Current Optics and Photonics
Vol. 3, No. 1, February 2019, pp. 33-39

ISSN: 2508-7266(Print) / ISSN: 2508-7274(Online)
DOI: https://doi.org/10.3807/COPP.2019.3.1.033

Development of a Mid-infrared CW Optical Parametric Oscillator Based on Fan-out Grating MgO:PPLN Pumped at 1064 nm

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(Received October 11, 2018 : revised November 15, 2018 : accepted November 27, 2018)

We report development of a frequency-stabilized mid-infrared continuous-wave (cw) optical parametric oscillator (OPO) based on a fan-out grating MgO:PPLN crystal pumped at 1064 nm. The OPO resonator was designed as a pump-enhanced standing-wave cavity that resonates to the pump and signal beams. To realize stable operation of the OPO, we applied a modified Pound-Drever-Hall technique, which is a well-known method for powerful laser frequency stabilization. Tuning a poling period of the fan-out grating of the crystal allows wavelength-tunable OPO outputs from 1510 nm to 1852 nm and from 2500 nm to 3600 nm for signal and idler beams, respectively. At the idler wavelengths of 2500 nm, 3000 nm and 3500 nm, we achieved more than 50 mW of output powers at a pumping power of 1.1 W. The long-term stability of the OPO was confirmed by recording the power and wavelength variations of the idler for an hour.

Keywords : Optical parametric oscillator, Mid-infrared laser, Laser power stabilization
OCIS codes : (190.4410) Nonlinear optics, parametric processes; (190.4970) Parametric oscillators and amplifiers; (140.3070) Infrared and far-infrared lasers

I. INTRODUCTION

Because of the excellent wavelength tuning ability, the development of optical parametric oscillators (OPOs) which can obtain the coherently tunable light sources from ultraviolet (UV) to mid-infrared (mid-IR) wavelengths have been the subject of many reports [1-7]. In particular, development of continuous-wave (cw) OPOs based on periodically poled (PP) nonlinear crystals made of $KTiOPO_4$ (KTP), $RbTiOAsO_4$ (RTA) and $LiNbO_3$ (LN) have been actively studied to obtain IR light sources which are required in a variety of applications such as optical radiometry, biological spectroscopy and frequency metrology [2-7]. For example, 532 nm pumped cw OPOs based on PPKTP can produce the near-IR radiation from 1037 nm to 1093 nm depending on the temperature and cavity length [2]. Using only very low threshold pump power approximated to be 300 mW, Bae *et al.* obtained widely tunable cw operation of singly resonant OPOs based on 5% MgO-doped PPLN (MgO:PPLN) corresponding to signal from 770 to 890 nm and idler from 1330 to 1680 nm, respectively [3]. Fève *et al.* achieved an experimental wavelength tuning curve from 1.5 μm to 3.5 μm by using a cylindrical PPKTP crystal pumped at 1064 nm [4]. Carleton *et al.* obtained 65 mW of idler output power from cw OPOs based on PPRTA and the tunable idler wavelength from 3.44 μm to 3.55 μm [5]. Bosenberg *et al.* experimentally studied output characteristics of cw OPOs based on PPLN pumped at 1064 nm, while the signal output was tunable from 1.45 μm to 1.62 μm in the near-IR range and idler output was tunable from 3.11 μm to 3.98 μm in the mid-IR range [6]. At 1 W of 1064 nm pump power, 70 mW of output power were achieved from cw OPOs based on PPLN, while the tuning of idler in a

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mid-IR range was recorded up to 4.02 μm by Stothard *et al.* [7].

Recently, mid-IR bands are called fingerprint regions of molecules and provide important information for remote sensing applications based on molecular spectroscopy [8-21]. In particular, optical parametric light sources such as solid state lasers, fiber lasers, interband cascade lasers (ICLs) and quantum cascade lasers (QCLs) have been actively used in spectroscopic studies to measure the strong absorption lines of molecules for gas trace [10, 11]. The mid-IR band has an outstanding potential in the medical sciences because it can detect health information in a non-invasive measurement of the radiated signals resulting from human bodies. In addition, research findings have shown that the induced collateral thermal damage caused by the use of a mid-IR laser in surgery is less than the damage resulting from shorter wavelengths [12-15]. The mid-IR band is considered to be important in defense science because it is not only able to observe very distant objects through air transmission windows, but it is also easy to monitor large areas at night by measuring radiation from the Earth's surface [16]. In addition, mid-IR is actively studied in the field of planetary observation because it is useful for detecting radiation due to earthquakes and volcanoes or for measuring resource exploration such as the water on the moon [17-20].

In order to successfully realize the above mentioned applications, a mid-IR light source with high wavelength accuracy and wide tunability should be secured. In this paper, we report the development of wavelength-stabilized and widely tunable mid-IR cw OPOs based on fan-out grating PPLN pumped at 1064 nm. By changing the poling period of the crystal, we could measure the wavelength of the signal and the idler from 1510 nm to 1852 nm and from 2500 nm to 3600 nm, respectively. Finally, we recorded the long term stability of output power and wavelength of the idler for 1 hour and we confirmed that the standard deviation of the idler output wavelength of the OPO was less than 1 pm.

II. EXPERIMENTAL SETUP

The schematics for the experimental setup of the cw OPO with PPLN crystal pumped at 1064 nm is shown in Fig. 1. The cw diode pumped solid state (DPSS) Nd:YAG laser (Mephisto, Coherent) corresponds to the pump light source which has the center wavelength of 1064 nm and a linewidth of 1 kHz. The maximum power of pump light source with single frequency output that was available was approximated to be 1.1 W. The optical isolator was used for preventing unwanted optical feedback which consist of back reflection and scattering of pump laser resulting from various optical components. To reduce the threshold power for starting the lasing of the OPO, we designed a pump-enhanced (PE) linear cavity which resonates for signal and pump beams. The cavity mirrors corresponding to input mirror, M1, and output mirror, M2, which have high reflectivity for pump and signal beams, comprise the PE linear cavity [21, 22]. M1 mirror has high reflectance ($R > 99\%$) for the signal and 5% transmittance for the pump but high transmittance ($T > 85\%$) for the idler. M2 mirror has 2% transmittance for the signal and high reflectance ($T > 99\%$) for the pump but a high transmittance ($T > 85\%$) for the idler. Those mirrors are plano-concave with a radius of curvature of -50 mm and are made on zinc selenide (ZnSe) substrates. The back of the M1 and M2 mirrors have wedge cut of 1 degree because it is

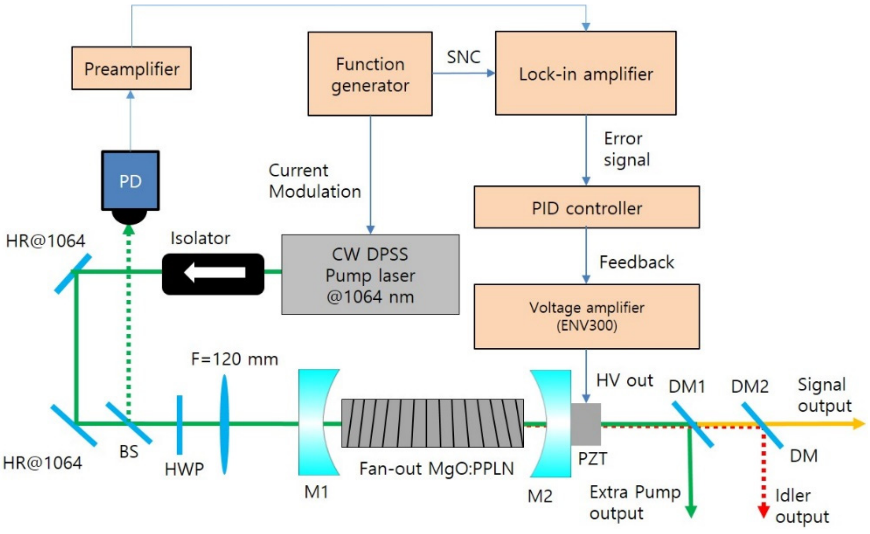

FIG. 1. The experimental schematics of mid-IR cw OPOs based on fan-out grating PPLN: HR@1064, high reflectivity mirror at 1064 nm; BS, beam splitter; HWP, half-wave plate; F, focal length; M, mirror; PZT, piezo-actuator; DM, dichroic mirror; BSP, beam sampler; PD, photodiode.

difficult to cover all of the IR wavelength band in which anti-reflection (AR) coating is expected. The nonlinear crystal used in this OPO setup was a PPLN with a fan-out grating [23]. This crystal is available for the continuous wavelength tunings because the period of the crystal can be changed continuously, and it is possible to change the wavelength of the OPO faster than the method of wavelength tuning by changing the temperature of the multi-channel grating on the oven. The dimension of the PPLN crystal used was 40 mm × 10 mm × 0.5 mm. They have continuously variable poling periods from 28 μm to 32 μm. During the experiment, the temperature of the crystal was maintained at 75°C by the oven. With manual translation for varying the poling period of the crystal, the cavity alignment of mid-IR cw OPO can be distorted with the poor wavelength repeatability, so we installed the fan-out crystal on an automated linear stage. In order to match the resonator mode inside the OPO cavity, collimated pump laser was focused by a plano-convex lens (F1) having a focal length of 120 mm. The beam waist experimentally measured by optical beam profiler (Beam'R2, Dataray Inc.) at the focal point was about 78.5 μm. To make pump, signal, and idler beams split into the different optical paths, we used two dichroic mirrors (DMs). DM1 and DM2 after produced light passes through the OPO cavity. Those dichroic mirrors were used to separate the pump and the signal beams, respectively, and the idler beam was designed to transmit straight. To measure the wavelength of the produced idler beam simultaneously with output power measurement, a very weak sampling light is divided by the beam sampler (BPS). However, since the reflection and transmission ratios of the dichroic mirrors are not perfect, filters were used to make the signal and idler beams more distinct and to remove light of other unwanted wavelengths. Although not shown in Fig. 1, the wavelength and power of final output signal and idler beams were measured using a Fourier transform infrared (FTIR) based spectrometer (OSA205C, Thorlabs) and a power meter (Labmax_Top, Coherent), respectively.

To optimize the OPO cavity length, we estimated geometric cavity length from the focusing parameter of $\xi = L_c/b$, where L_c is the length of the PPLN crystal and b is the confocal parameter. When the empirical optimal value of $\xi = L_c/b$ is 2.0 [14], the confocal parameter b should be 20 mm in our setup with a crystal length of 40 mm. The effective cavity length induced from confocal parameter is $L_{eff} = L_{geo} - L_c + L_c/n_p$, where n_p is the refractive index at pump wavelength in the PPLN. n_p is 2.23 and the L_{eff} confirmed from Ref. [3] is 98 mm. According to the above calculation, L_{geo} should be approximately 120 mm. With $b = 20$ mm, the expected beam waist of the optimized signal wave to the OPO cavity was 73.5 μm which can be calculated by a simple equation from Ref. [3]. This value is very similar to the above-mentioned experimentally optimized beam waist of the incident pump laser at the focal point inside the cavity.

While the OPO is oscillating above threshold pump power, cavity locking devices must be configured to keep the resonator stable. So we used a modified Pound-Drever-Hall (PDH) method, which is well-known as a cavity stabilization technique, to overcome the cavity fluctuation induced from the unwanted perturbations [24]. The diagram of the modified PDH technique for stabilization of the cw OPO system is depicted in Fig. 1. The frequency of the pump laser was piezo-electrically modulated by a 2 kHz rectangular signal with peak-to-peak 400 mV which was generated from the external function generator. This modulation is possible by externally controlled current modulation, which is a unique function of our pump laser. The lock-in amplifier is used for demodulation of the reflected pump to generate an error signal. And the PID controller adjusts the feedback signal to the voltage amplifier, which changes the high voltage (HV) applied to the piezo actuator (PZT).

III. EXPERIMENTAL RESULTS

Based on the PPLN crystal, the wavelength tuning capability of a frequency stabilized mid-IR cw OPO was measured in steps of the idler wavelength, which is actually the result of changing the poling period of the crystal. During the measurement, the temperature of the crystal was maintained at about 75°C and the pump power was 660 mW. The period of the PPLN was adjusted by moving the programmed automation linear stage system from 28 μm to 32 μm. The signal and idler beams were delivered to the FTIR spectrometer through the InF_3 fiber, allowing the wavelength to be measured as the period changed.

Figure 2 is the combined idler wavelength spectra

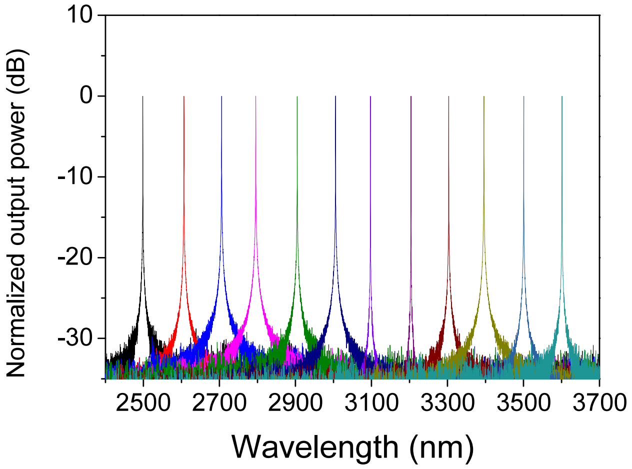

FIG. 2. The combined idler wavelength spectra recorded by FTIR spectrum analyzer. The poling period of the fan-out grating MgO:PPLN crystal was controlled by the automated linear stage system. Each single spectrum was measured from 2500 nm to 3600 nm in steps of 100 nm.

recorded by the FTIR spectrum analyzer, while the output wavelength produced from the cw OPO is stabilized by a modified PHD technique. Each single spectrum was normalized for direct comparison between all idler spectra and was measured from 2500 nm to 3600 nm in steps of 100 nm. Though not inserted into the data in this paper, the signal radiation is generated from 1510 nm to 1852 nm at the same time as the idler radiation. From the measured results, we can confirm that the wide wavelength tuning was successfully achieved and the idler wavelength tuning spectra were measured close to 30 dB compared to the background noise corresponding to the limit of the FTIR spectrometer.

As shown in Fig. 3, the measurement of output power characteristics of (a) signal at 1529 nm (square), 1648 nm (circle) and 1848 nm (triangle), and (b) idler at 2508 nm (square), 3003 nm (circle) and 3500 nm (triangle) were performed in steps of pump power. For the signal, when the cw OPO was pumped at 1.1 W, the maximum output power was approximated to 140 mW, 220 mW and 100 mW at 1529 nm, 1648 nm and 1848 nm, respectively. In comparison, for the idler in the same experimental condition, the maximum output powers of 57 mW, 62 mW and 64 mW were measured at 2508 nm, 3003 nm and 3500 nm, respectively. When we compare the output powers of signal and idler beams with the increase of the pump power, it can be seen that the idler increases linearly, but the signal is more distorted than the idler at the higher pump power above 0.6 W as shown in Fig. 3(a). These results indicate that there is a dependence on the pump power input, which is explained by the variation of the resonator conditions due to the thermal effect [3]. It is a phenomenon that occurs when a part of the pump power is absorbed linearly, so that the effect becomes stronger as the pump power is increased. Also, because our OPO cavity is resonant at the signal wavelength, the distortion of the signal is more clearly evident due to repeated change by the thermal effect, compared to the idler passing directly after the parametric light generation [3, 25].

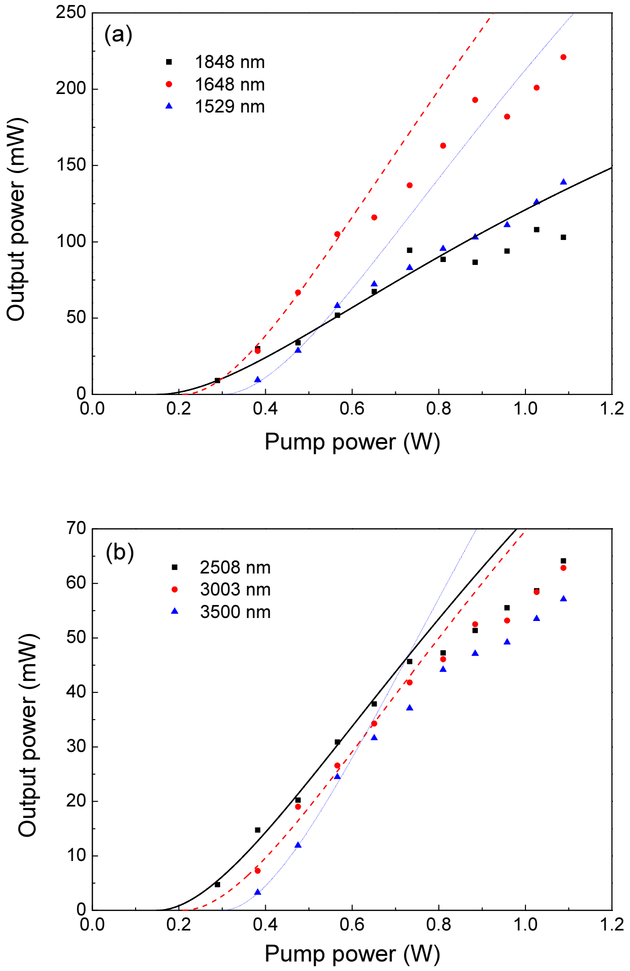

FIG. 3. The results of output power characteristics of (a) signal at 1529 nm (square), 1649 nm (circle) and 1848 (triangle) nm and (b) idler at 2508 nm (square), 3003 nm (circle) and 3500 nm (triangle) performed in steps of pump power. The maximum output powers of 57 mW, 62 mW and 64 mW were measured at 2508 nm, 3003 nm and 3500 nm. Threshold pump powers were approximated to be 150 mW, 210 mW, and 300 mW at 2508 nm, 3003 nm and 3500 nm, respectively.

Theoretical calculations of the conversion efficiency for a doubly resonant cw OPO with a Gaussian beam were fitted with the measured data to estimate the oscillation threshold of the OPO [26]. The conversion efficiency and the experimental results differ considerably as the pump power increases due to the thermal effect. The fittings were performed for a pump power of less than 0.6 W where the thermal effect is not strong. From the theoretically performed fitting results, we can find the point at which the output power becomes zero and estimate the oscillation threshold of the OPO. Solid, dashed, and dotted lines represent theoretical fitting lines to estimate oscillation threshold values at 1848 nm, 1648 nm, and 1529 nm, for signal wave, and at 2508 nm, 3003 nm, and 3500 nm, for idler wave. The oscillation threshold values of the cw OPO at 2508 nm, 3003 nm and 3500 nm were approximated to be 150 mW, 210 mW, and 300 mW, respectively.

As mentioned above, the mid-IR wavelength is the range of the light source that must be secured in terms of useful applications such as spectroscopy, gas sensing, military science, medical science and planet observation. Therefore, it is urgent to secure the power and wavelength stability of the mid-IR light source for successful applications in a variety of fields.

Figure 4 shows the measurement of the idler output power of the cw OPO pumped at 1.1 W while the OPO cavity length is locked on resonance by a modified PDH [24]. The measurement was performed for exactly 1 hour and the interval of the measurement was 1 second. The average value of the idler output power recorded for 1 hour was approximately 44.15 mW, 63.36 mW and 58.81 mW at 2507.68 nm, 3003.24 nm and 3499.63 nm, respectively.

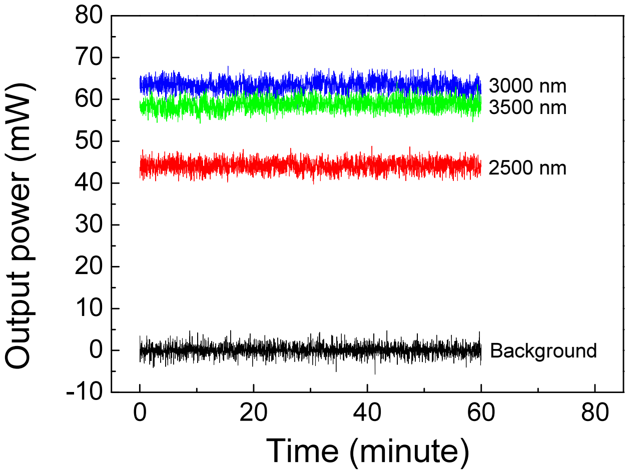

FIG. 4. The results of stability measurement for idler output of the cw OPO in steps of time. The output powers of the idler were recorded for 1 hour while the OPO cavity length is locked on resonance by modified PDH. The derived standard deviation of the idler output powers is approximately 1.29 mW, 1.34 mW, and 1.34 mW at 2507.68 nm, 3003.24 nm and 3499.63 nm, respectively, indicating a long term stability of less than 3%.

We also derived the standard deviation of the idler output power from the measured data for 1 hour, which is approximately 1.29 mW, 1.34 mW, and 1.34 mW at 2507.68 nm, 3003.24 nm and 3499.63 nm, respectively. These results indicate power stability of less than 3% for one hour, which is comparable to the stability of the cw OPOs previously reported in other papers [27-29]. For a PE cw OPO based on multi-grating PPLN pumped at 810 nm, the idler at 2740 nm showed the output power stability of about 2.6% [27]. The PE cw OPO developed by using PPRTA reported a level of output power stability of 5% [28]. The idler output at 1097 nm produced from fan-out designed MgO:sPPLT pumped at 532 nm was approximately 2.6% stable resulting from the measurement in one hour [29]. The noise spectrum on the baseline in Fig. 4 is the background noise of the air-cooled thermopile sensor (LM3, Coherent) used in the measurements and the measured standard deviation of the background noise was about 1.1 mW. This indicates that the output power stability of the cw OPO is almost identical to the background noise of the detector used for the measurement. From the results, we confirmed stable operation of the OPO by using the PDH technique while preventing unwanted factors.

In addition, we measured the wavelength stability of idler output as shown in Fig. 5, which is the result simultaneously performed with measurements for output power stability shown in Fig. 4. By separating the very weak field due to the idler sampling with the BSP and sending the light through the optical fiber to the FTIR spectrometer, we were able to measure the wavelength characteristics at the same time as the output power measurement. The accuracy and precision of the FTIR spectrometer used in this experiment were set to ±1 ppm and 0.2 ppm, which correspond to ±3 pm and 0.6 pm at 3000 nm. Figure 5 shows the results for wavelength variation of the idler measured for 1 hour while cw OPO operated with 1.1 W of pump power. The experiments were performed at center wavelengths of (a) 2057.68 nm, (b) 3003.24 nm and (c) 3499.63 nm where the standard deviations of the measured three wavelengths were approximated to be 0.33 pm, 0.48 pm, and 0.22 pm, respectively. At 3500 nm, when wavelength stability is converted to frequency, it represents a frequency stability of approximately 10 MHz, and is superior to the frequency stability reported in other reports corresponding to tens or hundreds of MHz [27-30]. These results mean that the wavelength fluctuation of the OPO is less than 1 pm because the cavity length is locked on the resonance with highly stable condition by the modified PDH technique [24]. Comparing the results in Figs. 4 and 5, we can confirm that there is no mode-hopping due to the external perturbations and thermal effect [3].

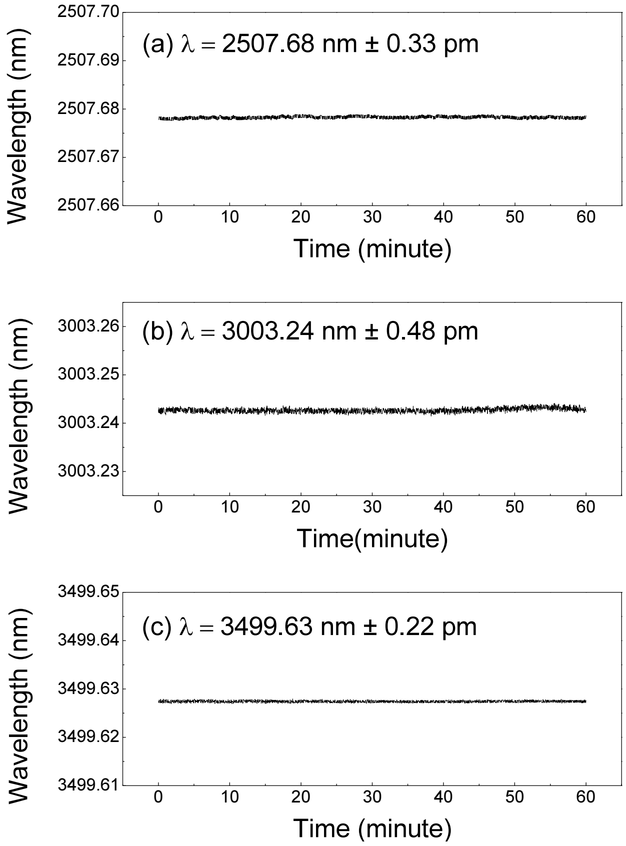

FIG. 5. The measured wavelength stability of idler beam corresponding to coincidently performed with output power measurement in steps of time. The standard deviations of the measured wavelength data at (a) 2057.68 nm, (b) 3003.24 nm and (c) 3499.63 nm were approximated to be 0.33 pm, 0.48 pm, and 0.22 pm, respectively.

IV. CONCLUSION

The mid-IR band is known as an important wavelength band for studying in a variety of remote sensing applications such as medical science, defense science, gas sensing, and planetary observation. To complete above-mentioned applications successfully, the performance of a mid-IR light source must be evaluated by measurement of power and wavelength stability. Moreover, since the wavelength range of mid-IR to be covered is relatively wide, it is necessary to secure a light source with good wavelength tunability. For these reasons, we tried to develop a wavelength tunable light source corresponding to mid-IR cw OPO based on fan-out grating PPLN crystal pumped at 1064 nm. In order to overcome power fluctuations and wavelength instability resulting from external perturbation and thermal effects, we applied the modified PDH technique, which locks the OPO cavity on resonance. We measured the tuning of the wavelength of the idler continuously from 2500 nm to 3600 nm in steps of 100 nm, which was performed by changing the poling period of the crystal from 28 μm to 32 μm. We designed a pump-enhanced cavity to reduce the operating threshold of the OPO to hundreds of mW. In this experiment, the lowest oscillation threshold of the OPO was measured to be 289 mW. From the measurement of the idler output power characteristics according to the pump power, it was confirmed that the signal changes more sensitively than the idler due to thermal effects. When the cw OPO was pumped to 1.1 W, idler output powers of cw OPOs at 2508 nm, 3003 nm, and 3500 nm corresponded to 57 mW, 62 mW and 64 mW, respectively. To measure the stability of OPO locked with modified PDH technique, the output power and wavelength variations in steps of 1 second were recorded for 1 hour. The long-term variation resulting from measured output power is a comparable level to the background noise of the thermopile detector used. From the results of the recorded wavelengths by FTIR spectrometer, it was confirmed that the standard deviation of measured wavelengths for 1 hour was less than 1 pm. These results conclude that our cw OPO can be operated with very high stability. We believe that our results will be very helpful in developing and stabilizing mid-IR cw OPOs for a variety of applications such as biochemistry, remote sensing, environmental science and spectroscopic metrology.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2015M1A3A3A03027287, Development of performance evaluation technologies for gamma-ray, neutron and mid-IR spectrometer) and in part by the Korea Research Institute of Standards and Science project ‘Establishment of National Physical Measurement Standards and Improvements of Calibration/Measurement Capability’, grants 18011043 and 18011033.

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