Chin. Phys. B Vol. 20, No. 11 (2011) 114215

Low noise, continuous-wave single-frequency 1.5-μm laser generated by a singly resonant optical parametric oscillator*

Liu Jian-Li(刘建丽), Liu Qin(刘 勤), Li Hong(李 宏), Li Peng(李 鹏), and Zhang Kuan-Shou(张宽收)†

State Key Laboratory of Quantum Optics and Quantum Optics Devices, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, *China*

(Received 9 February 2011; revised manuscript received 4 May 2011)

We report a low noise continuous-wave (CW) single-frequency 1.5-μm laser source obtained by a singly resonant optical parametric oscillator (SRO) based on periodically poled lithium niobate (PPLN). The SRO was pumped by a CW single-frequency Nd:YVO_4 laser at 1.06 μm. The 1.02 W of CW single-frequency signal laser at 1.5 μm was obtained at pump power of 6 W. At the output power of around 0.75 W, the power stability was better than ±1.5% and no mode-hopping was observed in 30 min and frequency stability was better than 8.5 MHz in 1 min. The signal wavelength could be tuned from 1.57 to 1.59 μm by varying the PPLN temperature. The 1.5-μm laser exhibits low noise characteristics, the intensity noise of the laser reaches the shot noise limit (SNL) at an analysis frequency of 4 MHz and the phase noise is less than 1 dB above the SNL at analysis frequencies above 10 MHz.

Keywords: singly resonant optical parametric oscillator, 1.5-μm laser, single-frequency operation, low noise

PACS: 42.65.Yj, 42.60.Mi, 42.72.Ai **DOI:** 10.1088/1674-1056/20/11/114215

1. Introduction

High power, low noise, continuous-wave (CW) laser sources at 1.5 μm with single-frequency operation are attractive owing to their applications, such as telecommunication, high-resolution spectroscopy, laser radar and environmental monitoring, especially in the scientific researches of quantum information and quantum optics. Up to now, various methods have been employed to obtain a 1.5-μm laser. The diode-pumped all-solid-state CW 1.5-μm lasers with multi-longitudinal-mode had been demonstrated in Er, Yb-codoped crystals, 250 mW of output power with 26.8% efficiency for $YCa_4O(BO_3)_3$,[1] and output power of 1 W with slope efficiency of 35% for $YAl_3(BO_3)_4$.[2] Owing to the poor optical quality and serious thermal lensing effect of the Er doped laser medium, it is difficult to obtain high power and robust CW single-frequency 1.5-μm lasers. High power and single-frequency operated lasers around 1.5 μm had been obtained by master oscillator fibre power amplifier.[3,4] Unfortunately, this kind of lasers showed excess noises far beyond the shot noise limit (SNL)[5] which were undesirable for generation of bright squeezed state and quantum entangled state in quantum optics experiments.[6,7] Compact and tunable all-solid-state mid-infrared laser can be obtained based on an optical parametric oscillator.[8,9] Moreover, CW singly resonant optical parametric oscillators (SROs) are the stable sources of tunable single-frequency radiation. Samanta and Zadeh[10] generated more than 2 W of CW single-frequency idler with signal over 856–1404 nm using an SRO based on MgO:sPPLT pumped by an optical pumped semiconductor laser. Melkonian *et al.*[11] obtained 100 mW CW single-frequency red laser from 619 to 640 nm using an SRO based on MgO: periodically poled stoichiometric lithium tantalate (PPSLT) pumped by an all-solid-state green laser. Lin *et al.*[12] obtained 5.3 W output at 1.58 μm using an SRO based on MgO:PPLN pumped by a Yb-fibre laser. In Ref. [12], the idler at about 3.2 μm was resonant in the CW SRO cavity and the output of signal at 1.58 μm was multi-longitudinal-mode operated. However, SRO is the most efficient

*Project supported by the National Natural Science Foundation of China (Grant No. 60878003), the Science Fund for Excellent Research Team of the National Natural Science Foundation of China (Grant No. 60821004), and the National Basic Research Program of China (Grant No. 2010CB923101).

†Corresponding author. E-mail: kuanshou@sxu.edu.cn

http://www.iop.org/journals/cpb http://cpb.iphy.ac.cn

way to generate low noise CW laser around 1.5 μm of single-frequency operation.

In this study, we report a low noise CW single-frequency 1.5 μm laser generated by an SRO based on PPLN pumped by an all-solid-state CW single-frequency Nd:YVO_4 laser at 1.06 μm. The signal around 1.5 μm was resonant in the SRO cavity and 1.02-W output of signal was extracted from an output coupler with the transmission of 1.8%.

2. Experimental setup

The experimental setup is schematically depicted in Fig. 1. The SRO was pumped by a home-made CW single-frequency diode-pumped Nd:YVO_4 laser at 1.06 μm, delivering up to the output of 8 W with the measured linewidth of 2 MHz (the measure time was 1 min). The stability of the laser power was better than ± 0.5% in the given three hours. After a half-wave plat (HWP) and an optical isolator, the pump beam was injected into the SRO. By rotating the second HWP we can control the pump polarization for phase-matching in the nonlinear crystal. The nonlinear crystal is a periodically poled lithium niobate (PPLN) (Deltronic Inc) with the dimension of 30 mm(length)×10 mm(width)×1 mm(thickness). The poled period used in our experiment is 29.8 μm. Both end faces of the PPLN are triple-band antireflective coated at pump, signal and idler wavelength ($R_{1.06\ \mu m, 1.5\ \mu m, 3.3\ \mu m} < 0.25\%$). The PPLN was temperature controlled by using a temperature controller with the accuracy of ±0.005 °C (Model YG-2009B).

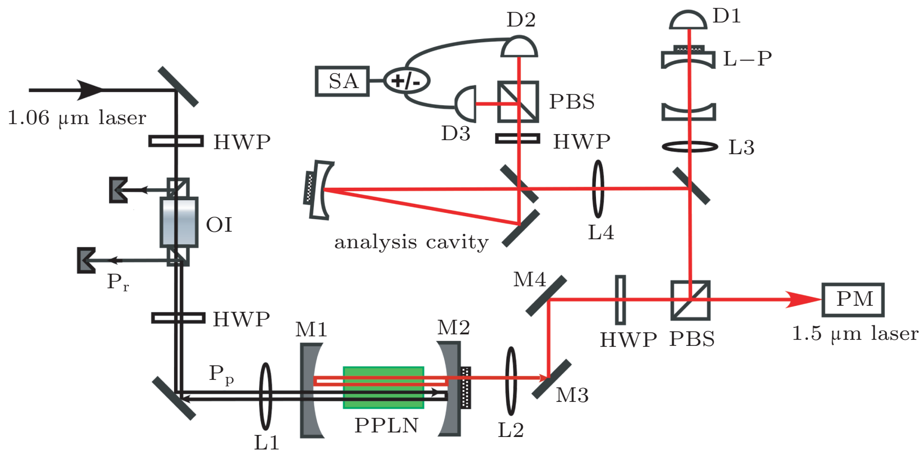

Fig. 1. (colour online) Experimental setup of the 1.5 μm laser generated by an SRO. HWP: half-wave plate; OI: optical isolator; L1–L4: lens; M1–M4: mirrors; PBS: polarizing beam splitter; PM: power meter; D1–D3: detector; F–P: confocal Fabry–Perot cavity; SA: spectrum analyser; P_p: pump beam; P_r: reflecting pump beam.

The SRO cavity was a linear cavity constructed by two curvature mirrors (M1 and M2) with radius of 26 mm. The M1 is the input coupler with high reflection for signal wavelength ($R_{1.5-1.6\ \mu m} > 99.8\%$) and high transmission for pump wavelength ($T_{1.06\ \mu m} > 99\%$). The M2 is the output coupler with partial reflection for signal wavelength ($T_{1.5-1.6\ \mu m} \sim 1.8\%$) and high reflection for pump wavelength ($R_{1.06\ \mu m} > 99.8\%$). Both mirrors are high transmission for idler around 3.3 μm. Because the host material of mirrors we used is K7 glass which is not transparent for the light at the wavelength around 3 μm, the idler generated from SRO was ignored in our experiment. To obtain high signal output power, we optimized the length of SRO cavity which was 63.5 mm. Using this cavity configuration, we find that the signal beam waist is 60 μm at 1.5 μm. The L1 is mode-matching lens used to match the 1.06 μm pump beam mode to the SRO cavity mode and a 98% mode-matching efficiency was achieved. Adjusting lens L1, the pump beam is focused on the centre of the PPLN with a beam waist of about 50 μm, resulting in optimum spatial overlap with signal beam. The L2 is collimating lens which made the SRO output to be a collimated laser beam. The M3 and M4 are high reflecting for signal wavelength. The HWP and polarizing beam splitter (PBS) were used as a variable beam splitter which divided the signal beam into two parts. The major part of the signal beam was measured by power meter (LabMax-TOP, Coherent) that is going to be used as a laser source in the future quantum optical experiment (for example, to generate a quantum entangled state at a telecommunication wavelength). The other part (about 30 mW) of signal beam was used to monitor the longitudinal-mode and measure the noises of 1.5-μm laser from SRO.

3. Experimental results and discussion

For long-term stable operation, the SRO was mounted on an invar plate and covered to isolate the air flow and the environmental vibration. When the PPLN was temperature controlled at 160 °C and the measured signal wavelength was 1.58 μm, the output power and pump depletion of SRO was measured as a function of pump power as shown in Fig. 2. The squares and circles are the measured signal output power and pump depletion, respectively. The solid line is the theoretical prediction.[13] Due to a transmission loss of about 25% between the pump laser and the SRO, a maximum pump power of 6 W was available at the input to the crystal. The CW SRO reached the oscillation threshold at 1.95 W of input pump power. The measured signal power increased steadily to the maximum value of 1.02 W at the pump power of 6 W, while the measured reflected pump power was 1.7 W and the pump depletion was 72%. We can see the pump depletion clamped at the value of 67%–80% over the entire pump range.

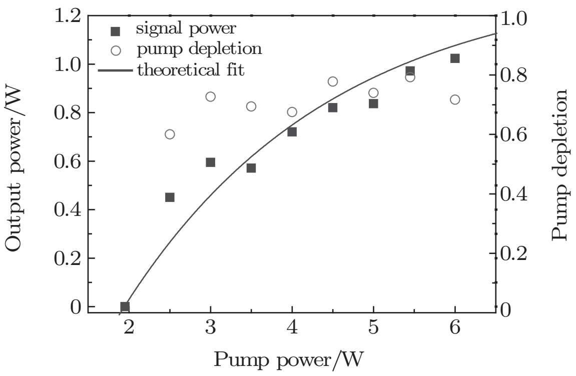

Fig. 2. Measured output power and pump depletion of SRO as a function of pump power.

When the SRO operated under the condition that the output power was the maximum, the signal output was kept on single-frequency operation but longitudinal-mode-hopping happened randomly every several minutes. Such mode-hopping are probably induced by absorption of the signal and idler in the crystal.[9,10] This absorption leads to thermally induced changes in the crystal's refractive index and to spectral clustering. However, we could adjust the SRO's condition to control the longitudinal-mode of signal that could operate stably for a long time. In the experiment, we controlled the length of SRO cavity by adjusting the offset voltage loaded on the piezoelectric transducer mounted on M2 to obtain a longitudinal-mode of signal that could operate stably without mode-hopping observed for a relative long time. In this condition, the pump threshold of CW SRO was 2.25 W. At pump power of 6 W, the measured stable single-frequency signal output power was 0.75 W and the measured reflected pump power was 2.45 W. The power stability of the signal output at the average output power around 0.75 W was measured by a power meter (LabMax-TOP, Coherent) and recorded by a computer as shown in Fig. 3. The stability of output power was better than ±1.5% and no mode hopping was observed in the given 30 min. The longitudinal mode of the signal was monitored by a scanned

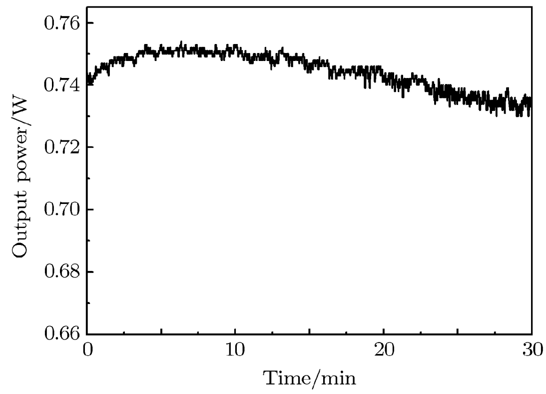

Fig. 3. Stability of the signal output at power around 0.75 W in 30 min.

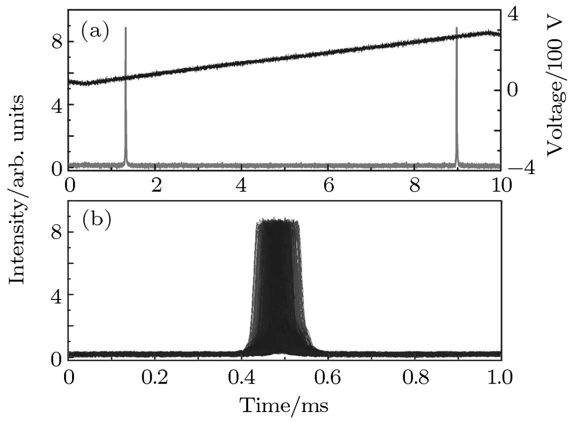

Fig. 4. Transmission intensity of the scanning Fabry–Perot interferometer.

confocal Fabry–Perot (F–P) cavity (with free spectral ranges of 750 MHz and fineness of 500) recorded by a digital storage oscilloscope (Tektronix DPO 7245). Figure 4 shows that the 1.5-μm laser is in single-frequency operation (Fig. 4(a)) and the frequency drift is better than 8.5 MHz in 1 min (Fig. 4(b)). The measured linewidth of 1.5-μm laser is 8.5 MHz (the measure time is 1 min).

The wavelength of the signal was measured using a monochromator with a resolution of 0.2 nm. The signal and idler wavelength as a function of PPLN temperature is shown in Fig. 5. The squares are the measured signal wavelength and the circles are the calculated corresponding idler wavelength at pump wavelength of 1.06 μm. The solid line is the theoretical prediction calculated by the Sellmeier equation.[14] The signal wavelength could be tuned from 1.57 μm to 1.59 μm when the temperature of the PPLN was tuned from 130 °C to 170 °C. The signal output power was about 0.75 W over the entire wavelength tuning range. The shorter signal wavelength is limited by the PPLN photorefractive effect. The PPLN should operate at high temperature for the efficient annealing of the crystal from its photorefractive effect. The longer signal wavelength is limited by the temperature controller (the efficient temperature control range is 120 °C–170 °C).

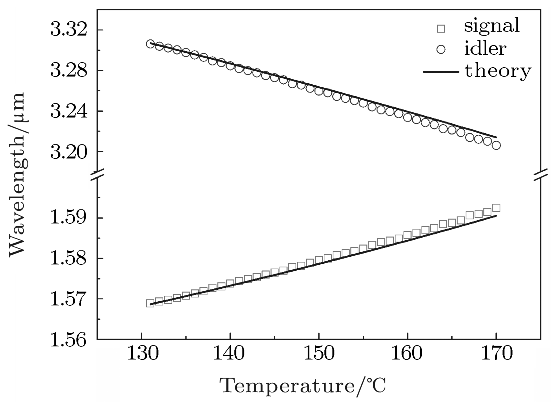

Fig. 5. Wavelength tuning range of the SRO as a function of PPLN temperature for a poled period of 29.8 μm. The diamonds are the experimental results and the solid curves represent the theoretical results according to the system.

In the quantum optical experiment, it has been shown that excess noise of pump laser source can reduce or even eliminate completely the quantum characteristics of the generated nonclassical states of light. It is important to measure and analyses the noise characteristics of the signal output at 1.5 μm emitted by the SRO. The intensity noise of the 1.5-μm laser was measured by using a balanced homodyne detection system.[15] A HWP and PBS were used to split the laser beam into two parts with equal power and detected by ETX-300 (Epitaxx) photodiodes. The noise power of detected signals were recorded by a spectrum analyser (N9010A, Agilent), as shown in Fig. 6. The sum signal gives the intensity noise of the 1.5-μm laser (the red line in Fig. 6) and the difference signal gives the SNL (the black line in Fig. 6) that was calibrated by a thermal white light source. It can be seen that the intensity noise of the 1.5-μm laser reaches SNL at the analysis frequency of 4 MHz. The phase noise of 1.5-μm laser was measured using an empty detuned ring cavity (the analysis cavity in Fig. 1) acted as a phase-to-amplitude converter.[16] The analysis cavity here we used has a finesse of 220 and bandwidth of 1.4 MHz, allowing for a complete conversion of phase to amplitude noise for analysis frequencies higher than 2 MHz.[17] We record the phase noise power at each analysis frequency by scanning the analysis cavity with triangular wave of 2 Hz. As shown in Fig. 6, the squares are the measured phase noise power of 1.5-μm laser. The phase noise is 5 dB above the SNL at the analysis frequency of 4 MHz and decreases with the increase of the analysis frequency. It is less than 1 dB above the SNL from 10 MHz to 20 MHz.

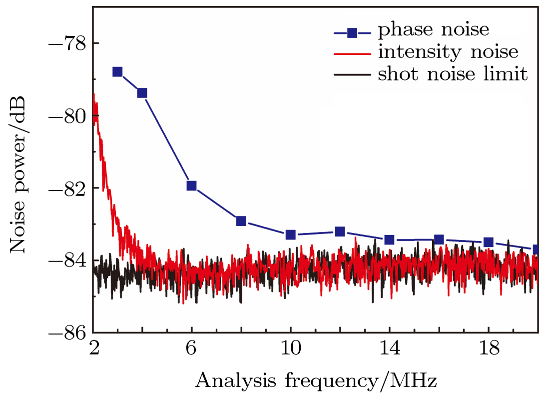

Fig. 6. (colour online) Measured intensity and phase noise power of 1.5-μm laser as functions of analysis frequency. The parameters of the spectrum analyser include: the resolution bandwidth is 100 kHz, the video bandwidth is 100 Hz and the sweep time is 1.4 s.

4. Conclusion

We have demonstrated a stable, low noise, CW single-frequency 1.5-μm laser source obtained by optical parametric process. By using a PPLN SRO that the signal around 1.5 μm was resonant in the cavity and output coupler transmission was 1.8% at 1.5 μm, 1.02 W output power of 1.5 μm signal laser was obtained with the maximum pump depletion of 80%. Thanks to the accuracy control of PPLN temperature and good vibration isolation performance of the SRO cavity, the SRO can be operated stably. At the output power of around 0.75 W, the power stability was better than ±1.5% and no mode-hopping was observed in 30 min, and the frequency stability was better than 8.5 MHz in 1 min. The signal wavelength could be tuned from 1.57 μm to 1.59 μm by tuning the PPLN temperature only. We also investigated the intensity noise and phase noise of the 1.5-μm laser. The intensity noise reaches the SNL at the analysis frequency of 4 MHz and the phase noise is less than 1 dB above the SNL at analysis frequencies above 10 MHz. This high quality 1.5-μm laser source is going to be used to generate bright squeezed state and quantum entangled state at the telecommunication wavelength which is useful for developing practical quantum telecommunication.

References

[1] Burns P J, Dawes J M, Dekker P, Piper J A, Jiang H D and Wang J Y 2004 *IEEE J. Quantum Eletron.* **QE-40** 1575

[2] Tolstik N A, Kurilchik S V, Kisel V E, Kuleshov N V, Maltsev V V, Pilipenko O V, Koporulina E V and Leonyuk N I 2007 *Opt. Lett.* **32** 3233

[3] Alegria C, Jeong Y, Codemard C, Sahu J K, Alvarez-Chavez J A, Fu L, Ibsen M and Nilsson J 2004 *IEEE Photonics Technology Letters* **16** 1825

[4] Sahu Y, Soh D, Codemard C A and Nilsson J 2005 *Opt. Lett.* **30** 2997

[5] Feng J X, Li Y M, Tian X T, Liu J L and Zhang K S 2008 *Opt. Express* **16** 11872

[6] Feng J X, Tian X T, Li Y M, Liu J L and Zhang K S 2008 *Appl. Phys. Lett.* **92** 221102

[7] Mehmet M, Steinlechner S, Eberle T, Vahlbruch H, Thüring A, Danzmann K and Schnabel R 2009 *Opt. Lett.* **34** 1060

[8] Geng Y F, Tan X L, Li X J and Yao J Q 2010 *Chin. Phys.* B **19** 114209

[9] Cui Q J, Xu Y T, Zong N, Lu Y F, Cheng X K, Peng Q J, Bo Y, Cui D F and Xu Z Y 2009 *Acta Phys. Sin.* **58** 1715 (in Chinese)

[10] Samanta G K and Zadeh M E 2010 *Opt. Lett.* **35** 1986

[11] Melkonian J M, My T H, Bretenaker F and Drag C 2007 *Opt. Lett.* **32** 518

[12] Lin S T, Lin Y Y, Huang Y C, Chiang A C and Shy J T 2008 *Opt. Lett.* **33** 2338

[13] Rosencher E and Fabre C 2002 *J. Opt. Soc. Am.* B **19** 1107

[14] Jundt D H 1997 *Opt. Lett.* **22** 1553

[15] Machida S and Yamamoto Y 1986 *IEEE J. quantum Electron.* **QE-22** 617

[16] Zhang T C, Poizat J P, Grelu P, Roch J F, Grangier P, Marin F, Bramati A, Jost V, Levenson M D and Giacobino E 1995 *Quantum Semiclass. Opt.* **7** 601

[17] Villar A S, Martinelli M and Nussenzveig P 2004 *Opt. Commun.* **242** 551