Dual-wavelength, two-crystal, continuous-wave optical parametric oscillator

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We report a cw optical parametric oscillator (OPO) in a novel architecture comprising two nonlinear crystals in a single cavity, providing two independently tunable pairs of signal and idler wavelengths. Based on a singly resonant oscillator design, the device permits access to arbitrary signal and idler wavelength combinations within the parametric gain bandwidth and reflectivity of the OPO cavity mirrors. Using two identical 30 mm long MgO:sPPLT crystals in a compact four-mirror ring resonator pumped at 532 nm, we generate two pairs of signal and idler wavelengths with arbitrary tuning across 850–1430 nm, and demonstrate a frequency separation in the resonant signal waves down to 0.55 THz. Moreover, near wavelength-matched condition, coherent energy coupling between the resonant signal waves, results in reduced operation threshold and increased output power. A total output power >2.8 W with peak-to-peak power stability of 16% over 2 h is obtained.

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Coherent multiwavelength light sources can be of great interest for applications in optical microscopy, frequency metrology, and short- and long-wavelength generation using nonlinear up- and down-conversion schemes. Optical parametric oscillators (OPOs) are now established as versatile and practical sources of widely tunable radiation from the UV to mid-IR [1]. In conventional OPO configuration, generation of a signal-idler wavelength pair is subject to energy conservation ($\omega_p = \omega_s + \omega_i$, where ω_p, ω_s, and ω_i are the pump, signal, and idler frequencies, respectively) and phase matching ($k_p = k_s + k_i$, where k_p, k_s, and k_i are the wave vectors of pump, signal, and idler, respectively), providing tuning across broad spectral regions. However, the generation of truly arbitrary signal-idler wavelength pairs with independent tuning is not permitted due to energy conservation and the phase-match condition. This limitation can have consequences, for example, in the generation of closely matched wavelengths, where the only solution is to tune the OPO to near degeneracy [2], with the concomitant difficulties.

As such, parametric amplification in dual crystals [3] or double pass in a single crystal [4] may be considered to provide two different signal and idler wavelength pairs. However, high pump depletion in the first crystal or the first pass, generating the first signal-idler pair, can deteriorate the pump beam quality available for the succeeding crystal or pass, hence affecting overall OPO performance in terms of threshold and output power in the second signal-idler pair. Additionally, thermal effects and crystal damage issues in these schemes at higher pump powers are major challenges to overcome.

Here, we present a novel and generic approach for the generation of two independently tunable pairs of signal and idler wavelengths from an OPO, which circumvents the constraints of energy conservation and phase matching and avoids pump depletion effects. Using a cw OPO in a single optical cavity, we generate two signal (idler) wavelengths, which are unbound by energy conservation and phase matching, and can be independently controlled to provide arbitrary tuning within the parametric gain bandwidth. Both signal waves are resonant within the same cavity, thus providing high circulating intensities and similar output powers at the two wavelengths. While operating at the same signal (idler) wavelength, the scheme results in a lower OPO threshold, higher intracavity and output power, and reduced thermal effects arising from the pump absorption. The scheme also offers potential for efficient generation of tunable terahertz radiation down to 0.55 THz.

The configuration of the dual-wavelength cw OPO is shown in Fig. 1. The OPO is designed as a singly resonant oscillator (SRO) in a compact ring cavity comprising four concave mirrors, M_1-M_4, of the same curvature ($r = 10$ cm). All mirrors are highly reflective ($R > 99\%$) for the signal (850–1000 nm), while highly transmitted ($T = 75\%$–95%) for the idler (1100–1400 nm) and pump ($T = 97\%$ at 532 nm). Two identical nonlinear crystals X_1 and X_2 (MgO:sPPLT, 30 mm long), containing a single grating ($\Lambda = 7.97\,\mu$m) [5] and housed in separate ovens with a temperature stability of ±0.1 °C, are placed at the two foci of the cavity. The crystal faces are antireflection-coated

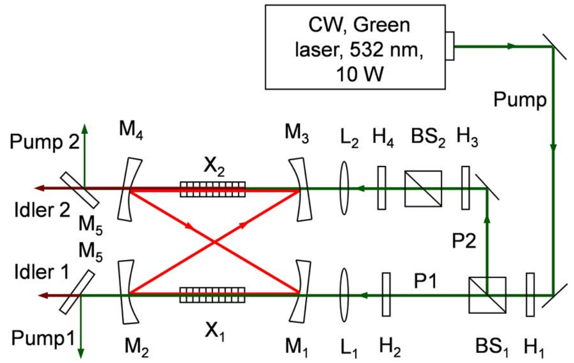

Fig. 1. (Color online) Experimental design of the T-SRO. H_{1-4}: half-wave plate, BS_{1-2}: polarizing beam splitter, L_{1-2}: lens, M: mirror, X_{1-2}: MgO:sPPLT crystal in the oven.

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($R < 0.5\%$) for the signal and pump, with a varying transmission for the idler ($T = 85$–99%). The two-crystal SRO (T-SRO) used a double-pumping scheme, where the crystals are pumped separately by dividing the pump radiation into two beams, $P1$ and $P2$, by employing a polarizing beam splitter cube, BS_1. The power ratio in the two beams is varied using the half-wave plate, H_1. A second half-wave plate, H_2, is used to yield the correct pump polarization for the phase-matching relative to the orientation of crystal X_1. Similarly, the power and polarization of $P2$ into crystal X_2 are controlled using a polarizing beam splitter cube, BS_2, and two half-wave plates, H_3 and H_4. Both pump beams are focused at the center of X_1 and X_2 using identical lenses, L_1 and L_2 ($f = 15$ cm), to the same beam radius, $w_{op} \sim 31\,\mu$m ($\xi = 1$). The T-SRO cavity provides a signal beam waist of $w_{os} \sim 41\,\mu$m at 900 nm, resulting in optimum spatial overlap in both crystals ($b_s = b_p$) [5]. The mirror, M_5, is used to extract idler power from the undepleted pump power. The pump source is a 10 W, cw green laser at 532 nm [5].

Although both crystals are coupled in a single cavity, due to independent pumping, their output characteristics are independent. Moreover, the design avoids the need for any phase control at the input to either crystal, since only few milliwatt of idler generated by each crystal reaches the other crystal, given high idler transmission of two intervening mirrors. To verify the independent performance of the output, we pumped both crystals at the same green power ($P1 = P2 = 5$ W) and measured the signal spectra at different crystal temperatures. Typical results are shown in Fig. 2. At $T1 = 77$ °C and $T2 = 110$ °C, the T-SRO has resonant signals at 971.4 nm (idler 1176.1 nm) and 939.4 nm (idler 1226.7 nm), respectively, with a frequency difference of 10.5 THz. As we increase $T1$ and decrease $T2$ to bring the oscillator to operate as a single-crystal SRO (S-SRO), then different combinations of $T1$, $T2$ result in resonant signals of frequency differences of 7 THz (82 °C, 104 °C) and 1.66 THz (88 °C, 96 °C). Further increase of $T1$ to 91 °C and decrease of $T2$ to 93.5 °C results in coherent energy coupling between the resonant signals of the same wavelength (955 nm), which is verified from the appearance of the additional spectral line at ~17 nm due to the increase in intracavity power and double-crystal length. While characterizing the T-SRO across the tuning range (850–1430 nm) [5], we observed that the shift in the additional spectral line is always at ~17 nm (~204 cm^{-1}) [6], irrespective to the signal wavelength, confirming the origin of the additional spectral line only as the stimulated Raman effect. The difference in the crystal temperatures ($T1 - T2 = 2.5$ °C) to generate the same wavelength is attributed mainly to the difference in crystal heating configurations [7] available for the two crystals. However, a slight difference in the grating periods of the individual crystals cannot be overruled. The T-SRO shows the same performance across the entire tuning range, confirming the versatility of this design in accessing any wavelength permissible by the parametric gain bandwidth and reflectivity of the cavity mirrors.

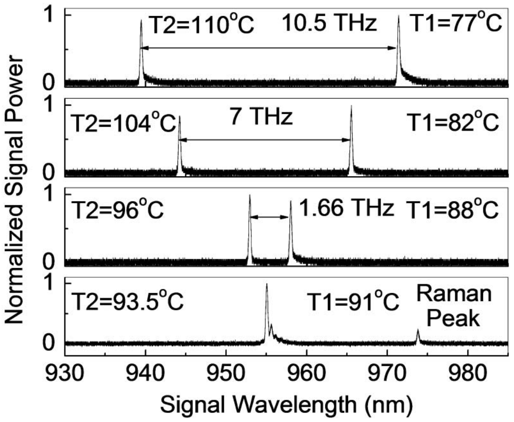

Fig. 2. Signal spectra of the T-SRO at independently varied crystal temperatures, $T1$ and $T2$. Pump power $P1 = P2 = 5$ W.

To observe the closest possible pair of distinct signal wavelengths, we varied the crystal temperatures toward each other, while recording the wavelengths. At $T1 = 90$ °C and $T2 = 94$ °C, two distinct signal wavelengths with the frequency difference of 0.55 THz ($\Delta\lambda \sim 1.76$ nm) were observed. This is due to the narrow spectral acceptance bandwidth (~0.9 nm) of the 30 mm long MgO:sPPLT crystals for parametric generation. Further change in crystal temperature produces gain overlap between the two SROs, and hence results in a single resonant wavelength. Reducing the spectral acceptance bandwidth of the MgO:sPPLT crystal, one can in principle generate two distinct signals with a frequency difference below 0.55 THz. This can be achieved by using longer crystals (currently limited to 30 mm long) or by operating the T-SRO far from degeneracy with signal wavelengths having higher dispersion, given that higher dispersion results in a narrower phase-matching bandwidth.

To verify coherent energy coupling between the resonant signal waves of the T-SRO, and hence the threshold reduction, we measured the output power of the T-SRO and S-SRO as a function of the total input pump power, while keeping crystal temperatures $T1 = 139$ °C and $T2 = 141.5$ °C; the results are shown in Fig. 3. In the T-SRO, both the crystals were pumped at equal powers, whereas for the S-SRO, one crystal was pumped while the other was kept inside the cavity on purpose to obtain a similar cavity mode condition to the T-SRO. The S-SRO has a threshold of 3.17 W, slightly higher than our previous report [5], attributed to the additional loss due to the second crystal. The maximum total output power (idler plus leaked-out signal) of the S-SRO is >2.52 W for a pump power of >9.5 W. The output power is nearly saturated at higher pump powers due to the thermal

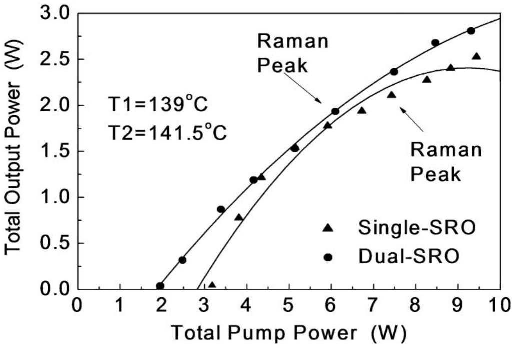

Fig. 3. Variation of the total output power from the S-SRO and T-SRO with the input pump power. Lines to guide to the eye.

effects, also evident in our earlier report [5]. We observed the Raman line at a pump power of 7.4 W.

In the case of the T-SRO, we have twice the crystal length as compared to the S-SRO, and hence intuitively one can expect a maximum 75% threshold reduction. However, the T-SRO has an operation threshold of 1.94 W ($P1 + P2$), resulting in a 39% threshold reduction with respect to the S-SRO, and provides a higher total output power (>2.81 W) without any sign of saturation. In the T-SRO, under coherent energy coupling, the signal field generated in one crystal is amplified in the other crystal, while the idler is completely transmitted after each crystal, resulting in a partial (<75%) threshold reduction. The Raman line now appears at a lower pump power of 6.1 W compared to the S-SRO. The threshold reduction and appearance of the Raman line at a lower pump power verifies coherent energy coupling between the resonant signal waves of the individual crystals. Additionally, the distribution of pump power reduces thermal effects and crystal damage risk, while enhancing the overall performance of the SRO by increasing output power and lowering the threshold. The design can also offer the possibility of operating the device at a higher total input pump power (>10 W), where crystal damage is the main challenge to overcome. While we do not observe optimum threshold reduction (75%) in the present device, this is compensated by the less concomitant difficulties of resonating both signal and idler fields in the same cavity, as in doubly resonant OPOs, that result in output power and wavelength instabilities. In the described T-SRO, the idler field generated at the input of each crystal automatically adjusts its phase depending on the initial phases of the pump and signal, thus avoiding the need of phase control elements, while maintaining stable output. We are currently performing theoretical modeling of the T-SRO, including estimates of the optimum threshold reduction under different conditions.

We measured the power stability of the two idler output beams under coherent coupling with the two crystals operating at the same signal wavelength (922.46 nm) with the results shown in Fig. 4. Figures 4(a) and 4(b) show the power stability of the idler (1256.84 nm) generated by X1 at T1 = 125.7°C and X2 at T2 = 128.2°C, respectively. Both crystals are pumped at almost the same pump power (P1 = 5.2W and P2 = 4.8W). Under free-running conditions, both idler beams have peak-to-peak power fluctuation <16% over 2 h, similar to that of the S-SRO [5]. This implies that the power instability can be attributed to the fluctuation in the laboratory environment rather than gain coupling fluctuations in the T-SRO. With the T-SRO operating at two distinct signal wavelengths, the idler beams have higher peak-to-peak power fluctuation (>20%) due to the increased threshold (3.17 W) in the absence of coherent coupling, with the input pump powers (≈5 W) close to the threshold. This can be improved by pumping individual crystals at higher input powers.

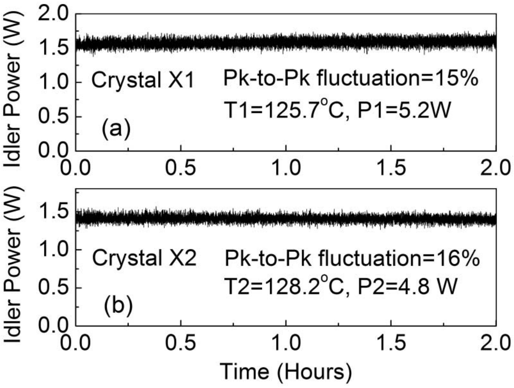

Fig. 4. Power stability of the two idler beams of the T-SRO under coherently coupled operation. Signal wavelength is 922.46 nm (idler 1256.84 nm).

In conclusion, we have demonstrated a novel two-crystal, cw SRO in a simple design to generate independently tunable signal and idler wavelengths with arbitrary values and a minimum separation as low as 1.76 nm (0.55 THz). Both signal wavelengths are resonated inside a single high-finesse cavity with high circulating power and a narrow linewidth, offering the potential for efficient terahertz generation. Coherence coupling between the resonant waves results in higher output power and lower operation threshold. Distribution of pump power into two crystals reduces thermal effects and optical damage risk to each crystal, facilitating operation at elevated pump powers (>10 W). The concept is generic and can potentially be deployed in any spectral range, using different nonlinear crystals, pump lasers in any time-scale, and their different combinations.

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