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Stable low noise 1.5 μm laser generated by a singly resonant optical parametric oscillator

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Abstract

We present a stable low noise continuous wave (CW) single frequency 1.5 μm laser generated by an output-coupled singly resonant optical parametric oscillator based on a periodically poled lithium niobate (PPLN) and a home-made CW single frequency Nd:YVO_4 laser at 1.064 μm as the pump source. A maximum signal power of 5.3 W can be obtained at a pump power of 16 W. The long-term power stability is better than $\pm$0.9% in a given two hours and the intensity noise reaches the shot noise limit for frequencies above 3 MHz. The signal wavelength can be tuned from 1.560 to 1.592 μm with PPLN temperature controlled from 120 to 180 °C. This kind of laser source can be used in quantum information processing research.

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

(Some figures may appear in colour only in the online journal)

1. Introduction

Stable low noise continuous wave (CW) laser sources with a high output at 1.5 μm are very attractive for building the practical squeezed source and the continuous-variable entanglement at the communication wavelength. As a consequence, this kind of light source is strongly needed for developing the practical long-distance quantum communication, quantum storage and quantum computation [1–5]. To the best of our knowledge, the 1.5 μm lasers that can be used in scientific research fields are erbium fibre lasers [4, 5], laser-diode pumped solid state lasers (DPSSLs) based on Er^{3+}, Yb^{3+} codoped medium [6, 7], and optical parametric oscillators (OPOs) [8]. Compared with the high power single frequency fibre lasers that exist with large excess noises [5] and DPSSLs where the output power is limited due to the serious thermal effect [7], the OPOs are an available way to build high power low noise 1.5 μm laser sources.

OPO is a mature technology to generate tunable coherent radiation in various spectral domains from visible to terahertz [9–13]. Compared with the triply resonant OPO and doubly resonant OPO, the singly resonant OPO (SRO) possesses several advantages, such as high power (watt-level), continuous wavelength tuning capability and good power stability. Thanks to the availability of high power pump sources and the developments of periodically poled nonlinear crystals, the CW SROs nowadays have already reached an unprecedented power level. In 2007, a SRO based on a MgO:PPLN pumped by a single frequency Yb-fibre laser at 1.064 μm was set up by Henderson *et al*, 5.1 W signal at 1.650 μm and 3.5 W idler at 2.996 μm were obtained at a pump power of 14.5 W [14]. In 2011, Kumar *et al* reported up to 9.8 W of signal at 1.629 μm together with 7.7 W of idler at 3.067 μm under a pump power of 28.6 W by a CW SRO based on MgO:PPLN [15]. Recently, Zeil *et al* obtained 19 W of signal at 1.55 μm together with 11 W of idler at 3.4 μm by employing a variable-reflectivity volume Bragg grating as the output coupler in a SRO [8]. It is worth noting that the SROs mentioned above are all pumped by the Yb-fibre laser and designed as a ring cavity. However, the large excess noise of the fibre laser will be transferred to the signal through the OPO process [16, 17]. And compared with the ring cavity, the two-mirror linear cavity provides advantages of simple setup, lower loss and less sensitivity to small misalignments [18–20].

In this letter, we demonstrate a stable low noise CW single frequency 1.5 μm laser generated by an output-coupled SRO (OC-SRO) based on a periodically poled lithium niobate (PPLN). A home-made stable CW single frequency Nd:YVO_4

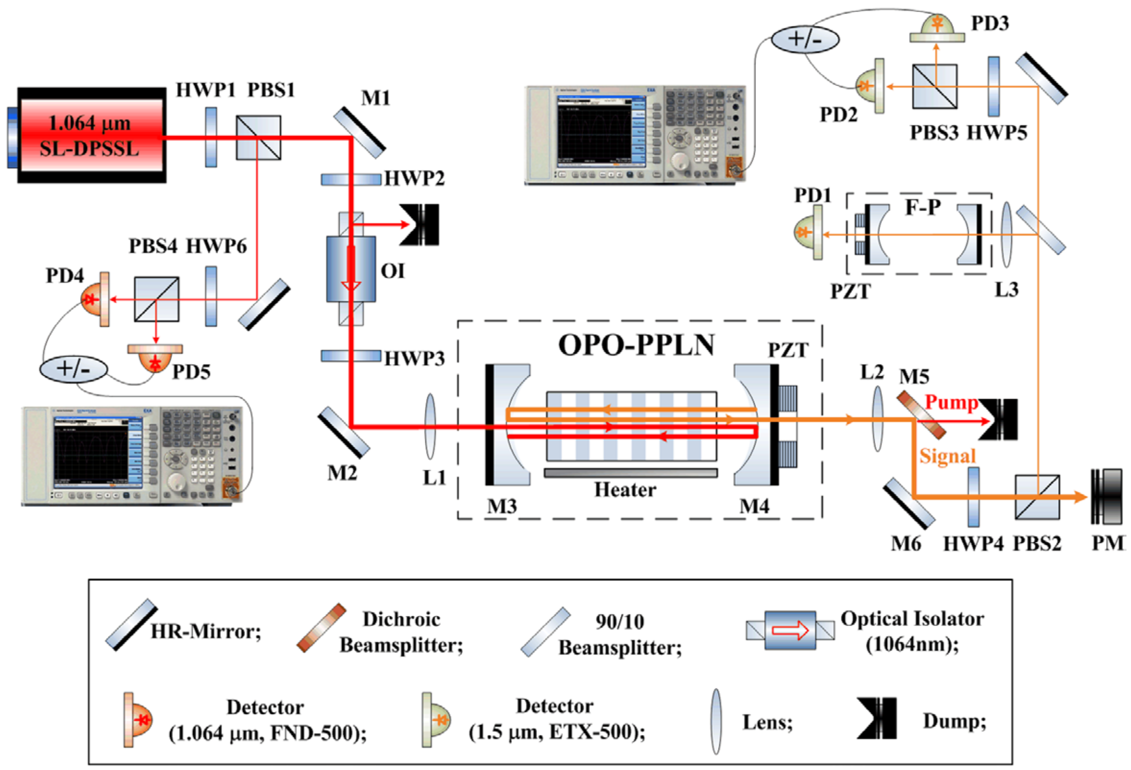

Figure 1. Schematic of the OC-SRO based on PPLN.

laser at 1.064 μm was employed as the pump source for a better noise property. The OC-SRO was designed as a two-mirror linear cavity and double-pass pump scheme in order to obtain a lower pump threshold and better stability. The characteristics of the 1.5 μm laser from the OC-SRO such as tuning characteristic, power stability, beam quality and intensity noise were investigated in detail.

2. Experimental setup

The experimental setup is schematically depicted in figure 1. The pump source is a home-made stable CW single-frequency Nd:YVO_4 laser at 1.064 μm [21], with a maximum output of 18 W, and power stability of better than ±0.5% in a given five hours. With a frequency doubling crystal LBO in the laser cavity acting as the nonlinear loss to suppress the axial mode hopping [22], our pump source can be mode-hop-free operated. A half-wave plate (HWP1) and a polarizing beam splitter (PBS1) were used to control the pump power injected into the OC-SRO. An optical isolator (OI) was used to eliminate the back-reflexion light. By rotating HWP3 we could control the pump polarization for phase-matching in the nonlinear crystal.

The OC-SRO is a linear cavity composed of two concave mirrors with a radius of curvature of 26 mm and a PPLN crystal. The PPLN crystal has a dimension of 1 mm (thickness) × 10 mm (width) × 30 mm (length) with eight poling periods ranging from 28.2 to 31.0 μm and both ends anti-reflexion coated for pump, signal and idler ($R_{1.06\,\mu m,\ 1.5\text{–}1.6\,\mu m,\ 3.1\text{–}3.6\,\mu m} < 0.25\%$). The input coupler (M3) is high reflexion (HR) coated for signal ($R_{1.5\text{–}1.6\,\mu m} > 99.8\%$) and high transmission for pump ($T_{1.06\,\mu m} > 99\%$). The output coupler (M4) is partial transmission coated for signal ($T_{1.5\text{–}1.6\,\mu m}$ ~ 2%) and HR for pump ($R_{1.06\,\mu m} > 99.8\%$). Note that the host material of the cavity mirrors is BK7 glass, which is not transparent for the light at the wavelength around 3.3 μm, the idler can not be extracted from OC-SRO.

To achieve high parametric conversion efficiency and reduce the thermal load in the nonlinear crystal, the pump and signal focusing parameters were selected to be fairly weak — nearly equal to one. To this end, the cavity length was set as 64 mm leading to the waist radii of the pump and signal mode in the centre of the PPLN crystal to be 48.5 and 59.5 μm, respectively. The pump beam was focused via a lens (L1) with 100 mm focal-length to a spot radius of about 49 μm at the centre of the PPLN crystal so that the mode match was realized. To achieve phase-matching and wavelength tuning, the crystal is housed in a copper oven and temperature controlled by a home-made temperature controller with an accuracy of 0.004 °C. For the sake of best stability, the oven was covered by polyarylsulfone shell, which improves the thermal isolation. The OC-SRO cavity was built on a Super Invar base and shielded against the acoustic disturbances and air flow. This kind of design as well as the use of a stable mode-hope-free pump source ensured the OC-SRO operated stably.

3. Experimental results

In the wavelength tuning investigation, to prevent the photorefractive damage of the PPLN crystal, the experiments were carried out under a pump power of 10 W and the PPLN temperature varied from 120 to 180 °C. The wavelength of signal from OC-SRO was measured using a monochromator

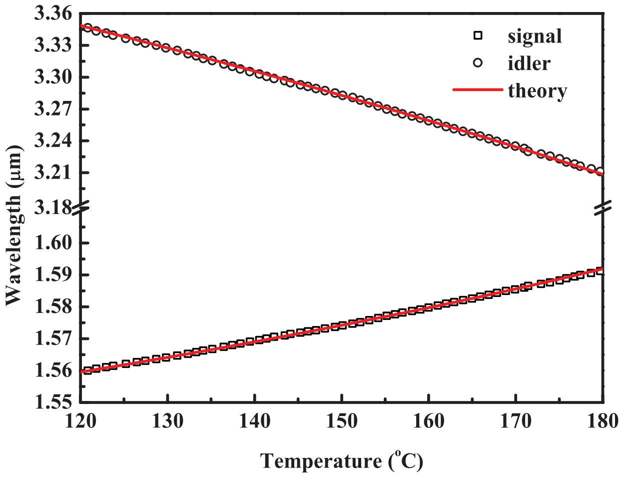

Figure 2. Signal and idler wavelengths as functions of PPLN temperature.

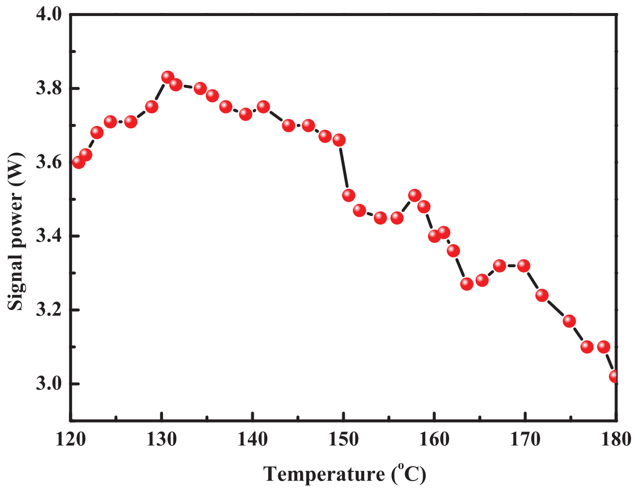

Figure 3. Signal power of the OC-SRO as a function of PPLN temperature.

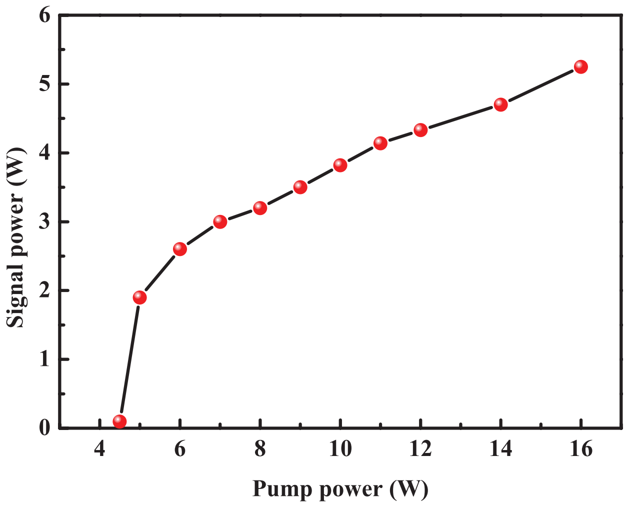

Figure 4. Signal power as a function of pump power.

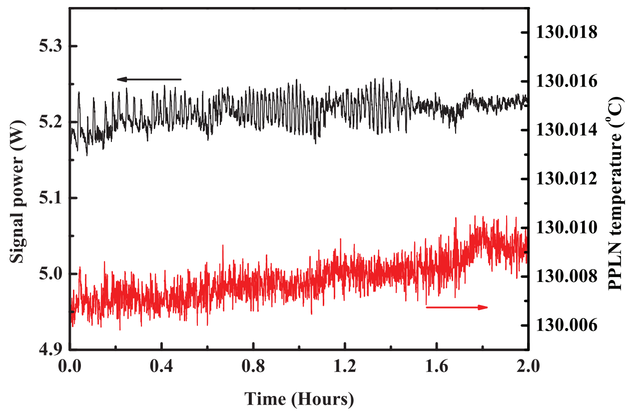

Figure 5. Stabilities of signal power and PPLN temperature.

with a resolution of 0.2 nm (Model: WDG50-Z, BOIF), while the idler wavelength was calculated according to the energy conservation. The signal wavelength tuning characteristic depended on the PPLN temperature and was studied at a selected poling period. Figure 2 gives the experiment result at a poling period of 29.8 μm. The squares indicate the measured signal wavelength and the circles are the calculated idler wavelength at a pump wavelength of 1.064 μm. The solid line is the theoretical prediction calculated by the Sellmeier equation [23]. It can be seen that the signal wavelength can be tuned from 1.560 to 1.592 μm when PPLN temperature is controlled from 120 to 180 °C.

Meanwhile, the signal power of the OC-SRO was measured by a power meter (Model: LabMax-TOP, Coherent) when the PPLN temperature was tuned and the pump power was 10 W, as shown in figure 3. More than 3 W of signal power can be achieved when PPLN temperature was changed from 120 to 180 °C, namely the signal wavelength was tuned from 1.560 to 1.592 μm. When the PPLN temperature was controlled to 130 °C, the maximum signal power of 3.83 W can be obtained at a wavelength of 1.565 μm. The longitudinal-mode of the signal was monitored using a scanning confocal Fabry–Perot interferometer with a free spectral range of 750 MHz and fineness of 500. The signal was in single frequency operation when the wavelength tuned from 1.560 to 1.592 μm.

When the PPLN temperature was controlled at 130 °C and pump power was 16 W, the cavity was optimized. Then the signal power was measured by gradually decreasing the pump power, as shown in figure 4. The maximum signal power of 5.3 W can be obtained at a pump power of 16 W. We notice the signal power dropped rapidly and the pump threshold is 4.5 W, which is a little high. This behavior is mainly due to the fact that the OC-SRO is optimized at high pump power and the thermal effect induced by the absorption of the signal and idler in the crystal exists. When we realigned the cavity at low pump power, the lower pump threshold of 3 W can be reached.

The long-term power stability was recorded by the power meter at PPLN temperature of 130 °C and signal power of 5.2 W, as shown in figure 5 (black line). The measured peak-to-peak power fluctuation is less than ±0.9% in a given two hours. During the measurement, the OC-SRO was in single frequency operation without any mode hop. The PPLN temperature was simultaneously monitored by a thermistor (Model: TCS651, Wavelength Electronics, Inc.) that was in the copper oven and driven by a 100 μA constant current source

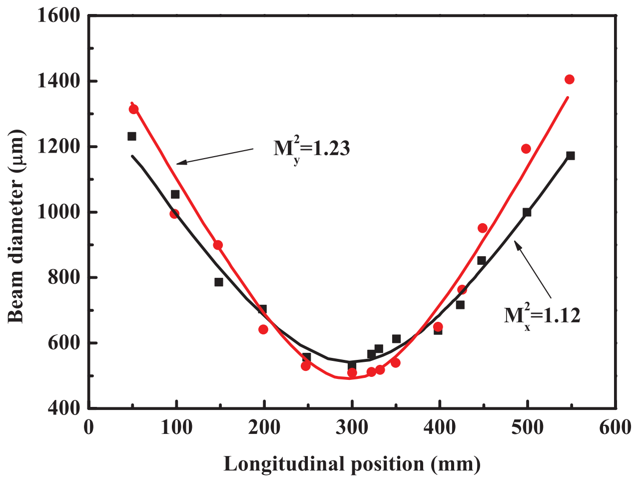

Figure 6. Measured signal beam quality.

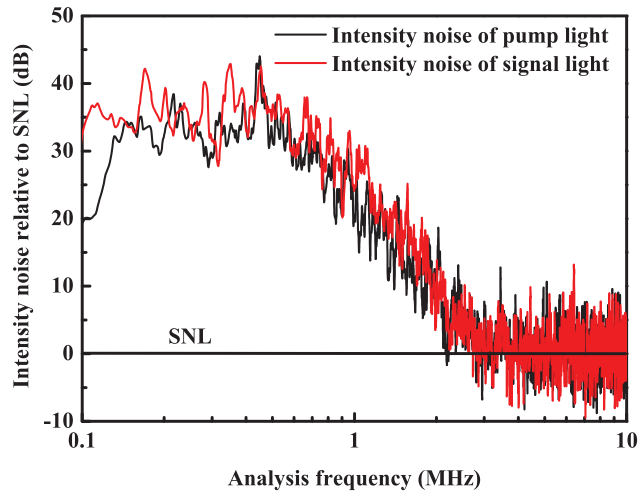

Figure 7. Intensity noise spectra of the pump and signal relative to SNL.

with stability of less than 0.1 μA. Using the measured voltage across the thermistor with an accuracy of 0.01 mV, the crystal temperature can be obtained by the calculated resistance of the thermistor. As shown in figure 5 (red line), the measured peak-to-peak temperature fluctuation is less than ±0.002 °C in the given two hours. The excellent temperature stability makes the variation of the parametric gain less and ensures the OC-SRO operates stably.

The beam quality of the signal output was measured using a laser beam analyzer (Model: M-200, Spiricon) at PPLN temperature of 130 °C and signal power of 5.2 W, as shown in figure 6. The output beam was almost diffraction limited and of very high beam quality, with measured M^2 values of $M^2{}_x$ = 1.12 and $M^2{}_y$ = 1.23.

Noise is a critical parameter in quantum optics experiments. The intensity noises of the signal output and pump laser were measured by self homodyne detection systems [24] that are formed by HWP5, PBS3 and a pair of photodetectors (D2 and D3, Model: ETX 500) as well as HWP6, PBS4 and a pair of photodetectors (D4 and D5, Model: FND 500), respectively, as shown in figure 1. The common-mode rejection ratio of the pair of photodetectors is more than 40 dB and the laser power injected into the photodetector was precisely adjusted to 4 mW. The sum and subtraction of the detected signals were recorded by a spectrum analyzer (N9010A, Agilent). The sum signal gives the intensity noise power of the laser and the subtraction signal gives the shot noise limit (SNL), which was calibrated by a thermal white light source. To investigate the detail of the intensity noise at the range of low frequency, the parameters of the spectrum analyzer was set as a resolution bandwidth of 1 kHz, video bandwidth of 100 Hz and sweep time of 1 s. For a clear comparison, the pump and signal intensity noises relative to the SNL are plotted on a log–log scale and 0 dB indicates that the noise level equals the SNL, as shown in figure 7. The black and red curves give the intensity noises of the pump and signal, respectively. Two curves are basically matched which indicates the signal intensity noise is mainly caused by the transferred noise from the pump. The intensity noise of the signal output reaches the SNL for frequencies above 3 MHz.

4. Conclusions

We build a CW single frequency 1.5 μm laser generated by an OC-SRO based on a PPLN crystal. With the help of a homemade stable low noise CW single frequency Nd:YVO_4 laser at 1.064 μm as the pump source and an excellent temperature controller to control the PPLN crystal temperature, the OC-SRO can be operated stably with low noise performance. The maximum signal power of 5.3 W can be obtained at a pump power of 16 W with a pump threshold of 4.5 W. The long-term power stability is better than ±0.9% in a given 2 h and the intensity noise reaches the SNL for frequencies above 3 MHz. The signal wavelength can be tuned from 1.560 to 1.592 μm with PPLN temperature controlled from 120 to 180 °C. This high quality 1.5 μm laser source can be used to build the practical squeezed source and the continuous-variable entanglement at the communication wavelength that is strongly needed in the quantum information processing research.

Acknowledgments

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