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Generation of 16.6 W of tunable mid-infrared radiation with an Yb-fiber-laser-pumped, continuous-wave optical parametric oscillator

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Mid-Infrared (mid-IR) continuous wave (cw) tunable laser sources are of prime interest for variety of applications including trace gas detection [1] and remote sensing. Photoacoustic spectroscopy and cavity-leak-out spectroscopy are some of the well-established techniques, which make use of tunable mid-infrared laser sources for trace gas analysis [2]. Singly resonant optical parametric oscillators (SROs) represent attractive sources for such applications. Using the most widely used nonlinear material, periodically poled lithium niobate (PPLN), cw SROs has been extensively demonstrated previously. However, attainment of high optical powers in the near- and mid-IR is an experimentally challenging proposition, essentially due to heavy thermal loading of the nonlinear crystal resulting from the high intracavity signal power at increased pump powers. This can lead to saturation and subsequently a substantial drop in efficiency, thus limiting the available output power. To date, a maximum of 10 W of idler at 3 μm from 50 W of pump at 20% efficiency has been reported in a cw SRO [3]. These issues could be overcome by introducing output coupling at the signal wavelength, thus reducing the thermal load and extending the tuning range along with improved efficiency of the device [4], which has enabled considerable increase in the overall extraction efficiency up to 59% resulting in a total power of 8.6 W (5.1 W signal, 3.5 W idler) for 15 W of pump power [5]. In the present work, we report 16.6 W (8.3 W of signal and 8.3 W of idler) of output power from a cw SRO for 26.8 W of pump power at an extraction efficiency to 62% using the out-coupling approach. To our knowledge, this is the highest optical output power in the mid-infrared generated from a cw OPO. Moreover, the device is based on an Yb fiber laser pump, resulting in a highly compact, practical, and portable design.

A schematic of the experimental setup is shown in Fig. 1. The fundamental pump source is a cw ytterbium fiber laser (IPG Photonics, YLR-30-1064-LP-SF), delivering a linearly polarized single frequency radiation at 1064 nm with maximum output power up to 30 W. An isolator at the output end of the fiber protects the laser from any back reflections. The pump source has an $M^2<1.01$ and a nominal linewidth of 89 kHz.

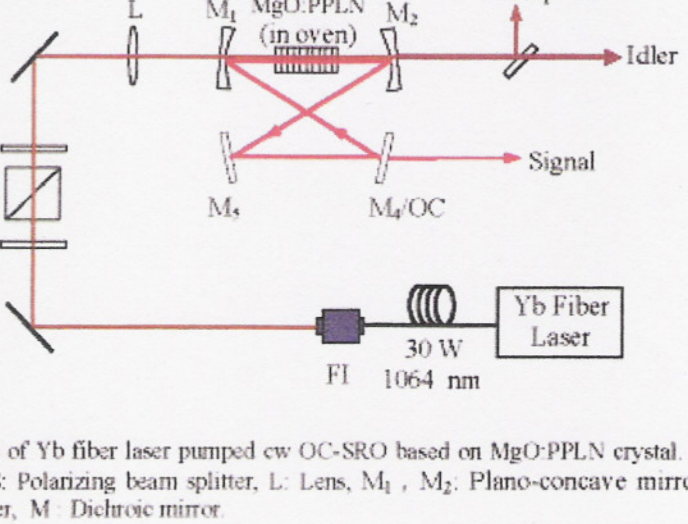

Fig. 1. Experimental setup of Yb fiber laser pumped cw OC-SRO based on MgO:PPLN crystal. FI: Faraday isolator, λ/2: Half-wave plate, PBS: Polarizing beam splitter, L: Lens, M_1 , M_2: Plano-concave mirrors, M_3 , M_4:Plane mirrors, OC: Output coupler, M : Dichroic mirror.

In order to maintain stable output characteristics, the pump laser is operated at the maximum power and the fundamental power to the crystal is varied by using a combination of half-wave plate and polarizing beam splitter. A second half-wave plate is used to control the polarization for phase-matching the nonlinear crystal. The fundamental beam is focused to a beam waist radius of 67 µm at the centre of the crystal. The nonlinear crystal is a 50 mm long, 5% MgO-doped periodically poled lithium niobate (MgO:PPLN), with five different grating with periods ranging from 29.5 µm to 31.5 µm, in steps of 0.5 µm. The crystal is housed in an oven that can be temperature tuned from room temperature to 200 °C. The OPO comprises of a symmetric ring resonator that consists of two plano-concave mirrors, M_1 and M_2, and two plane mirrors, M_3 and M_4. All mirrors have R>99%@ 1.3-1.9 µm and T>90%@2.2-4 µm, thus ensuring SRO operation. The out-coupled SRO (OC-SRO) operation is achieved by replacing a mirror M_4 , which is high reflecting at the signal wavelength, by an output coupler with T~5% across 1.3-1.9 µm.. A proper cavity design ensures the pump and generated signal beam waists to be positioned at the center of the crystal. A dichroic mirror, *M*, separates the generated idler from the pump.

The OPO is tuned by changing the temperature of the nonlinear crystal, temperature tuning. The variation of the temperature from 55 °C to 120 °C resulted in the generation of idler wavelength ranging from 3015 nm to 3148 nm using 31 µm grating period. The idler power generated is greater than 7 W over the entire tuning range. Also the pump depletion is recorded to be greater than 80% through out the tuning range. The power scaling measurements are performed at a constant temperature of 100 °C. An output idler power of 7.6 W is generated at 3060 nm using 31 µm grating period as shown in Fig. 2. A saturation effect is observed in the idler power. Also the crystal heating due to absorption at signal wavelength has limits the room temperature operation of the SRO. Owing to the fact that a huge amount of signal power is resonating in the cavity, the thermal heating of the crystal is efficiently handled by out-coupling the signal power partially there by, not only extending the tuning range of the OPO, but also increasing the efficiency of the device. In order to achieve this, one of the plane mirror in the SRO cavity is replaced by a 5% output coupler resulting in a OC-SRO. Although the threshold of the OC-SRO is higher than the SRO, a signal power of 8.3 W at 1629 nm and an idler power of 8.3 W at 3067 nm is generated resulting in a total output power of 16.6 W at 26.8 W of input pump power corresponding to a overall extraction efficiency as high as 62%. Also, the effect of thermal management is clearly seen from the idler wavelength which has increased from 3060 nm in an SRO to 3067 nm in a OC-SRO, showing the decrease in the crystal temperature due to absorption of the signal wavelength. The OC-SRO thus enabled the tuning of the OPO from room

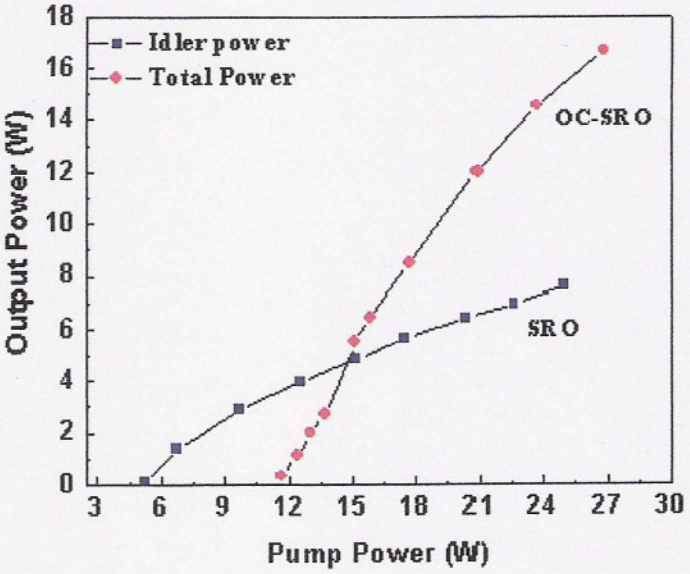

Fig. 2. Output power measured as a function of pump power in a HR cavity and 5% out-coupled cavity (OC-SRO)

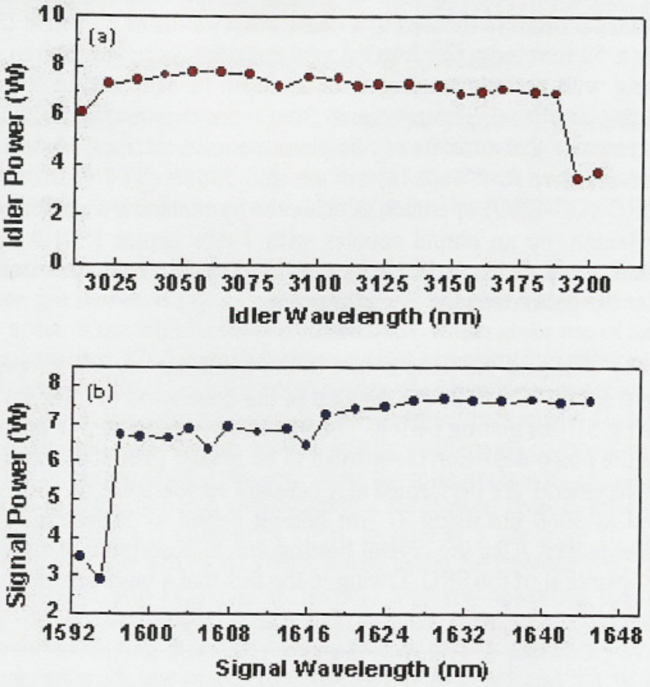

Fig.3. (a) Idler and (b) signal power recorded as a function of idler and signal wavelength in a MgO:PPLN CW-OC-SRO using 31 µm grating period

temperature to 125 °C, resulting in the generation of the signal wavelengths from 1593 nm to 1645 nm and idler wavelengths ranging from 3012 nm to 3204 nm using the 31 µm grating period, as shown in Fig. 3. The generated signal and idler power is greater than 7 W almost throughout the entire tuning range.

In conclusion, we have demonstrated a compact, practical, fiber-laser-pumped cw OPO providing record output power with wide tunability and high extraction efficiency in the infrared. The use of signal output coupling not only has extended the useful tuning range of the device, but also enabled thermal management with improved performance, generating up to 16.6 W of output power for an input pump power of 26.8 W at an extraction efficiency of 62%. With further optimization of output coupling, we expect further improvements in the performance of the OC-SRO with regard to output power and efficiency. Characterization of spatial beam quality and spectral output, and measurements of frequency stability and linewidth of the device are currently underway and will be reported. The high cw mid-infrared optical power generated by this OC-SRO will pave the way for the realization of tunable cw OPOs beyond >5 µm using two-step pumping schemes, with the output from the present device as the pump for a secondary cascaded cw OPO.

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