Continuous-wave, single-frequency intracavity singly resonant optical parametric oscillator at 1.5-μm wavelength

Jianli Liu (刘建丽), Yongmin Li (李永民), Qin Liu (刘 勤), Yaoting Wang (王垚廷), and Kuanshou Zhang (张宽收)*

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

**E-mail: kuanshou@sxu.edu.cn*

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We present a 1.5-μm continuous-wave (CW) single-frequency intracavity singly resonant optical parametric oscillator (SRO) based on periodically poled lithium niobate (PPLN). The SRO is placed inside the ring cavity of a single-frequency 1.06-μm Nd:YVO$_4$ laser pumped by a laser diode. The device delivers a maximum single-frequency output power of 310 mW at a resonant signal wavelength of 1.57 μm. The signal wave could be tuned from 1.57 to 1.59 μm by temperature tuning of PPLN crystal over the range of 130 − 170 °C.

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Continuous-wave (CW) optical parametric oscillators (OPOs) have now been established as practical and efficient sources of broadly tunable mid-infrared radiation. Singly resonant OPO (SRO), where only the signal wave is in resonance within the optical cavity, is more stable and practical because it does not need complex electronic cavity-stabilizing mechanisms. In particular, the intracavity SRO with SRO cavity coupled in the laser cavity can take full advantage of the high intracavity laser power. In 1997, Colvillle *et al.* built the first intracavity CW SRO by use of a KTP SRO located within a Ti:sapphire laser cavity[1]. Then, a number of works have been done based on the intracavity CW SRO[2−5]. Coherent light sources in the wavelength range of 1.5 − 1.6 μm are useful in optical communication, atmospheric spectroscopy, etc. Intracavity SRO is a promising approach to generate the laser source at such wavelength range. However, the former research works[6−10] mainly concentrated on the pulsed laser output. In this letter, we report a 1.5-μm CW single frequency intracavity SRO based on periodically poled lithium niobate (PPLN) by locating the SRO within a laser diode (LD) pumped Nd:YVO$_4$ ring laser cavity. A maximum single-frequency output power of 310 mW is obtained at a resonant signal wavelength of 1.57 μm when the LD pump power is 20 W. The signal tuning range is 1.57 − 1.59 μm while the temperature of the PPLN crystal is tuned from 130 to 170 °C.

Figure 1 shows the schematic of the experimental setup. The Nd:YVO$_4$ ring laser was pumped by a 25-W fiber-coupled LD with the central wavelength of 808 nm by controlling the temperature of the LD. The size of the *a*-cut Nd:YVO$_4$ crystal was 3 × 3 × 6 (mm). Both end faces of the Nd:YVO$_4$ crystal were antireflection (AR) coated at 1.064 μm and 808 nm. The ring laser cavity was constructed by two concave mirrors and four plane mirrors. M1 and M2 were plane input couplers with 45° AR coating at 808 nm and 45° high-reflection (HR) coating at 1.064 μm. M3 and M6 were plane mirrors with 45° HR coating at 1.064 μm. M4 and M5 were concave mirrors with 0° HR coating at 1.064 μm. The radius of both concave mirrors was 100 mm. The optical length between two concave mirrors was 96 mm and the rest optical length of the resonator was 480 mm. Such a cavity design made the resonator stable condition of $|A + D| \leq 2$ and the mode match between pump beam and laser beam be satisfied. The laser kept single-frequency operation by using an optical diode formed by a terbium gallium garnet (TGG) crystal and a half-wave plate (HWP). The SRO cavity formed by a PPLN crystal, two beam splitters (BS1, BS2), and two concave mirrors (M7, M8) was placed inside the laser cavity to utilize the high intracavity laser power. BS1 and BS2 were coated for high transmission at the fundamental wave ($T_{1.06\mu\text{m}} = 98\%$) and high reflectivity at the signal wave ($R_{1.5-1.6\mu\text{m}} > 99.7\%$). M7 was HR coated at signal wave ($R_{1.5-1.6\mu\text{m}} > 99.7\%$) and its radius was 100 mm. M8 was partially transmission coated at the signal wave ($R_{1.5-1.6\mu\text{m}} = 98\%$) and its radius was also 100 mm. Because of the difficulty of mirror coating at about 3 μm, the idler wave inside SRO was ignored. BS1, BS2, M7, and M8 defined the nearly-concentric standing-wave SRO cavity, and the beam waist of the signal wave in the PPLN crystal was about 60 μm. The size and poled period of the PPLN crystal we used in our experiment was

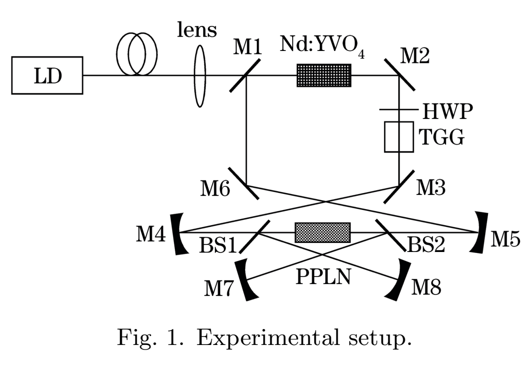

Fig. 1. Experimental setup.

$30 \times 10 \times 1$ (mm) and 29.8 μm, respectively. The two end surfaces of the PPLN were optically polished and triple-band AR coated at pump, signal, and idler wavelengths. The temperature of the PPLN crystal operated at the range of $130 - 170$ °C to avoid its photorefractive effect.

The threshold of the SRO was measured to be 10 W of LD pump power. Figure 2 shows the extracted signal power from the output coupler M8 as a function of the LD pump power. The maximum output power of 310 mW was obtained at a resonant signal wavelength of 1.57 μm when the LD pump power was 20 W. The mode of signal output was monitored by a scanning confocal Fabry-Perot cavity, as shown in Fig. 3. Despite the frequent mode hops, it was observed that the device kept single-frequency operation. It was noted that when the LD pump power was above 20 W the signal output power began to decrease, but the fundamental field of laser still increased. This is probably due to the thermal effect of the PPLN crystal that destabilizes the SRO cavity[4,11].

The wavelength of the signal output was measured using a monochromator with a resolution of 0.2 nm. Figure 4 shows the signal and idler wavelengths as functions of the crystal temperature. The theoretical fitting calculation using the Sellmeier equation is also shown in the figure. When the temperature of the PPLN crystal was tuned from 130 to 170 °C, the measured signal wavelength was tuned from 1.57 to 1.59 μm with the corresponding idler wavelength tuning range of $3.20 - 3.30$ μm. The output power of the signal from SRO was about 300 mW over the entire wavelength tuning range.

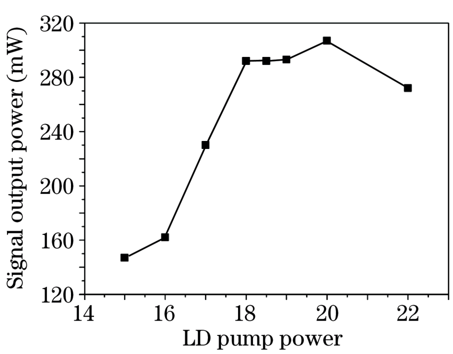

Fig. 2. Output power of signal light versus LD pump power.

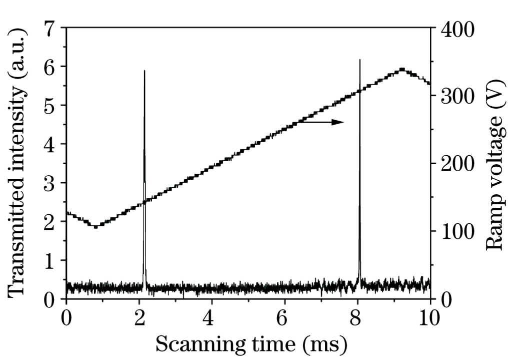

Fig. 3. Transmitted intensity of the scanning confocal Fabry-Perot cavity.

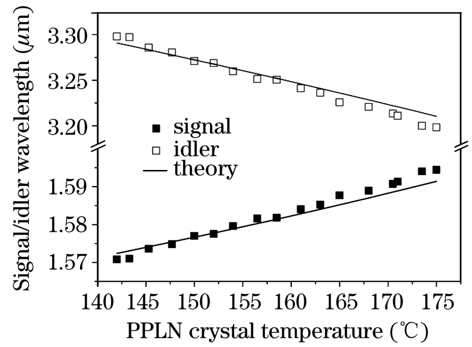

Fig. 4. Wavelength tuning characteristics of the intracavity SRO.

Further tuning of the signal output from the intracavity SRO was limited by the temperature controller.

In summary, a 1.5-μm CW single frequency intracavity SRO based on PPLN has been demonstrated. The wavelength of the signal output from SRO device could be tuned from 1.57 to 1.59 μm by the temperature tuning of PPLN crystal. The measured signal output power was 310 mW. The low down-conversion efficiency of the current setup is mainly due to the low SRO escape efficiency and high intracavity linear loss of the laser cavity. It could be potentially improved by reducing the coating losses and using an idler resonance cavity.

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