Joint Thermal Effects of VBG and Nonlinear Crystal in a Singly Resonant OPO

Xionghua Zheng, Guangyuan He, Baofu Zhang, Jing Guo, Zhongxing Jiao, and Biao Wang

***Abstract*— A continuous-wave singly resonant optical parametric oscillator employing a volume Bragg grating as one of the end mirrors is demonstrated. Due to the high intracavity power, the minute absorption of the grating leads to the thermal induced surface deformation and reflection peak shift. In this letter, the former effect is confirmed to be a cause of beam quality degradation of the resonant signal, while the latter, together with the thermal effects of the nonlinear crystal, leads to unconventional behaviors of power and stability. To the best of our knowledge, the joint effects of the grating and the nonlinear crystal are studied for the first time in details by changing the thermal effects of grating in varied strengths.**

***Index Terms*— Volume Bragg grating, thermal effects, nonlinear crystal, optical parametric oscillator.**

I. Introduction

COHERENT sources producing continuous-wave (cw) radiation with narrow linewidth and wide tuning range in the infrared region are of great interest for applications including high-resolution molecular spectroscopy, trace gas detection and atom physics [1]–[3]. OPOs with periodically poled crystals have been the common choice for these applications. However, without spectral selection, the spectral bandwidth of OPO is inherently broad and thus not suitable when narrow linewidth is required. Although designs based on an intracavity etalon or birefringent filter as spectral selecting and tuning element are satisfactory in most cases, they suffer from additional cavity losses and therefore an increased threshold [4], [5]. As alternatives, VBGs written in photothermal refractive (PTR) glass have shown great advantages in wavelength stabilization, tuning, and spectral narrowing of various lasers [6], [7] and OPOs [8], [9] due to their narrow diffraction bandwidth, high peak reflectivity and sensitive angular selectivity.

Manuscript received November 2, 2015; revised January 23, 2016; accepted February 15, 2016. Date of publication February 18, 2016; date of current version March 29, 2016. This work was supported in part by the National Natural Science Foundation of China under Grant 61308056, Grant 11204044, and Grant 11232015, in part by the Research Fund for the Doctoral Program of Higher Education of China under Grant 20130171130003, and in part by the Fundamental Research Funds for the Central Universities of China under Grant 14lgpy07.

X. Zheng, B. Zhang, J. Guo, Z. Jiao, and B. Wang are with the School of Physics and Engineering, Sun Yat-sen University, Guangzhou 510275, China (e-mail: zhengxh8@mail2.sysu.edu.cn; jkbowry11@163.com; ryanguo333@gmail.com; jiaozhx@mail.sysu.edu.cn; wangbiao@mail.sysu.edu.cn).

G. He is with the Institute of Nuclear Engineering and Technology, Sun Yat-sen University, Guangzhou 510275, China (e-mail: frankhe201@gmail.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2016.2531751

The VBG acts simultaneously as a cavity mirror and a narrowband spectral filter in the OPOs or laser systems. The high diffraction efficiency of VBG not only contributes to decreasing threshold, but also rises the intracavity power to the order of hundred watts. Therefore, any minute absorption in the VBG is sufficient to induce noticeable thermal effects. Previous studies on thermal effects of VBGs have been focused on the Bragg wavelength shifting, reflectivity reducing and spectrum broadening in various laser systems [10]–[12]. In these laser systems, the emission wavelength from the laser crystal was potentially constant. In a VBG-based OPO (VBG-OPO), situation can be somewhat different since sufficient thermal load on the nonlinear crystal induces a shift in spectral gain due to phase matching condition. A temperature control offers great alleviation, however, these thermal effects are inevitable unless the absorption of the VBG can be further reduced. Therefore, further investigation on the combined thermal effects of the nonlinear crystal and VBG in a high-power, cw OPO would be of great importance for achieving stable, narrow-linewidth infrared radiation for practical applications.

In this letter, we demonstrate a high-power, singly resonant, cw OPO which employs a VBG as an end-mirror of the four-mirror linear cavity. The VBG is mounted in copper blocks with different sizes and without accurate temperature control; this allows us to change the thermal effects of VBG in different strengths. We confirm the effect of spectral narrowing and locking of the VBG by comparing with OPOs employing a common output-coupling (OC-OPO) or all highly reflective mirrors (HR-OPO). Investigations of power and spectral characteristics on different working points are performed in our experiment, and results are interpreted by the joint thermal effects of the VBG and nonlinear crystal. In addition, the beam qualities of the resonant signal are measured, and the results suggest a degradation effect of VBG on beam quality.

II. Experimental Setup

The layout of the VBG-OPO is depicted as Fig. 1. The pump system consists a commercial cw Nd:YVO_4 solid-state laser as seed source and two amplifier stages, delivering stable output power up to 21 W at 1064 nm with a ~0.8 mm diameter in TEM_{00} spatial mode (M_x^2~1.2, M_y^2~1.1). A combination of a half-wave plate (HWP) and a polarizing beam splitter (PBS) is used to vary the pump power for OPO without disturbing the pump system. The pump beam is confocally focused to yield a beam waist radius of ~55 μm inside the crystal by a single lens (f=75 mm), corresponding to a focusing parameter

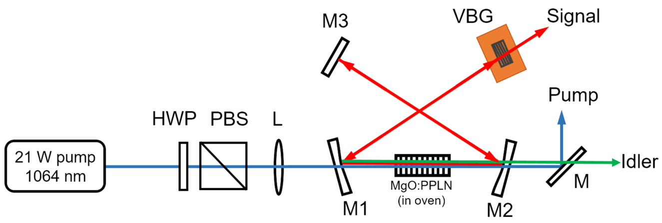

Fig. 1. Schematic of the cw VBG-OPO based on a four-mirror linear cavity.

of ξ_p~1.3 [13]. The parametric oscillator is a standard four-mirror standing-wave cavity while one of the end mirror is replaced with a reflective VBG. All mirrors in cavity are highly reflective (R>99.9%) for the signal and transparent for the idler and pump. The geometric separation between the concave mirrors M1 and M2 (r=100 mm) is 140 mm, and the distance between a curved and a flat mirror (M3)/grating is 170 mm. The resonant signal in the cavity has a beam radius of ~70 μm at the center of the crystal, corresponding to a focusing parameters of ξ_s~1.2, slightly deviating from the ξ_p.

A 5% doped MgO:PPLN (HC Photonics Inc.) is employed as nonlinear crystal, which is in a dimension of 50×8.6×1 mm^3, containing 7 separated grating periods from 28.5 μm to 31.5 μm. In our experiment, the crystal is used in a poling period of 30.0 μm at ~125.0 °C for a phase matching at signal wavelength of 1535 nm, as calculated from the relevant Sellmeier equations [14]. Both end faces of the crystal are antireflection-coated to avoid residual etalons, and one of them is angle-polished (0.7°). The crystal is housed in an oven of which the temperature can be stabilized within ±0.1 °C ranged from room temperature to 200 °C. The VBG (Ondax 114-er217-001) used as an end mirror in the cavity is highly reflective at the signal wavelength and the peak reflectivity is specified as 97% with a bandwidth of 0.8 nm. Facets of the VBG are antireflection-coated and angle-cut (0.5°) in order to reduce optical losses and minimize etalon effects. The VBG substrate, in a dimension of 2 × 2 × 2 mm^3, is covered with indium foil and mounted in copper carriers. A dichroic mirror M separates the generated idler output from the residual pump and signal radiation. In addition to the VBG-OPO, by replacing the VBG with a mirror that is highly (R>99.9%) or partial reflective (R=98.5%) at the signal wavelength, a HR-OPO and an OC-OPO are also demonstrated in our experiment, respectively.

III. Results and Discussions

To investigate the thermal effect of the VBG, we divided the heat dissipation of VBG into three cases. In the first case, the VBG was mounted in a small copper block which served as a heat sink. The small copper block is a circular plate with 12.7 mm in diameter and 4.1 mm in thickness; in the second case, the small copper was replaced by a larger one, which was a circular plate in diameter of 25.4 mm and in thickness of 7 mm; in the third case, a fan was added to the second case, providing air current across the front surface of the copper block. A square hole in the center of each copper block is disposed to fix the VBG. The ability of dissipating

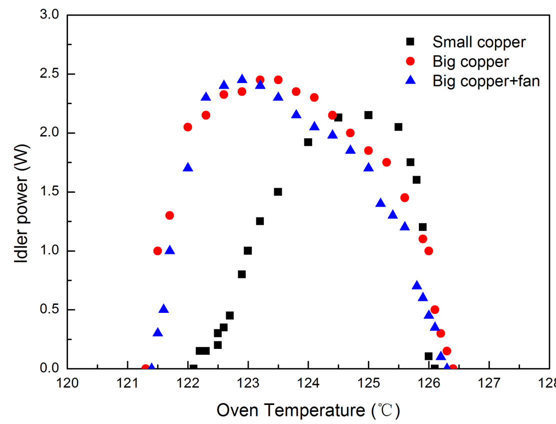

Fig. 2. Idler power versus oven temperature at a pump power of 21 W.

heat from VBG is enhancive from the first to three cases. We scanned the temperature of the MgO:PPLN to find out an optimal operating point at a fixed pump power of 21 W. The output idler power as a function of oven temperature is plotted in Fig. 2. The temperature tuning curves are visibly asymmetric, similar to behaviors that have been reported in high power second harmonic generation, which stems from the residual absorption of fundamental power in the nonlinear crystal [15], [16]. Moreover, for a fixed pump power, the maximum idler power is achieved at an oven temperature of 125.0 °C in the first case, while this temperature drops to 122.9 °C in the third case. In our experiment, these are attributed to the joint effects of the thermal load on nonlinear crystal as well as on VBG.

As previously reported, a minute absorption of the resonant radiation results in a temperature rising, and hence a redshift of phase-matching wavelength λ_p for the parametric process, or a redshift of peak reflectivity λ_v of VBG [10], [11]. From this, a physical explanation for the asymmetry of temperature tuning curves can be understood by a careful analysis on these thermal effects simultaneously. Take the first case for example, in which the thermal wavelength shift induced by the intracavity absorption is assumed to be more pronounced in VBG than that in PPLN. For the lower temperature situation, as we increase the oven temperature from T, by an amount of ΔT, the phase-matching wavelength λ_p undergoes a red-shift. Owing to the fact that λ_v is at longer wavelength than λ_p, a better overlap of them is induced and a consequent higher intracavity power. The enhanced intracavity power, however, slightly holds back the overlap of λ_v and λ_p since the redshift of λ_v is larger than that of λ_p, thus accounts for the curb in rising to the maximum power. If we further increase the oven temperature beyond the curve maximum to the right half, then λ_v is at shorter wavelength than λ_p. The decrement of intracavity power caused by the increase of oven temperature will further separate λ_v and λ_p, and consequently results in an accelerative decrease in power versus oven temperature. For the second and third cases, thermal wavelength shift of λ_p is assumed to be more pronounced than that of λ_v. Similarly, the additional change in overlap between λ_v and λ_p resulting from the joint thermal effects account for the accelerative increasing

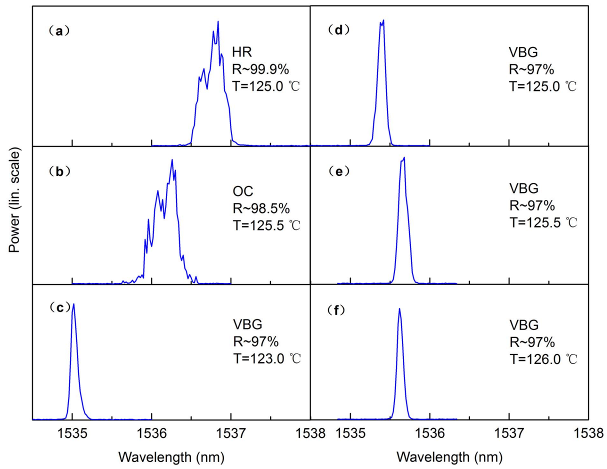

Fig. 3. Signal spectra at the maximum pump power of 21 W of the (a) HR-OPO, (b) OC-OPO, and (c-f) VBG-OPO with small copper block.

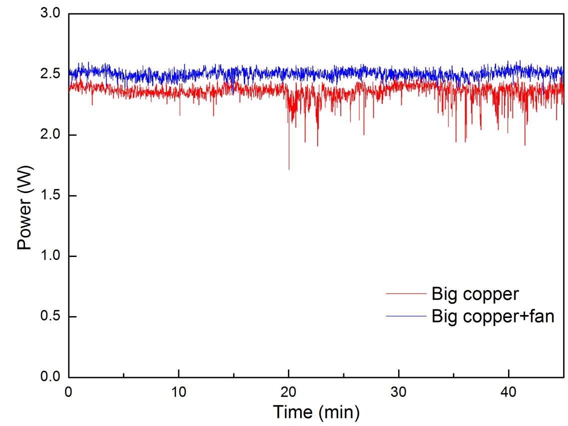

Fig. 4. Idler power stability of the VBG-OPOs. Red: VBG with big copper block; blue: VBG with big copper block and a fan.

towards the maximum power at the low temperature and curb in power decreasing at high temperature.

In our experiment, the temperature of VBG with small copper block was observed to increase from room temperature (25 °C) to 80 °C soon after the OPO started. Giving 2.9 W as output signal power, the corresponding intracavity power is ~190 W. Thus temperature increase of VBG versus intracavity power is 0.29 K/W. The absolute frequency scan rate of VBG is measured to be ~1.6 GHz/K [9], so that in the first case the peak frequency shift of VBG versus intracavity power, namely, the shift rate of λ_v, is 0.46 GHz/W. For the PPLN, it has been proved that the signal absorption solely explains the crystal heating. The temperature increase of PPLN versus intracavity power is 8 mK/W [17] and the shift of phase-matching frequency of the signal versus temperature is 47 GHz/K [14], which arrives at 0.37 GHz/W as the shift rate of λ_p. This confirms our hypothesis that the shift rate of λ_v is greater than that of λ_p in the first case. As for the VBG with big copper block in the second or third cases, the maximum temperature of VBG of 50 °C indicates a shift rate of λ_v of 0.21 GHz/W, smaller than that of λ_p. This again confirms our hypothesis and leads to the asymmetry of temperature tuning curves in Fig. 2. Therefore, the thermal wavelength shift of VBG and PPLN might compensate each other if a proper heat sink for VBG is selected, and a symmetric temperature tuning curve is then expected. The reduction of maximum power in the first case in comparison with that of the other two also implies a decrement of peak reflectivity of the VBG under high flux irradiation.

The signal spectra of the HR-OPO, OC-OPO and VBG-OPO with small copper block as heat sink are measured at the maximum pump power of 21 W and shown in Fig. 3. All these spectra are the average trace of 5 sweeps. Multimode operations were observed in both HR-OPO and OC-OPO, and the corresponding signal (idler) powers are 0.2 W (2.5 W) and 3.15 W (3.5 W), respectively. This is believed to result from the multimode pump laser and sufficient parametric gain. In VBG-OPO, the signal bandwidth (~0.12 nm) is substantially narrowed by a factor of ~4, compared with that in HR-/OC-OPO (~0.50 nm). For T=125.0 °C where maximum output power is available (2.9 W for signal, 2.15 W for idler), wavelength fluctuation is observed. This is again believed to be thermal origin due to the sufficient intracavity power [11], [12].

The idler power stability of the VBG-OPOs in the second and third cases are recorded and depicted in Fig. 4. For the third case, the VBG-OPO shows a stability of 1.4% rms in 45 minutes, and the oven temperature is fixed at 122.9 °C for a maximal idler power. For the second case, the OPO seems to experience more fluctuation after 20 minutes during the measurement at oven temperature of 123.2 °C, though no active disturbing was applied. It should be noted that the stability of VBG-OPO in the first case was not available because it was not able to keep running for more than 30 minutes.

This interesting phenomenon, can also be explained by the joint effects of PPLN and VBG. In our experiment, a passive disturbance is possibly induce by the pump instability, room temperature shift, random air current, or imperfect mechanical stability of the table. Any disturbance will induce a fluctuation on the intracavity power, thus both the VBG and PPLN experience a temperature fluctuation and hence a wavelength shift. For VBG with big copper, we should take the relative location of λ_p and λ_v and the fact that thermal wavelength shift of λ_p is more pronounced than that of λ_v into consideration. Namely, giving a certain change in intracavity intensity, whether the frequency shift of the spectral gain peak is compensated or enlarged by the shift of the VBG's reflection peak. It is concluded that power fluctuation tends to be compensated at high temperature while exacerbates at low temperature. The conclusion is opposite for VBG-OPO with small copper block. In our experiment, the VBG-OPO in second case operated at a temperature of 123.2 °C for the maximum power at the first 20 minutes, and somehow shifted to a lower temperature, so that the power fluctuation exacerbates in the last 25 minutes. As for the VBG with small copper block, due to the poor heat dissipation, a small fluctuation in power can lead to a great change of thermal effect in VBG. In this way, the VBG with small copper is easily shift into thermal fluctuation-exacerbation regime, and

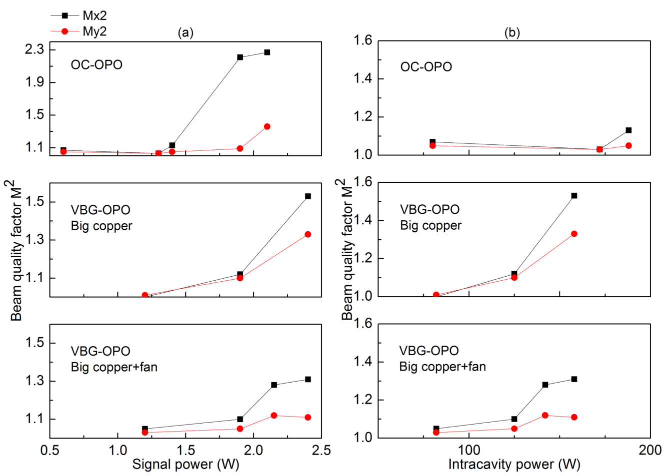

Fig. 5. Quality factors of the signal beam versus signal power (a) and intracavity power (b).

even stop operating after a few large fluctuation. Furthermore, once the working VBG-OPO with small copper is blocked for several seconds, realignment is needed to restart the OPO, indicating that such a strong thermal effect not only induce a thermal frequency shift, but also change the optical paths.

The quality factors of the signal beam were measured at different output power in three configurations respectively, as shown in Fig. 5(a). Evidently, the beam quality dependence on power indicates a thermal origin. For a certain output signal power, the OC-OPO generally shows a worse beam quality than the other two configurations. This is attributed to the thermal lens effect of PPLN due to intracavity power absorption. If a constant reflectivity of the VBG is assumed, intracavity powers of the OPOs are available, which helps to verify the impact of VBG on beam quality. This is reasonable since the VBG is located at the second waist of signal, which is large ($\sim$290 μm) in order to minish the thermal induced reflectivity shift of VBG [10]. As given in Fig. 5(b), considering a certain intracavity power, namely, an equal thermal effect of PPLN, the OC-OPO generally gives a better beam quality than the other two configurations. Therefore, it can be concluded that the VBG leads to the degradation of beam quality, mainly because of the thermal induced surface deformation [10]. This holds true even if we take the thermal induced reflectivity reduction of VBG into consideration. The inferior of beam quality in x-direction compare to that in y-direction keeps the same even though we rotated the VBG by 90°, and this is believed to be related with the pump beam quality and the thermal dissipation of the PPLN.

IV. Conclusion

In conclusion, VBGs with thermal effects in varied strengths are employed as end-mirrors of the OPOs in our experiment, allowing detailed studies on the joint thermal effects with PPLN. Results show that the VBG do impose a spectral narrowing and locking effect on the resonant signal, while the thermal distortion of VBG degrades beam quality. The most interesting result is that the joint thermal effects of VBG and PPLN can lead to either thermal self-locking or thermal fluctuation-exacerbation, determined by the relative strength of their thermal effects and the oven temperature. These are considerable for practical applications involving VBGs with high diffraction efficiency in high-power OPOs. A proper oven temperature takes advantage of the thermal self-locking effect, and relaxes the requirements for thermal and mechanical stability of the crystals and cavities. Realignment is necessary after a great change of intracavity intensity. Temperature control of the VBG is also recommended. In future studies, more work needs to be done to get a comprehensive and quantitative understanding of the joint thermal effects.

References

[1] E. V. Kovalchuk *et al.*, "High-resolution Doppler-free molecular spectroscopy with a continuous-wave optical parametric oscillator," *Opt. Lett.*, vol. 26, no. 18, pp. 1430–1432, 2001.

[2] S. M. Cristescu, S. T. Persijn, S. te Lintel Hekkert, and F. J. M. Harren, "Laser-based systems for trace gas detection in life sciences," *Appl. Phys. B*, vol. 92, no. 3, pp. 343–349, 2008.

[3] P. G. Mickelson *et al.*, "Repumping and spectroscopy of laser-cooled Sr atoms using the $(5s5p)^3P_2$-$(5s4d)^3D_2$ transition," *J. Phys. B, Atom., Molecular Opt. Phys.*, vol. 42, no. 23, pp. 235001-1–235001-4, 2009.

[4] S. E. Bisson, K. M. Armstrong, T. J. Kulp, and M. Hartings, "Broadly tunable, mode-hop-tuned cw optical parametric oscillator based on periodically poled lithium niobate," *Appl. Opt.*, vol. 40, no. 33, pp. 6049–6055, 2001.

[5] A. K. Y. Ngai, S. T. Persijn, G. von Basum, and F. J. M. Harren, "Automatically tunable continuous-wave optical parametric oscillator for high-resolution spectroscopy and sensitive trace-gas detection," *Appl. Phys. B*, vol. 85, nos. 2–3, pp. 173–180, 2006.

[6] B. L. Volodin, S. V. Dolgy, E. D. Melnik, E. Downs, J. Shaw, and V. S. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," *Opt. Lett.*, vol. 29, no. 16, pp. 1891–1893, 2004.

[7] B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Tunable single-longitudinal-mode ErYb:glass laser locked by a bulk glass Bragg grating," *Opt. Lett.*, vol. 31, no. 11, pp. 1663–1665, 2006.

[8] Y. He and B. J. Orr, "Narrowband tuning of an injection-seeded pulsed optical parametric oscillator based on a self-adaptive, phase-conjugate cavity mirror," *Opt. Lett.*, vol. 29, no. 18, pp. 2169–2171, 2004.

[9] M. Vainio, M. Siltanen, T. Hieta, and L. Halonen, "Continuous-wave optical parametric oscillator based on a Bragg grating," *Opt. Lett.*, vol. 35, no. 10, pp. 1527–1529, 2010.

[10] T. Waritanant and T.-Y. Chung, "Influence of minute self-absorption of a volume Bragg grating used as a laser mirror," *IEEE J. Quantum Electron.*, vol. 47, no. 3, pp. 390–397, Mar. 2011.

[11] S. Tjörnhammar, B. Jacobsson, V. Pasiskevicius, and F. Laurell, "Thermal limitations of volume Bragg gratings used in lasers for spectral control," *J. Opt. Soc. Amer. B*, vol. 30, no. 6, pp. 1402–1409, 2013.

[12] X. Zhang, J. Feng, B. Xiong, K. Zou, and X. Yuan, "Diffraction of volume Bragg gratings under high flux laser irradiation," *Opt. Exp.*, vol. 22, no. 7, pp. 8291–8297, 2014.

[13] S. Guha, F.-J. Wu, and J. Falk, "The effects of focusing on parametric oscillation," *IEEE J. Quantum Electron.*, vol. 18, no. 5, pp. 907–912, May 1982.

[14] O. Gayer, Z. Sacks, E. Galun, and A. Arie, "Temperature and wavelength dependent refractive index equations for MgO-doped congruent and stoichiometric $LiNbO_3$," *Appl. Phys. B*, vol. 91, no. 2, pp. 343–348, 2008.

[15] S. C. Kumar, G. Samanta, and M. Ebrahim-Zadeh, "High-power, single-frequency, continuous-wave second-harmonic-generation of ytterbium fiber laser in PPKTP and MgO:sPPLT," *Opt. Exp.*, vol. 17, no. 16, pp. 13711–13726, 2009.

[16] S. Ghavami Sabouri, S. Chaitanya Kumar, A. Khorsandi, and M. Ebrahim-Zadeh, "Thermal effects in high-power continuous-wave single-pass second harmonic generation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 5, Sep./Oct. 2014, Art. no. 7500210.

[17] M. Vainio, J. Peltola, S. Persijn, F. J. M. Harren, and L. Halonen, "Thermal effects in singly resonant continuous-wave optical parametric oscillators," *Appl. Phys. B*, vol. 94, no. 3, pp. 411–427, 2009.