$HgGa_2S_4$–based RISTRA OPO pumped at 1064 nm

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Abstract: Idler beam quality at 6.3 µm from $HgGa_2S_4$ OPO is compared for linear, planar ring and RISTRA cavities. The last one produces smooth, circular profile and much higher focal fluence.

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Recently, the concept of Rotated Image Singly-Resonant Twisted RectAngle (RISTRA) cavity for optical parametric oscillators (OPOs) was shown to be a very successful tool for achieving high output beam quality (low M^2 values) also in the mid-IR spectral range, using $ZnGeP_2$ nonlinear crystals pumped near 2 µm [1,2]. However, our first attempt to employ such cavity design with $CdSiP_2$ (CSP), which can be pumped at 1064 nm with negligible two-photon absorption (TPA), failed and basically only smoothing of the idler spatial distribution was observed [3]. Obviously some of the prerequisites, on the first place the absent spatial walk-off in the 90°-phase-matchable CSP, were not satisfied in this experiment. Therefore, we decided to examine the RISTRA concept with the most promising non-oxide mid-IR crystal for 1-µm pumped OPOs, $HgGa_2S_4$ (HGS), with which we obtained idler energy of 3 mJ at ~6.3 µm with a linear cavity [4]. Here we compare RISTRA cavity with linear and ring cavities whose parameters are as close as possible and investigate the effect of the spatial walk-off by changing the pump beam diameter.

The most important advantage of the defect chalcopyrite type HGS (point group $\bar{4}$) over the commercially available chalcopyrite $AgGaS_2$ (AGS) is the ~1.8 times higher nonlinear coefficient d_{36} at slightly increased band-gap value (2.79 eV for HGS vs. 2.7 eV for AGS), i.e. at somewhat improved damage resistivity. Due to its wide band-gap, HGS, similar to AGS, can be pumped near 1 µm by short or ultrashort pulse laser sources (e.g. Nd:YAG at 1064 nm) without any TPA.

The pump source was a diode-pumped Q-switched Nd:YAG laser / amplifier emitting ~8-ns pulses with maximum energy of 250 mJ at 1064 nm at a nominal repetition rate of 100 Hz. To improve the spatial beam profile (eliminate diffraction rings producing hot spots) a vacuum diamond pinhole was installed in the focus of a telescope. The M^2 parameter measured behind the telescope amounted to ~2. After an attenuator the polarization state of the pump beam was horizontal which defines the *critical* plane or the walk-off plane in the optically negative HGS, while vertical will be the *non-critical* plane. The beam size (at e^{-2} level intensity) was reduced by a second telescope to D=2.25 mm (small diameter) for the first series of measurements while it was D=5.35 mm (large diameter, comparable to the crystal aperture) without this telescope for the second series of measurements. The repetition rate was reduced to 10 Hz in both cases, either by a mechanical shutter synchronized to the internal Pockels cell driver of the laser or by driving the Pockels cell at 10 instead of 100 Hz although the pump diodes were operated at 100 Hz.

Table 1. Mid-IR OPOs based on RISTRA cavities pumped by multi-frequency and single- or multi-transversal mode structure pump sources for which the beam quality of the output (M^2) has been reported. The Fresnel number is defined as $D^2/(\lambda_S L)$. N: number of round trips, W: walk-off relative to pump diameter D, i.e. $W=l\times\tan\rho/D$, η: slope efficiency, q: quantum efficiency, HT: high transmission, NA: information not available.

	pump	crystal	cavity	N	W	signal	idler
Ref. 1	2050 nm, M^2 ~1, 20 ns, 72 mJ, 100 Hz, D=4.5 mm	ZGP, type-I eeo, θ=NA, l=10 mm, ρ=11.4 (s,i) mrad, AR(p, s, i)	L=109 mm, L*=130.5 mm, R_{OC}(s)=50%, T_{OC}(i)=HT λ/2: Al_2O_3 Fresnel number: 55	46	2.7%	3400 nm, 11.5 mJ, η: 22%, q: 26.5%, @3.6×threshold: M^2_c:<1.8, M^2_{nc}:<1.8	5163 nm, not studied
Ref. 2	2053 nm, M^2 ~1, 38 ns, 44 mJ, 100 Hz, D=3.75 mm	ZGP, type-I, eeo, θ=56°, l=16 mm, ρ=11.8 (s,i) mrad, AR(p, s, i)	L=130 mm, L*=164.4 mm, R_{OC}(s)=65%, T_{OC}(i)>98%, λ/2: MgF_2, uncoated, Fresnel number: 36	69	5%	3012 nm, 10.25 mJ, η: 29.7%, q: 34.2%, @4.5×threshold: M^2_c:1.38, M^2_{nc}: 1.43	6450 nm, 5.67 mJ, η: 16.3%, q: 40.5%, @4.5×threshold: M^2_c:1.74, M^2_{nc}:1.81
Present work	1064 nm, M^2~2, 8 ns, 12 mJ, 10 Hz, D=2.25 mm	HGS, type-II, eoe, θ=50.26°, l=13.44 mm, ρ=17.8(p), 16.8 (i) mrad, AR(p, s)	L=128 mm, L*=150 mm, R_{OC}(S)=72%, R_{OC}(I)=95%, λ/2: 1.2 mm, quartz, AR Fresnel number: 30	16	10.3%	1280 nm, not studied	6300 nm, 0.36 mJ, η: 5.6%, q: 17.5%, @2.5×threshold: M^2_c:3.1, M^2_{nc}:3.5
Present work	1064 nm, M^2~2, 8 ns, 42 mJ, 10 Hz, D=5.35 mm	HGS, type-II, eoe, θ=50.25°, l=17.88 mm, ρ=17.8(p), 16.8 (i) mrad, AR(p, s)	L=128 mm, L*=155 mm, R_{OC}(S)=66%, R_{OC}(I)=83%, λ/2: 1.6 mm, MgF_2, uncoated Fresnel number: 175	15	5.8%	1280 nm, not studied	6300 nm, 0.8 mJ, η: 4.7.%, q: 11.8%, @2.5×threshold: M^2_c:4.8, M^2_{nc}:5.4

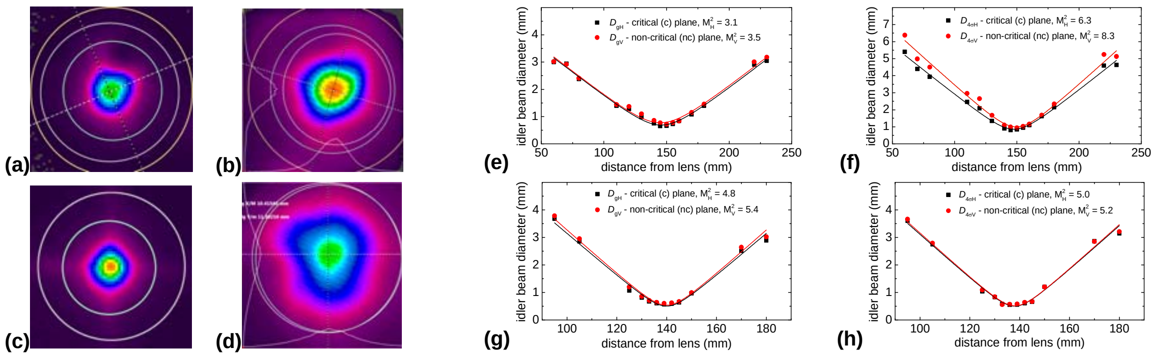

Fig. 1. Idler beam profiles (a)-(d) and corresponding diameter fits in the two planes (e)-(h) at 2.5 times RISTRA threshold: (a), recorded at 14 cm and (b), recorded at 42 cm from OC, as well as (e) and (f) refer to small (D=2.25 mm) pump diameter and 12 mJ pump energy; (c), recorded at 19 cm and (d), recorded at 63 cm from OC, as well as (g) and (h) refer to large (D=5.35 mm) pump diameter and 42 mJ pump energy.

All cavities studied were singly resonant for the signal at λ_S~1280 nm and pumped in single pass. However, the angle of incidence on the mirrors was different: 0° in the linear cavity, ~30° in the 3-mirror equilateral planar ring cavity, and 32.7° in the RISTRA cavity. Both, output couplers (OCs) and input couplers (all other mirrors) were designed for the RISTRA cavity whose monolithic construction fixes the angle of incidence and this, together with the different polarizations (p or s) in the planar and RISTRA cavities led to some differences in the mirror parameters at the three wavelengths which were unavoidable. In comparison to the other cavities, the RISTRA configuration contained also a half-wave plate ($\lambda/2$) for compensation of the polarization rotation of the signal. The physical length of the RISTRA cavity was L=128 mm and we tried to keep the round trip optical length L^* of all cavities equal, for comparison. Two similar HGS crystals (Table 1, 15" parallelism) were used in the two series of experiments; input and output faces were AR-coated with a single quarter-wave layer for the signal (s) which was effective also for the pump (p) while the reflection losses for the idler (i) corresponded to the Fresnel reflection. The first crystal had length of l=13.44 mm and aperture of 10×10 mm^2 and the second one – l=17.88 mm and aperture of 8.57×7 mm^2.

Due to the above mentioned differing cavity losses, OPO threshold was different for the three types of cavities studied but the slope efficiencies η were very close. Thus, we compared the idler characteristics at 2.5-3 times threshold for the two different pump diameters D. The idler beam profiles were recorded by a SpiriconTMPyrocam III camera equipped with $LiTaO_3$ pyroelectric detector (active area: 12.4×12.4 mm^2, element size: 0.1×0.1 mm^2), and fitted by Gaussian dependence giving D_g values in the two planes and also by second-moments giving equivalent $D_{4\sigma}$ values, although the integration domains (apertures) for some measurements were not optimum for the latter method. Finally, idler beam quality was studied with a 10-cm focusing lens fitting the diameters to a square root expression to derive M^2 values in the horizontal (H) and vertical (V) planes, see Fig. 1.

In the present OPO eoe phase-matching is dictated by maximum nonlinearity (lowest threshold) considerations and the idler is walk-off decoupled only from the resonated signal but not from the low quality pump which is not single frequency. This is the worst scenario for RISTRA. Thus, the M^2 values obtained (Table 1) can be considered still as promising; note, that signal near 1280 nm results in more than two times larger Fresnel number compared to the 2-µm pumped OPOs with ZGP. Also the number of round trips is much lower in the present work (Table 1), i.e. cavity modes are less established (note that the lower quantum efficiencies are related to some extent to the imperfect out-coupling of the idler). For D=2.25 mm, we obtained lower M^2 values (of the order of 3) and the RISTRA cavity makes the idler profile slightly more symmetric but does not improve M^2. Increasing D to 5.35 mm leads to larger M^2 values which is more pronounced for the linear and planar ring cavities. From the two series of experiments we saw no experimental evidence for the significance of the walk-off effect on the idler beam quality: although in linear cavities in most cases M^2 was slightly lower in the critical plane, in the planar ring cavities the idler beam was more divergent in this plane and the ellipticity was more pronounced. The RISTRA image rotation made the picture more symmetric assuming the better M^2 value but this was for the uncritical direction. Finally, average focal fluences of 1 J/cm^2 are calculated both for D=2.25 and 5.35 mm with the RISTRA output energies, with a 100 mm lens and collimated idler beam at 6.3 µm of a diameter D_0=½" at the lens, while this value is only 0.1 J/cm^2 for the large Fresnel number linear cavity in [4] even though the output energy is 3 mJ. In any case, the RISTRA cavity has definite advantages over the other cavities at high idler energies (large pump diameters), providing not only lower M^2 values but also symmetric beam shape and equal focal distance in the two planes.

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