OPO cavity. The reflectivity of the cavity mirrors M_1 and M_2 is specified to be 0.99 and 0.98, respectively, from which we estimate the spectral bandwidth of the OPO cavity to be 7.4 MHz with an intracavity transmission of 0.984 [11]. For comparison, the spectral bandwidth of the ECDL is typically less than 1 MHz for an integration time of 1 ms. The power of the injection beam was approximately 3 mW before entering into the OPO cavity through M_2. From the impedance matching condition, we estimate that the OPO cavity reflects approximately 7% of the injection power [2] so that 2.8 mW was coupled into the cavity as the injection power. The total signal output power of the free-running OPO (in the self-guided operation) was approximately 75 mW at the pump power of 2.4 W.

In order to achieve injection locking, the ECDL frequency should be within the cavity mode where the OPO oscillates. In practice, we first adjusted the ECDL wavelength to the fluorescent D_1 line of an Rb atom in a vapor cell (not shown in Fig. 1). Then, the OPO frequency was finely tuned to the same fluorescent line by adjusting the cavity length while keeping the PDH lock. Mode hops occurring for a frequency tuning of one free spectral range of the cavity (850 MHz) were used to bring the OPO mode to the ECDL frequency. In order to confirm the phase coherence between the ECDL and the OPO, we built a Mach–Zehnder interferometer by combining the injected beam of the ECDL and the OPO signal wave at a 50∶50 beam splitter. A CCD imaging sensor is used to observe the interference pattern that is expected when the OPO is injection locked by the ECDL.

In the normal operating condition of the OPO with the nearly concentric stable cavity configuration as described in [11], observation of the expected injection locking was not successful. We assumed that the multiple spatial mode of the OPO output beams due to thermal effects in the MgO:PPLN crystal is responsible for a degradation of the spatial mode matching of the injection beam into the OPO beam mode. In contrast, successful injection locking is achieved in the self-guided operation of the OPO by increasing the length of the OPO cavity beyond the stability boundary [13]. Under this condition, the OPO can operate only through formation of a thermally induced waveguide in the crystal by pump beam absorption, which results in the improved spatial mode of the OPO output beams. Once the spatial mode matching of the injection beam to the OPO beam mode is improved through the self-guided operation, optical injection locking of the cw OPO could be realized as the frequency of the ECDL is tuned in to the spectral mode of the OPO signal output.

Figure 2 shows two interferometer images between the OPO and the ECDL output beams measured by the CCD sensor. Figure 2(a) was captured when the ECDL frequency was far from the OPO signal mode frequency, while Fig. 2(b) was captured when the ECDL frequency was tuned within the OPO signal mode. The contrast of the interference fringe is maximized by balancing the power of two incident beams by using separate neutral density filters for each path. The high contrast of the interference fringe of Fig. 2(b) confirms the high phase coherence between the OPO and the ECDL through injection locking. The fringe was stable as long as the injection locking was maintained, which confirms that the frequency of the OPO is phase coherently controlled by the injection laser frequency.

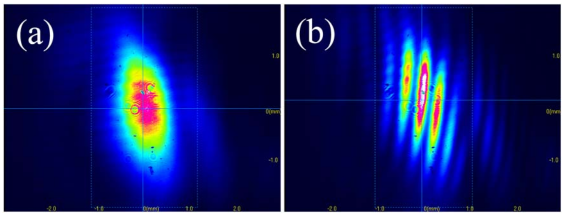

Fig. 2. (Color online) Interferometer images between the cw OPO and the ECDL output beams at 795 nm (a) before and (b) after injection locking.

In order to quantitatively measure the effect of the injection locking upon the spectral characteristics of the cw OPO, we constructed a delayed self-heterodyne measurement setup with a 13 km fiber delay and an acousto-optic modulator driven at 50 MHz for the OPO idler output as shown in Fig. 1(c) [15]. Figure 3 shows the frequency spectra of the OPO idler output, which are recorded with a fast photodiode and radio frequency spectrum analyzer at a resolution bandwidth of 100 kHz and a sweep time of 10 ms. The spectrum of the free-running OPO in Fig. 3(a) indicates that the spectrally narrow mode of the idler output undergoes a fast and random fluctuation within a frequency range of 9 MHz. From this measurement, we can estimate that the spectral linewidth of the free-running OPO is close to 4.5 MHz for an integrating time much longer than 10 ms, which is dominantly limited by the spectral bandwidth of the OPO cavity. Note that the linewidth of the pump laser (model Verdi of Coherent, Inc.) is specified to be smaller than 1 MHz.

In contrast, the spectrum of the injection locked cw OPO of Fig. 3(b) shows a stable double-structured profile, which is averaged for several seconds. The narrow

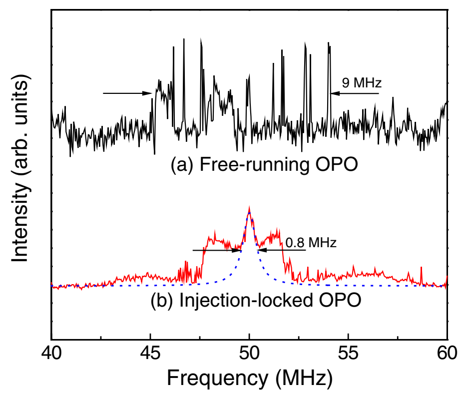

Fig. 3. (Color online) Beat spectrum of the OPO idler output measured by the self-heterodyne method (a) before and (b) after injection locking.

peak at the center corresponds to the beat spectrum of the injection locked OPO output, while the broad flat-top profile with a width of approximately 5 MHz indicates the frequency instability at the boundary of the locking range. A Lorentzian fit is applied, as indicated with the dotted curve in Fig. 3(b), to determine the spectral width of the center peak to be 0.8 MHz as a full width at half-maximum. This corresponds to a spectral linewidth of the OPO idler output of 0.4 MHz.

As the origin of the 5 MHz flat-top profile observed in Fig. 3(b), we presume that the locking bandwidth is smaller than the spectral width of the center peak. If the locking bandwidth is large enough compared to the spectral linewidth of the injection laser, we expect a beat spectrum with a high-contrast Lorentzian profile and two instability sidebands indicating the locking range boundary [2,16]. However, in the beat spectrum of Fig. 3(b), the Lorentzian profile is not resolved from the instability sidebands. According to the basic theory of injection locking, the equation for estimation of the full locking range is given by $\Delta\nu_{\mathrm{lock}} = 2\Delta\nu_{\mathrm{cav}}\sqrt{P_{\mathrm{inj}}/P_{\mathrm{free}}}$, where $\Delta\nu_{\mathrm{cav}}$ denotes the spectral bandwidth of the free-running OPO cavity, P_{inj} and P_{free} and the power of the injection laser and the free running OPO output, respectively [2]. From the measured values of $P_{\mathrm{inj}} = 2.8$ mW, $P_{\mathrm{free}} = 75$ mW, and $\Delta\nu_{\mathrm{cav}} = 4.5$ MHz, we estimate $\Delta\nu_{\mathrm{lock}} = 1.7$ MHz for the full locking range. We expect that the real locking bandwidth should be smaller than this calculated value because the spatial mode matching between the injection laser and the OPO cannot be perfect even for the self-guided operation mode.

In summary, we demonstrated, for the first time to our knowledge, the optical injection locking of a singly resonant cw OPO by an ECDL at 795 nm. The improvement of spatial mode matching through self-guided operation of the OPO with the thermally induced waveguide in the nonlinear crystal was the key to achievement of the injection locking. The phase coherence of injection locking is confirmed by measurement of a high-contrast interference fringe between the OPO output and the injection laser. The high-resolution measurement of frequency spectrum of the OPO output based on the delayed self-heterodyne method showed that the spectral linewidth of the cw OPO is reduced from 4.5 to 0.4 MHz by injection locking. We conclude that improvement of performance through injection locking is possible for a cw OPO as long as the spatial mode of the OPO output is close to the fundamental mode.

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References

1. H. L. Stover and W. H. Steier, Appl. Phys. Lett. **8**, 91 (1966).
2. A. E. Siegman, in *Lasers* (University Science Books, 1986), Chap. 29.
3. S. W. Chiow, S. Herrmann, H. Miller, and S. Chu, Opt. Express **17**, 5246 (2009).
4. Z. Chen, J. Hou, P. Zhou, X. Wang, X. Xu, Z. Jiang, and Z. Liu, Opt. Commun. **282**, 60 (2009).
5. I. Breunig, D. Haertle, and K. Buse, Appl. Phys. B **105**, 99 (2011).
6. C. D. Nabors, S. T. Yang, T. Day, and R. L. Byer, J. Opt. Soc. Am. B **7**, 815 (1990).
7. E. J. Mason and N. C. Wong, Opt. Lett. **23**, 1733 (1998).
8. D. H. Lee, M. E. Klein, J. P. Meyn, P. Gross, R. Wallenstein, and K. J. Boller, Opt. Express **5**, 114 (1999).
9. P. Groß, K. J. Boller, and M. E. Klein, Phys. Rev. A **71**, 043824 (2005).
10. S. T. Wong, K. L. Vodopyanov, and R. L. Byer, J. Opt. Soc. Am. B **27**, 876 (2010).
11. I. H. Bae, H. S. Moon, S. Zaske, C. Becher, S. K. Kim, S. N. Park, and D. H. Lee, Appl. Phys. B **103**, 311 (2011).
12. I. H. Bae, H. S. Moon, S. K. Kim, S. N. Park, and D. H. Lee, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optical Society of America, 2012), paper JW4A70.
13. I. H. Bae, H. S. Moon, S. K. Kim, S. N. Park, and D. H. Lee, Appl. Phys. B **106**, 797 (2012).
14. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B **31**, 97 (1983).
15. T. Okoshi, K. Kikuchi, and A. Nakayama, Electron. Lett. **16**, 630 (1980).
16. C. J. Buczek, R. J. Freiberg, and M. L. Skolnick, Proc. IEEE **61**, 1411 (1973).