User's manual and tutorial for the image rotating RISTRA OPO

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Laser Safety

Exposure to the laser radiation emitted by the RISTRA optical parametric oscillator (OPO), and by the class 3B and class 4 lasers used to pump the RISTRA OPO, poses a significant ocular hazard. Owners of these laser systems, and of OPOs like the RISTRA bear the responsibility of providing appropriate safeguards for the users of high power laser systems within their facility. They are also responsible for implementing safety programs to adequately control the hazards associated with laser use. In the United States, the accepted governing standard for laser safety is ANSI Z136.1, *The Safe Use of Lasers*. Outside of the United States, international standards such as IEC 60825-14, *Safety of Laser Products*, are commonly used. It is strongly recommended that laser owners follow the governing standard in their country to ensure regulatory compliance and to provide safety programs to protect their employees, their facilities, and the public. Additional resources for laser safety are available from the Laser Institute of America;

- http://webstore.ansi.org (search for Z136.1)
- http://www.laserinstitute.org/

Warranty

AS-Photonics, LLC warrants to the end-user customer that the RISTRA products will be free from defects in materials and workmanship under normal use and service for a period of one (1) year from the date of original purchase. The end-user assumes responsibility for the burning of eyeballs, crystals, mirrors or waveplates.

How to use this manual

This document is a combination of a manual and a tutorial. Like any manual it contains instructions on how to assemble and use the RISTRA OPO, and it also includes appendices with physical dimensions, example performance specifications, and example cavity mirror coating specifications. It also describes some useful accessories for assembling and working with the RISTRA cavity. If you are already well acquainted with the operation of nonplanar image-rotating OPOs such as the RISTRA then you can devote your attention to section 5 & section 6 and Appendices A–D that refer to assembly and accessories.

If you are like most users and aren't well acquainted with the RISTRA OPO then you should consider reading Sections 1–3 before working with this device. These sections describe the theory of operation of the RISTRA OPO, provide guidance on when use of the RISTRA is advantageous, and introduce the power and utility of numerical modeling. We've included these subjects because, unlike many laser products, the RISTRA is delivered in a form that may require the user to specify and order its optical components and nonlinear crystals, and carry out assembly, installation, and initial alignment. For experienced workers in the field of crystal nonlinear optics these tasks may pose no challenge. For others with less R&D laboratory experience – say those that want to incorporate a RISTRA OPO in a remote sensing platform where the alternative might be a commercial solid state laser – deploying the RISTRA may pose a significant challenge. Understanding this device from a more fundamental perspective should make that task less intimidating.

AS-Photonics distributes numerical models to aid in designing mirror sets for the RISTRA cavity and for selecting the appropriate nonlinear crystal, including its length. This is the subject of section 3. AS-Photonics can also provide assistance with modeling and cavity design, including suggesting vendors for mirror sets, crystals, and for custom intra-cavity waveplates. Feel free to contact us if you have any questions or feel you need assistance. Unfortunately we cannot provide services for prototyping and laboratory validation. We are also not currently equipped for delivering "breadboard" or "brassboard" optical assemblies, however we may be able to suggest others that can provide these services.

Export control restrictions

The RISTRA can be exported to most EU- and NATO-member countries and a few others (this includes Australia, Japan, South Korea, New Zealand, Sweden, and Switzerland, among others) with a few restrictions. For most other countries, an export license must be obtained. This takes time and is available only for certain unrestricted end-use applications.

1 Background material

Nanosecond optical parametric oscillators (OPOs) are versatile sources of tunable coherent light that generate pulse energies ranging from less than 1 μ J to greater than 100 mJ. When their output is mixed in subsequent sum- or difference-frequency generation stages they can produce wavelengths from the deep UV to the mid-IR, and beyond. To generate wavelengths shorter than approximately 3.6 μ m nanosecond OPOs are typically pumped by the harmonics of Q-switched, flashlamp-pumped Nd:YAG lasers, while for longer wavelengths diode-pumped Ho:YLF is a popular choice. Although wavelength agility and solid-state pumping make OPOs versatile and practical they have one major shortcoming: OPO beam quality tends to be poor if output energies exceed more than a few mJ. The reason for this is simple. Higher output energy requires higher pump energy but the damage thresholds for nonlinear crystals, and for dielectric coatings on cavity mirrors, set limits for the peak pump irradiance (W/cm²), and for its time integral, fluence (J/cm²). To reduce the risk of optical damage requires increasing the pump beam diameter. However to obtain high conversion efficiency OPO cavities are typically short relative to the length of the pump pulse. Consequently for a fixed cavity length an increase in the beam diameter also increases the number of higher-order transverse cavity modes that can oscillate. For essentially all conventional OPO cavity designs, increasing the ratio of beam diameter to cavity length reduces beam quality, so we are confronted with a fundamental problem – how do we accommodate large diameter pump beams without destroying beam quality? A good solution is to use an advanced OPO cavity design such as the image rotating RISTRA.

1.1 Fresnel numbers and the operating principles of the RISTRA OPO

Good beam quality is obtained from any nanosecond OPO if the pump-beam diameter is sufficiently small relative to the round-trip length of the cavity. This condition is conveniently expressed by the cavity Fresnel number $\mathscr{F} = D^2/\lambda L^1$, where *D* is the pump beam diameter, λ the resonated wavelength, and *L* the round-trip length of the cavity. Physically \mathscr{F} provides a measure of diffractive coupling across the transverse dimensions of the beam, with $\mathscr{F} = 1$ indicating the cavity supports a single, lowest-order spatial mode, resulting in a beam profile similar to the lowest order Gaussian from a high-quality HeNe laser. Unfortunately in nanosecond OPOs $\mathscr{F} \approx 1$ is almost impossible to realize unless the pulse energy is very low, otherwise the peak optical power might exceed the damage thresholds for optics and crystals in the cavity.² Therefore beam diameters are relatively large so that $\mathscr{F} \geq 30$ is common, with the result that beam quality can be significantly diminished, even for pulse energies of only a few mJ. For output energies ≥ 100 mJ maintaining the pump fluence significantly below typical damage thresholds, say a fluence of 1–2 J/cm², requires even larger beam diameters, so that "safe" operating conditions can easily result in $\mathscr{F} > 200$.

For a conventional nanosecond OPO cavity with two flat mirrors little can be done to reduce \mathscr{F} except lengthening the cavity, which reduces conversion efficiency, so we must consider other cavity designs to obtain good beam quality. One well developed class of high- \mathscr{F} cavities that do improve beam quality are the diffractively-coupled unstable resonators used in nanosecond solid state lasers. In these unstable cavities, where magnification is > 1, magnification improves beam quality by smoothing variations in phase and amplitude across the beam diameter. Unstable resonators can similarly improve

¹Here, \mathscr{F} is four times larger than the more commonly used definition of $\mathscr{F} = r^2/\lambda L$, where *r* is the pump beam radius.

²We note that $\mathscr{F} = 1$ is possible, especially for stable resonators, but pulse energies are generally restricted to < 1 mJ.

beam quality in nanosecond OPOs but their use is usually limited to phase matching with periodically poled materials [1], where \mathscr{F} is small due to the 0.5–3 mm crystal apertures, or with non-critical phase matching in bulk crystals [2], otherwise the birefringent walkoff that accompanies angle-critical phase matching disrupts the azimuthal symmetry about the cavity axis. For a flat-mirror high- \mathscr{F} cavity there is little diffractive coupling, however birefringent walkoff, if present, behaves much like magnification in one transverse dimension, giving essentially the same beam clean-up as an unstable resonator. While walkoff is one-dimensional its clean-up effects can easily be extended to both transverse directions using image rotation [3, 4]. This is the idea behind the RISTRA OPO, where its nonplanar geometry was designed to produce a convenient image rotation angle of 90° [5].

To illustrate how the Fresnel number \mathscr{F} affects beam quality, and also demonstrate beam clean-up from birefringent walkoff, with and without image rotation, Figure 2(a)-(d) contains contour plots of spatial fluence profiles from two different OPOs for various operating conditions. It also includes profiles for small- and large-diameter pump beams that were used for varying \mathscr{F} from ~ 33 to > 400. The OPOs contained one or two xy-cut KTP crystals with $\theta = 58^{\circ}$, $\phi = 0^{\circ}$, and $\rho = 47.65$ mrad (where ρ is walk off). They were pumped by the 532 nm second haromonic of a Q-switched, injection seeded Nd:YAG laser. The OPO cavities were singly resonant and injection seeded at the signal wavelength of 800 nm. In Fig. 2a the OPO cavity was a three-mirror ring pumped by the near-perfect Gaussian beam shown in Fig. 2e with $\mathscr{F} \sim 33$. In Fig. 2b a Dove prism was inserted into the cavity with it's base oriented at 45° to the plane of the cavity to induce 90° image rotation [4]. Note how the far-field fluence profile of the signal wave in Fig. 2a is elongated in the direction perpendicular to birefringent walkoff, denoted by the far-field angle θ_{\parallel} , and is compressed in the parallel direction, denoted by θ_{\parallel} . The improved beam quality in the || direction is due to walkoff, although for a three-mirror ring OPO it is also enhanced by image inversion. With the Dove prism inserted in the cavity the central portion of the far-field fluence is round and symmetric and confined within a far-field divergence angle of < 1 mrad. The weak shoulder with four-fold symmetry in Fig. 2b appears to be an artifact of scattering from the Dove prism and from the $\lambda/2$ retardation plates that were added to the cavity. To better illustrate the small amplitude of this shoulder, Figure 3 shows surface plots of all the contours in Figure 2.

To demonstrate what image rotation can achieve for large \mathscr{F} , Fig. 2c shows the same three-mirror ring-cavity OPO pumped by the large diameter, lower quality beam in Fig. 2f With \mathscr{F} increased to ~ 200 we observe poor beam quality that includes a far-field divergence angle that is much larger in the perpendicular direction. In contrast the far-field fluence profile for the RISTRA OPO in Fig. 2d with $\mathscr{F} > 400$, has a very tightly focussed symmetric central spot surrounded by a weak shoulder. The surface plot of the far-field fluence in Fig. 3d again provides a better illustration of the relative heights of the peak and shoulder.

As the fluence profiles in Figure 2 and Figure 3 suggest, image rotation is very effective for improving beam quality in nanosecond OPOs, especially when \mathscr{F} is large and the pump beam quality is less than ideal. However the effectiveness of image rotation is influenced by several parameters and is therefore not the same under all operating conditions. The requirements for image rotation to work effectively are that the ratio of walkoff displacement to beam diameter, where walkoff displacement = crystal length × walkoff angle, and the ratio of the pump-pulse duration to cavity round-trip-time, together provide enough time for the diffractive clean-up process to effectively "fill in" the entire beam profile during the pump pulse. Beam quality also depends on the polarizations of the mixing waves, where ideally the polarization of the resonated wave is orthogonal to the polarization of the pump and unresonated wave. For the RISTRA OPO with cavity length of ~ 109 mm, typical "good" operating parameters for a 6 mm diameter pump beam might be a crystal length of 15 mm with birefringent



Figure 2: (a) Far field fluence profile for a three-mirror ring cavity OPO with $\lambda_{sig} = 800$ nm and $\mathscr{F} \sim 33$. θ_{\parallel} and θ_{\perp} are far field angles where \parallel is the direction of walkoff. (b) Same as (a) with intra-cavity Dove prism for 90° image rotation. (c) Same as (a) with $\mathscr{F} \sim 200$. (d) Far field fluence for RISTRA OPO with $\lambda_{sig} = 800$ nm. (e) Small diameter Gaussian beam used to pump OPO in (a) and (b). (f) Low-quality large diameter beam used to pump OPOs in (c) and (d). All OPOs pumped 3–4 × threshold. See text for additional details. *AS-Photonics, LLC* 3 *RISTRA OPO user's guide*



Figure 3: Surface plots of fluence profiles in Figure 2. Note the small amplitude of the shoulders on the profiles in (b) and (d) relative to their respective peak heights. See text for additional details.

walkoff angle ≥ 50 mrad, and a pump pulse duration of at least 10 ns.³Using *xz*-cut KTP as an example, desirable phase matching conditions would include $532(o) \rightarrow 800(e) + 1588(o)$ where the resonated wave at $\lambda = 800$ nm has extraordinary polarization and undergoes birefringent walkoff, and the pump and unresonated wave have ordinary polarization. The walkoff angle of 47.65 mrad is sufficient, but is probably smaller than ideal for the large diameter of the low-quality pump beam shown in Figs. 2f & 3f. Another example of good phase matching for these wavelengths could be obtained from a type-II BBO crystal with $532(e) \rightarrow 800(o) + 1588(e)$ where the walkoff angles for the *e*-polarized pump and idler are 63.03 mrad and 61.93 mrad, respectively.

Although the pump and resonated waves in the two previous examples of good phase matching parameters have orthogonal polarizations, this is not an absolute requirement for using the RISTRA OPO. When these polarizations are parallel the beam quality of the resonated wave will be more strongly influenced by the beam quality of the pump, but image rotation will retain its clean-up capabilities. For example, a 1064 nm pumped RISTRA using the *xz*-cut of the crystal KTA that resonates a 1550 nm signal wave will likely use $1064(o) \rightarrow 1550(o) + 3393(e)$ at $\theta = 79.6^{\circ}$ with $d_{\text{eff}} = 3.12$ pm/V rather than $1064(o) \rightarrow 1550(e) + 3393(o)$ at $\theta = 41.6^{\circ} d_{\text{eff}} = 2.00$ pm/V even though the pump and resonated signal share the same polarization. And why make this choice? It's a matter of choosing increased conversion efficiency as opposed to optimum beam quality. This difference in d_{eff} is not large, it's big enough to substantially increase the threshold for oscillation, and decrease the overall conversion efficiency. This compromise is often encountered for generation of eye safe wavelengths using a pump wavelength of 1064 nm.

2 Physical characteristics of the RISTRA cavity

As its name implies the RISTRA geometry is derived from a rectangle that is twisted to form a nonplanar cavity that produces exactly 90° of image rotation. The configuration for a RISTRA cavity that contains two nonlinear crystals and two $\lambda/2$ retardation plates is shown in Figure 5, along with name conventions for the cavity mirrors, nonlinear crystals, and $\lambda/2$ -plates. The rectangle's ratio of length/width = $\sqrt{2}$, and after twisting, the angle of incidence on all four of its mirrors M1– M4 is 32.765°, or 32.8° for the purpose of specifying dielectric coatings. The cavity is twisted such that the planes containing the paths M4 \rightarrow M1 \rightarrow M2 and M1 \rightarrow M2 \rightarrow M3 are perpendicular, with s(p)-polarizations at M1 becoming p(s)-polarization at M2 after passing through crystal C1. The length/width ratio and angles of incidence were determined from a rigorous but general method for designing image rotating cavities presented in Ref. [5]. For the purpose of building a RISTRA OPO you can neglect the rigor, but if you need to order cavity mirrors, you will need to understand a few of its characteristics, and they are explained below.

As described in subsection 1.1 the RISTRA cavity achieves high beam quality through the use of angle-critical birefringent phase matching, which requires rotation of the crystals. Because the cavity polarizations must match the eigenpolarizations of the crystals, and must also correspond to *s*- and *p*-polarizations at the cavity mirrors, the crystals are oriented in the cavity so they rotate in the following manner: *p*-polarization at mirror M1 corresponds to an *o*-wave in crystal C1 and *s*-polarization at M2; *s*-polarization at M1 corresponds to an *e*-wave in C1 and *p*-polarization at M2. The convention for M3, C2, and M4 is the same but rotated by 90°, so that *s*-polarization at M3 corresponds to an *o*-wave in

³For some crystals the effective nonlinearity, d_{eff} , is large enough that a crystal length of 15 mm may be too long for optimum performance. This is discussed in section 3.



Figure 4: RISTRA OPO mechanical assembly for a two-crystal oscillator.

C2, and so on. Inspection of Figure 5 should make this clear but, realizing that nonplanar geometry can be confusing at first glance, we've included example one- and two-crystal cavity mirror specifications in Appendix C.

For a one-crystal cavity C2 is omitted, keeping C1 placed in the lower leg, and only one $\lambda/2$ retardation plate is required, typically in the position of WP1. For a single-crystal cavity the waveplate can also be located at the position of WP2. This could be advantageous for a cavity containing the crystal ZGP pumped at > 2 μ m with a signal wavelength $\leq 3.7 \mu$ m. Most readily available birefringent materials used for waveplates might absorb the resulting idler wavelength $\geq 4.5 \mu$ m and suffer thermal distortion. The additional loss of idler following reflections from M3 and M4 can help eliminate such problems. Otherwise one- and two-crystal cavities are similar with one important exception. When a single waveplate is used, the signal polarization between M3 and M4 will be elliptical, but it will revert to linear following reflection from M4 as long as *s*- and *p*-reflective phase shifts are identical on M3 and M4 – in other words, M3 and M4 are identical mirrors. The correct orientation for *s*- and *p*-polarizations can be obtained at C1 with the $\lambda/2$ -plate placed in the location of either WP1 or WP2. Note that with two crystals the polarization between M3 and M4 must be linear, and this condition, along with matching cavity polarizations to the eigenpolarizations of the crystals, can only be achieved using two waveplates.

Because *s*- and *p*-polarizations are exchanged between M4 and M1, the direction of propagation in the RISTRA cavity can be selected to achieve the best pump-beam input coupling as determined by phase matching in a particular crystal. For example, a 532 nm pumped two-crystal cavity that resonates an 800 nm wave using *xz*-cut KTP with $532(o) \rightarrow 800(e) + 1588(o)$ would efficiently couple a *p*polarized pump (*o*-wave in C1) through M1 and use M4 as the pump-exit mirror where the pump wave



Figure 5: Two-crystal RISTRA cavity (denotes Rotated-Image Singly-Resonant Twisted RectAngle). M1–M4 are cavity mirrors; WP1 and WP2 are $\lambda/2$ retardation plates; C1 and C2 are nonlinear crystals. For the two-crystal configuration shown here, with propagation through C1 from left to right, WP1 must be a double-wavelength $\lambda/2$ plate for the pump and resonated wave while WP2 can be a single-wavelength $\lambda/2$ plate for the resonated wave alone. For a single-crystal configuration only WP1 or WP2 is required and can be a single-wavelength plate. Because nonplanar cavities rotate polarization and support right- and left-circularly polarized resonances, WP1 and WP2 are required to maintain linear polarizations parallel to the eigen-polarizations of the crystals. See text for additional details.

is again *p*-polarized. M2 would be the output coupler for the *p*-polarized 800 nm signal (*e*-wave in C1). If instead we chose type-II BBO with $532(e) \rightarrow 800(o) + 1588(e)$ then we should achieve better input coupling through M2 where the pump is *p*-polarized (*e*-wave in C1) so that the pump beam exits through M3, with M1 the output coupler where the signal is *p*-polarized (*o*-wave in C1).

While the relationship between phase matching and the direction of propagation is an important one, any cavity design should also consider that dielectric coatings are generally easier to make when they reflect a short *s*-polarized wave and transmit a longer *p*-polarized wave. For phase matching available with some crystals this condition can't always be met, but when possible, it can make the task of the optical coater easier, because it allows relaxed specifications for reflection and transmission at the idler wavelength. The cavity mirror coating designs in Appendix C incorporate these ideas.

2.1 Insensitivity to tilt of cavity mirrors

In addition to offering good beam quality when \mathscr{F} is large the RISTRA OPO cavity also possesses the useful property that its cavity mirrors require no adjustments – in fact in our design they can't be adjusted. This characteristic of the RISTRA results from a universal property of nonplanar resonators, namely, low sensitivity to small tilts of their cavity mirrors. These cavities have a unique axis even when they are formed by flat mirrors. Unlike familiar two-mirror cavities, when a mirror is tilted slightly, the cavity still has an optical axis, although the axis is displaced a small amount relative to its previous position. For this reason the RISTRA was designed without cavity mirror adjustments. As shown in Figure 4 the RISTRA mechanical assembly consists of a solid cylinder. Machined faces position the mirrors, with three points on spring-loaded retaining rings aligned with three points on the machined faces to define planes. The assembly is quasi-monolithic and very stable, with low sensitivity to vibration. Note that insensitivity to tilt does not apply to beams that are injected into the cavity. For injection seeded operation the seed beam must be interferometrically aligned to the RISTRA's axis.

2.2 Modes of the RISTRA cavity

Owing to its nonplanar image-rotating geometry the RISTRA cavity supports modes of oscillation that may be unfamiliar to some users. When empty – no birefringent crystals and no $\lambda/2$ retardation plates – the RISTRA cavity supports modes consisting of superpositions of right- and left-circularly polarized resonances. These include nondegenerate hollow modes that are radially-polarized or have hybrid radial-tangential polarization, and also linearly-polarized filled modes, with the specific mode depending on the polarization of the light injected into the cavity, and the on the length of the cavity [6]. When configured for use as an OPO the RISTRA supports an on-axis mode that closes after one round trip of the cavity. This is the dominant high-gain mode with good beam quality. We note that the RISTRA also supports two linearly-polarized nondegenerate hollow vortex modes with charge m = ± 1 [7]. Broadband oscillation can support an admixture of vortex modes for certain mixing conditions, especially when \mathscr{F} is large, while injection-seeded operation can be configured to obtain essentially pure $m = \pm 1$ vortex modes, if desired. These modes can be excited by laterally displacing the seed beam and tuning the seed frequency $\pm 1/4$ free spectral range (FSR) away from the one-time around mode. Adding a small tilt to the seed beam will further help excite these modes, and a pump beam with donut shaped spatial profile will also enhance excitation of the vortex modes. Unless you are explicitly trying to excite vortex modes, donut-shaped pump beams are not a good choice for pumping a RISTRA OPO. See subsection 6.3 for further details on injection seeding the RISTRA OPO, and see Figure 25 for how to recognize cavity fringe patterns indicating the presence of the four-times around vortex modes.

3 Modeling performance of the RISTRA OPO using SNLO

In addition to distributing the standard SNLO nonlinear optics modeling software, AS-Photonics also distributes free software designed specifically for modeling the RISTRA OPO.⁴ Given the high cost of nonlinear crystals and custom cavity mirror coatings, selecting crystal lengths and determining the optimum output coupling for any OPO, especially for the RISTRA, is no place for guesswork. The SNLO based RISTRA models are easy to run and provide very good guidance for selecting crystal lengths and output coupling to optimize performance.

Because the RISTRA is a four-mirror ring that accepts one crystal in each of its two longer cavity legs, and because there are two mirror reflections between each crystal, it can be configured for various modes of operation. These include a conventional OPO using one or two crystals; OPO + intracavity sum-frequency generation (SFG) with $\omega_{SFG} = \omega_{pump} + \omega_{signal}$; OPO + intra-cavity difference-frequency generation (DFG) with $\omega_{DFG} = \omega_{signal} - \omega_{idler}$, and also OPO + intra-cavity 2 ω generation. Although models exist that accommodate these additional mixing processes, we'll consider only the most commonly used – those for one- and two-crystal OPOs. AS-Photonics can provide assistance with modeling the other cavity configurations on special request.

⁴The standard SNLO distribution can be downloaded at http://www.as-photonics.com/SNLO.html, and the RIS-TRA software can be downloaded from http://www.as-photonics.com/RISTRA-Modeling.html

3.1 Selection of nonlinear crystals

Designing an OPO begins by selecting the best crystal for your application. Sometimes crystal selection is simple and sometimes it isn't, but either way SNLO's QMIX provides most of the information you'll need to make the best choice. Three important criteria a crystal must possess are adequate transmission at the signal, idler, and pump wavelengths, the ability to phase match, and sufficiently large nonlinearity, d_{eff} . Also important are the "good" operating parameters discussed in the latter part of subsection 1.1 which involve polarizations of the mixing waves and adequately large birefringent walkoff. A final consideration not addressed by QMIX is the availability of well-developed high-quality crystals. You'll find the list of crystals in QMIX is large but many are unavailable or unsuitable for use in OPOs. Crystals that are commonly used in RISTRA OPOs pumped by the harmonics of Nd:YAG and Nd:YLF include KTP, BBO, KTA, and perhaps BiBO. For 2 μ m pumping with lasers such as Ho:YLF the crystal ZGP is a very good choice. Other well-developed crystals such as bulk LiNbO₃ (not PPLN) and LBO have undesirable polarizations for the mixing waves, have small d_{eff} , or smaller than desirable birefringent walkoff.

To provide an example of crystal selection that offers several good choices let's consider a 532 nm pump to generate an 800 nm signal. After examining various crystals we narrow the list to the xz-cut of KTP, *xz*-cut of KTA, type-II BBO, and the *xz*-cut of BiBO. From the QMIX output in Figure 6 we see KTP at $\theta = 58.2^{\circ}$ and $\phi = 0^{\circ}$ phase matches with $532(o) \rightarrow 800(e) + 1588(o)$ and has $d_{\text{eff}} = 3.21$ pm/V and $\rho = 47.65$ mrad, so it appears to be a good choice. KTA at $\theta = 61.7^{\circ}$ and $\phi = 0^{\circ}$ offers the same phase matching as KTP but has smaller ρ and smaller $d_{\rm eff}$ and it's more expensive, so we won't consider it further in this example. Type-II BBO at $\theta = 27.3^{\circ}$ phase matches with $532(e) \rightarrow 800(o) + 1588(e)$ so it meets the criteria for good polarizations, but $d_{\rm eff} = 1.62$ pm/V, which is small. However the walk off angles $\rho^{532 \text{ nm}} = 63.03 \text{ mrad}$ and $rho^{1588 \text{ nm}} = 61.93 \text{ mrad}$ are larger than for KTP, so BBO may be of interest for large diameter beams and pump pulse lengths ≤ 8 ns. Finally BiBO at $\theta = 45.9^{\circ}$ and $\phi = 0^{\circ}$ phase matches with $532(o) \rightarrow 800(e) + 1588(o)$, the same polarizations as KTP, has $d_{\text{eff}} = 2.12 \text{ pm/V}$ and $\rho = 88.94$ mrad, so with it's large walkoff it's also attractive for large beam diameters. For lowest oscillation threshold and perhaps the highest conversion efficiency KTP may be the best choice, but BBO and BiBO are definitely in the running. So which crystal do we choose? We'll consider a few more of their characteristics, and if we still can't decide, we'll compare the relative performance of OPOs containing these crystals using the RISTRA models.

Environmental conditions such as elevated humidity could affect our choice and we find BBO is mildly hygroscopic, while KTP and BiBO are inert with respect to moisture. We note that BiBO is attractive because its d_{eff} is larger than that of BBO. However BBO and KTP are very well developed, can be cut with large dimensions, and high quality crystals are available from numerous vendors. BiBO, on the other hand, is relatively new and some of its physical characteristics may be less well known. So, lacking an obvious choice at this point, we'll see what the models tell us in subsection 3.4. Before we do that, let's consider another example of crystal selection that's not as simple, and as we'll see, amounts to a choice between the lesser of two evils.

A common application for nanosecond OPOs is generation of eye-safe wavelengths using the fundamental of an Nd:YAG or Nd:YLF laser for the pump. A signal wavelength of 1550 nm is convenient because it's widely used in the telecom C-band, making stabilized lasers for injection seeding readily available, so let's select a crystal for $\lambda_{pump} = 1064 \text{ nm.}^5$ QMIX suggests three choices,

⁵It's well known that type-II *xz*-cut KTA at $\theta = 90^{\circ}$ and $\phi = 0^{\circ}$ phase matches non-critically with $1064(0) \rightarrow 1533.5(o) + 3475.3(e)$ at 300 K. This is an obviously bad choice for the RISTRA OPO because $\rho \approx 0$ mrad.

KTP, KTA, and LiNbO₃ but we reject LiNbO₃ because the cut with $d_{\text{eff}} = 4.01 \text{ pm/V}$ at $\theta = 47.0^{\circ}$ phase matches with $1064(e) \rightarrow 1550(o) + 3393(o) + 3393(o)$ while the cut for $\theta = 58.6^{\circ}$ phase matches with $1064(e) \rightarrow 1550(0) + 3393(e)$ but has $d_{\text{eff}} = 0.447 \text{ pm/V}$, which is impractically small. Unfortunately KTP is also unacceptable because transmission at 3393 nm is approximately 57% for a length of 10 mm, or in terms of Beer's law, the absorption coefficient $\alpha \approx 0.057/\text{mm.}^6$ That leaves KTA but as shown from the QMIX output in Figure 7, *xz*-cut KTA offers two relatively poor choices, which we mentioned previously in subsection 1.1. For the desirable (*oeo*) mixing with $1064(o) \rightarrow 1550(e) + 3393(o)$ at $\theta = 41.6^{\circ}$, d_{eff} is only 2.0 pm/V, which is smaller than we'd like for pumping at 1064 nm. For mixing with $1064(o) \rightarrow 1550(o) + 3393(e)$ at $\theta = 79.6^{\circ}$, $d_{\text{eff}} = 3.12 \text{ pm/V}$, which is adequate for a 1064 nm pump wavelength, but the pump and signal share *o*-polarization so the OPO's signal-beam quality will be more dependent on the beam quality of the pump. This is particularly true given ρ is only 14.88 mrad. Nonetheless, the lower oscillation threshold and higher conversion efficiency force us to choose (*ooe*) mixing even though we are also choosing lower beam quality. We'll validate this choice from model results in subsection 3.5.

3.2 Getting started with the RISTRA models: Capabilities, limitations, and a brief description of input parameters

Before we test our crystal selections from subsection 3.1 we need to discuss a few basic concepts for modeling nanosecond OPOs. Modeling is a simple task because the RISTRA models run fast on a desktop PC, and also because a little intuition further speeds the iteration process used to find a good design. If you've modeled cw OPOs or cw buildup cavities for 2ω generation, where mode stability and mode matching are critical, you'll find modeling of nanosecond OPOs with flat mirrors comparatively simple.

The RISTRA models are based on SNLO's 2D-cav-LP module. They include two-dimensional spatial profiles, walkoff, diffraction, and image rotation, but cannot accommodate broadband oscillation. They are only capable of treating the case of single frequency oscillation using a single frequency pump, but they still provide good predictions of output energy for most .broadband systems. Single frequency operation is not a choice but a necessity imposed by limitations in available computer memory and processing speed. Although a broadband equivalent to 2D-cav-LP does exist it's too numerically intensive for everyday use and therefore an equivalent broadband model for the RISTRA cavity has not been developed. This means single-frequency oscillation on one of the RISTRA's four-times around modes.⁷ If you're developing a broadband system and need to estimate its line width this can be done in a time-efficient manner using SNLO's PW-OPO-BB, which models a central ray without diffraction or walkoff. Meaningful results will be obtained from PW-OPO-BB as long as memory requirements don't exceed 2 Gb – the maximum that can be allotted to SNLO. Oscillation near or exactly at degeneracy

⁶Crystal transmission versus wavelength can be viewed in the file CRYST_TR.DAT located in the directory C:\SNLO. Low idler transmission increases the threshold for oscillation and can cause unwanted heating of the crystal.

⁷For oscillation on a four-times around vortex mode, use an injection-seeded idler-resonant cavity, offset the idler seed beam about 1–2 mm, use a large diameter pump beam, say 6 mm with super-Gaussian coefficient of 4, and add $\pm \pi/2$ of R-L phase to the resonated idler wave. You might need to increase the *x*-gird value to 64 to generate a beam with a deep, symmetric, hollow center.

can't be accommodated in Type I phase matching, but it can be approximated.⁸

Now that we've described the limits of the RISTRA models, let's begin by examining the inputs they require from the GUI shown in Figure 8. The crystal is 532 nm pumped KTP with data taken from the example QMIX output shown in Figure 6. You'll notice that we've set all crystal reflections to zero, and all mirror reflections to zero as well – except for the signal. Although we can guess these missing values, at this early stage in our design we keep things simple to allow for quick comparisons to other configurations. In addition, we've set all crystal loss to zero, which is valid for these wavelengths in KTP. However, loss should be included when it's $\geq 10\%$ per cm of crystal. Use Beer's law, $I = I_0 e^{-\alpha L}$ where L is the crystal length, to obtain α (1/mm) for inclusion in the model. You'll also notice there are only two mirrors. This is because the model assumes 100% reflection on the other two, so if we later refine our inputs we need to take R < 100% into account. In this example, where the left mirror is a high reflector at 800 nm with $R_{\text{left}} = 0.99$ and the right mirror the output coupler with $R_{\text{right}} = 0.70$, we would accommodate two additional R = 0.99 reflectors at 800 nm by resetting $R_{\text{left}} = (0.99)^3$, or ≈ 0.97 .

The RISTRA model has five inputs for pump, signal, and idler energies – three "left" and two "right." In this example we set both idler energies and the left-signal to tiny values of 10^{-12} , while the right-signal is set to 1 mW for injection seeding, and the pump set to 100 mJ. The pulse duration for the signal seed-beam is "0" because it is cw, although the model also accommodates pulsed injection seeding by setting the seed duration to a nonzero value and by using an appropriate pulse delay. Note that the 10 ns duration of the non-resonant idler exceeds the pump duration by 2 ns. This extends the calculation time so the tail of the signal pulse doesn't appear truncated if you select "power" to plot the pulse temporal profiles.

The models offer spatial profiles with super-Gaussian coefficients of 1–5. A coefficient of 1 produces the familiar lowest order Gaussian, and a super-Gaussian coefficient of 4 provides a good approximation to a "globally" flat-topped beam profile. Real beam profiles usually contain small-scale fluence variations such as ring patterns or "lumpiness" – for lack of a better description. Fortunately small fluence variations can usually be ignored in simulations and are therefore not accommodated by the standard RISTRA models. Note that beam diameters in all SNLO models use FWHM, and not the more familiar $1/e^2$ relevant to lowest-order Gaussian profiles. Also, the models accept irradiance profiles, and not fields, so a lowest-order Gaussian has the form $I_0e^{-2r^2/a^2}$ where I_0 is the peak irradiance, *r* the radial coordinate, and *a* the $1/e^2$ radius, with $d_{\text{FWHM}} = 1.18a$.

Continuing down the input list, birefringent walkoff from QMIX is entered for the *e*-waves, and pump beam offset can be adjusted to optimize efficiency. Be sure to monitor its effect on spatial fluence profiles, especially on the near-field depleted pump beam, so that offset increases azimuthal symmetry, but does not have the opposite effect. This will be obvious when you run the models.

As mentioned previously, mirror reflectivity is zero except at 800 nm, but can be set to more realistic values as the model is refined. Also, the two missing mirrors (M3 and M4 in Figure 5) would be accommodated from the product $R_{\text{left}}R_3R_4$ for each wavelength, and for a two-crystal cavity, we would set $R_{\text{right}}^{\text{pump}}$ to a high value such as 0.99 so the pump beam also passes through the second crystal C2. Below the *R* values the nine entries for phases that will generally be set to zero for the flat-mirror

⁸Degeneracy can usually be accommodated with reasonable accuracy by increasing the difference between the group velocity indices for the signal and idler. If PW-OPO-BB stops running because your machine runs out of memory, increase the difference until the calculation will finish. Also, allocate 2Gb of memory to SNLO if your machine has sufficient resources. See the instructions with SNLO on how to set memory allocation.

RISTRA cavity – unless you want to model a vortex beam. The *z*- and *x*-grid numbers are nominally 30 and 32, although you'll occasionally need to increase the spatial grid density to higher values, at the price of increased computation time. If your pulse temporal profiles aren't smooth, or the spatial fluence has more structure than you expect, the grid density may be too low or the pump energy too high. Also, monitor changes in output energy with grid density. If energy changes appreciably by increasing the *x*-grid number, you may need to use a higher density grid for accurate results. Note that it's acceptable to initially use a low *x*-grid density for faster computation, and increase the density as you refine your model parameters.

The two parameters for crystals, length and d_{eff} , can have dramatic effects, which we'll demonstrate in the following sections. In a one-crystal model we use a single entry for the crystal length. However in a two-crystal version use two entries for length in the same text box. Note that the two crystals can have different lengths, but the nonlinearity d_{eff} has the same value for each OPO crystal. For either one or two crystals, the grid size should accommodate the beam with largest diameter, which is usually the pump, and can be automatically determined by the model. This works well for lowestorder Gaussians. However, for flat-topped beams it may be better to manually set the size to maximize the filled-in portion of the grid, but make sure that none of the waves walk off the grid. The phase mismatch Δk , while usually zero, can be set to other values as necessary, and again, is the same in each crystal. Finally, the text box for signal/idler swap will be zero unless you're modeling a special case of oscillation at degeneracy where the signal and idler polarizations are rotated 90° after each successive cavity pass.

3.3 Basic modeling concepts: How to optimize performance of nanosecond OPOs

Once the input text boxes contain values – none can be empty – you can run the model. What you'll then do is optimize performance by adjusting crystal length, output coupler reflectivity, and perhaps beam diameter, but in many cases pump parameters such as maximum energy, pulse duration, and the beam profile will be constrained by what the pump laser can actually deliver. The resulting model outputs include energy, power and normalized power, fluence in the near- and far-field, spectra, and M^2 as it evolves in time and also its averaged values. Movies of the spatial profiles are also provided so you can observe their evolution in time. The one-crystal model output window corresponding to the inputs in Figure 8 is shown in Figure 9. Of all the outputs the two we'll find most useful are energy and power, with power in the form of pulse temporal profiles. The temporal profiles allow us to graphically observe conversion efficiency and how it's affected by back conversion. Our goal is to achieve the highest efficiency for a given pump energy while minimizing back conversion. We'd also like to build an OPO that operates with fluence and peak power well below typical damage thresholds for crystals and mirror coatings.

Starting with the inputs in Figure 8 we'll illustrate two important concepts: How to "read" the temporal profiles, and how using two crystals – especially crystals of unequal length – can enhance conversion efficiency. We'll initially change two of the inputs in Figure 8 by increasing pump energy to 200 mJ and decreasing $R_{\text{right}}^{\text{signal}}$ to 0.60. The depleted and undepleted pump, signal, and idler temporal profiles exiting the right mirror are shown in Figure 10 for two different crystal lengths. The message to read from the temporal profiles in Figure 10 is that parametric back-conversion, where energy from the signal and idler sum-frequency mix to generate "new" pump energy, can reduce conversion efficiency. And because the new pump is 180° out of phase with the original pump, back-conversion also affects beam quality. In Fig. 10a the recovery in amplitude of the depleted pump pulse following the onset

of oscillation is the characteristic signature of back-conversion. Modeling can be used to understand this effect and what steps are taken to reduce it. For example in Fig. 10b the crystal was shortened to 12 mm, there is less back conversion, and the output energy increased slightly. You should also investigate how changing the output coupling, pump energy, and the pump-beam spatial profile, can all affect conversion efficiency.

Finally, changes in conversion efficiency can be quantified by calculating the percent pump depletion from the model outputs. This is done by dividing the difference of the undepleted and depleted pump energies by the undepleted pump energy at the mirror where the pump beam exits the cavity – usually M2 (right) when using one-crystal and M4 (left) when using two-crystals. Undepleted pump energy is obtained by running the model with $d_{\text{eff}} = 0$ to accurately account for loss of pump energy due to any absorption in the crystal, and due to loss from mirror and crystal coatings. For example when the pump beam exits through M4, percent pump depletion would be calculated from

Percent depletion =
$$100 \times \frac{E_{\text{pump}}^{\text{left}}(d=0) - E_{\text{pump}}^{\text{left}}(d\neq 0)}{E_{\text{pump}}^{\text{left}}(d=0)}$$
. (1)

Although a small amount of pump energy leaks through M2 in a two crystal design (or M1 for reversed propagation), where $R_{\text{pump}}^{\text{right}(\text{left})} \ge 0.99$, and the leakage when $d_{\text{eff}} = 0$ differs from when $d_{\text{eff}} \neq 0$ due to pump depletion in the first crystal, that small difference in leakage can be safely ignored when calculating percent pump depletion. Note that if the direction of propagation is reversed you must monitor $E_{\text{pump}}^{\text{left}}$ or $E_{\text{pump}}^{\text{right}}$ as appropriate.

Now let's test a two-crystal design by running the RISTRA model. Starting again with the inputs in Figure 8 we set $R_{right}^{pump} = 0.99$ so the pump beam continues through the second crystal, and then we try various combinations of crystal lengths until we achieve the highest signal energy with lowest back conversion. A simple way to think about the operation of this two-crystal oscillator is we deplete just enough pump energy in the first crystal to achieve oscillation. After two mirror reflections we've rejected essentially 100% of the unresonated idler, then we deplete the remaining pump energy in the second crystal to achieve maximum amplification of the signal wave with little back conversion. With a little intuition as our guide, and the power of modeling at our disposal, we choose the length of C1 to be shorter than C2. After a few trial runs we achieve pump depletion of 72% with signal energy of 98.7 mJ using crystal lengths of 7 mm followed by 14 mm. The pulse temporal profiles exiting the right and left mirrors are shown in Figure 11.

You may be wondering if it's wise to use two crystals with such different lengths. It depends on polarization, beam diameter, and the size of the walkoff angle, ρ . When circulating an *e*-wave like we're doing here the unequally compensated walkoff displacement might cause problems, especially if a large diameter beam clips one of several apertures in the RISTRA assembly. It could also be bothersome for injection seeding – that is, if you're expecting a high degree of symmetry when using two crystals – because the unequal walkoff displacement in the two long legs of the cavity will result in a cavity mode that's displaced from the geometric central ray of the cavity. For small diameter beams or when circulating an *o*-wave, the unequal walkoff displacement might be ignored. However, a large diameter *e*-polarized pump beam could also potentially clip one of the apertures in the RISTRA assembly. Of course any one-crystal design that circulates an *e*-wave suffers similar problems regardless, but it's worth keeping this issue in mind when you design an OPO.

3.4 Model results for $\lambda_{pump} = 532$ nm, $\lambda_{signal} = 800$ nm for KTP, BBO, and BiBO

Following our brief introduction to modeling of nanosecond OPOs we can pick up where we left off at the end of subsection 3.1 and make a final choice between KTP, BBO and BiBO. We'll start with our result from subsection 3.3 for the KTP RISTRA where 200 mJ of 532 nm pump energy combined with a crystal length of 12 mm produced a maximum energy of 51.4 mJ at 800 nm. If we now update all input parameters relevant to type-II BBO cut at $\theta = 27.3^{\circ}$ and apply our modeling methodology we find a maximum energy of 43.3 mJ for a crystal length of 17 mm with $R_{\text{right}}^{\text{signal}} = 0.70.9$ Repeating this process for type-II *xz*-cut BiBO at $\theta = 45.9^{\circ}$ we find a maximum energy of 49.9 mJ for a crystal length of 17 mm with $R_{\text{right}}^{\text{signal}} = 0.62$. Because $\rho^{\text{signal}} = 88.84$ mrad for BiBO is large, we also offset the pump beam by 0.7 mm. From this exercise we find KTP generates slightly more signal energy than BiBO, but BBO produces less by about 15%. For some applications we would be done at this point but there are two other things to consider. If the pump beam quality is less than optimum – and it almost always is – we might achieve better signal beam quality from BiBO than from KTP, especially when the beam diameter is large or the pump pulse duration is shorter than 7-8 ns. On the other hand if the beam diameter is small, and in particular if the pump profile is lowest order Gaussian, then KTP should offer higher efficiency and less beam profile distortion due to its smaller walkoff angle.¹⁰ Finally, we know we can obtain more energy using two crystals. However, subsection 3.3 already discussed two-crystal designs so we won't test them here.

3.5 Model results for $\lambda_{pump} = 1064$ nm, $\lambda_{signal} = 1550$ nm for KTA

In subsection 3.1 we gave an example of crystal selection for a 1064 nm pumped 1550 nm eyesafe OPO that amounted to choosing the lesser of two evils. The chosen crystal was KTA and the anticipated performance for its two available *xz*-cuts forced us to compromise beam quality for higher conversion efficiency. We'll now justify that choice using the RISTRA model. Unfortunately conversion efficiency decreases as the pump wavelength increases, and d_{eff} for 1064 nm pumped KTA is actually smaller than d_{eff} for the 532 nm pumped KTP OPO in subsection 3.4. Consequently the factor of two increase in λ_{pump} suggests we consider a two-crystal design to begin with, otherwise the pump fluence may be impractically high. We'll begin by modeling the *xz*-cut of KTA at $\theta = 79.6^{\circ}$ with $1064(o) \rightarrow 1550(o) + 3393(e)$ and $d_{\text{eff}} = 3.12 \text{ pm/V}$.

For consistency we'll retain the 6 mm diameter 4th-order super-Gaussian pump beam, but increase the pump energy to 300 mJ, and we'll start with two 17 mm long crystals. Otherwise pump pulse duration and the injection seed power remain the same as shown in Figure 8. In our previous calculations for KTP, BBO, and BiBO we optimized efficiency by setting pump-beam offset to a nonzero value, but for *xz*-KTA at $\theta = 79.6^{\circ}$ where ρ^{idler} is only 14.88 mrad we ignore this correction. For $R_{\text{right}}^{\text{signal}} = 0.65$ we obtain signal energy of 126 mJ but see evidence of back-conversion. We next try reducing the length of C1 and find 14 mm results in a small increase in signal energy to 131 mJ. The left and right depleted pump temporal profiles are now similar to those in Figure 11. We also run the model several times with lower pump energy to find the oscillation threshold, arbitrarily defined as ≤ 1 mJ of signal energy, occurs at slightly less than 90 mJ of pump energy. Finally, we check the average M^2 values at full

⁹Note that for a crystal with a $10 \times 10 \text{ mm}^2$ aperture the maximum length accommodated by the RISTRA assembly is approximately 17 mm. A crystal this large may result in a reduced tuning range due to the restricted crystal bays in the RISTRA body.

¹⁰Measurements that demonstrate beam distortion due to walkoff for Gaussian beams are shown in Ref. [8].

energy. Although the model's pump-beam profile has smooth irradiance and no wavefront aberration, common polarization of the pump and resonated wave will usually increase M^2 , and that is the case here. For the signal we find $M_w^2 = 2.97$ and $M_p^2 = 2.96$, where subscripts w and p denote the directions parallel and perpendicular to walkoff, respectively. These are good M^2 values for a high- \mathscr{F} OPO, but with different mixing the RISTRA cavity can produce even better beam quality.

We'll now test performance of the *xz*-cut at $\theta = 41.6^{\circ}$ where the mixing is $1064(o) \rightarrow 1550(e) + 3393(o)$, $\rho^{\text{signal}} = 45.00$ mrad, and $d_{\text{eff}} = 2.00$ pm/V. Changing the inputs for walkoff, d_{eff} , refractive indices, and adding 0.35 mm of pump beam offset, we find the signal energy drops to 42.2 mJ. However, M_w^2 and M_p^2 improve to 1.56 and 1.55, respectively. We increase the length of C1 to 17 mm to compensate for the smaller d_{eff} and also increase $R_{\text{right}}^{\text{signal}}$ to 0.75 and obtain a signal energy of 79.4 mJ. We note that R = 0.75 is relatively low output coupling for a nanosecond OPO and although we observe no back-conversion, we won't further increase $R_{\text{right}}^{\text{signal}}$. We also locate the 1 mJ oscillation threshold and find it occurs with pump energy slightly less than 160 mJ. For the higher signal energy M_w^2 and M_p^2 increase slightly to 1.74 and 1.72, respectively. While the beam quality is impressive the low conversion efficiency and high threshold are clearly undesirable, so for most applications we can tolerate a reduction in beam quality as suggested in subsection 3.1. Note however that a "real" pump beam with wavefront aberrations and a "lumpy" spatial irradiance profile will most likely result in lower beam quality than the model suggested for the *xz*-cut of KTA at $\theta = 79.6^{\circ}$.

3.6 Model results for $\lambda_{pump} = 2050$ nm, $\lambda_{signal} = 3800$ nm for ZGP

As a final example we'll model one- and two-crystal RISTRA OPOs using the IR crystal ZGP pumped at 2050 nm by a laser with spatial and temporal characteristics typical of Q-switched diode-pumped Ho:YLF. As we noted in subsection 3.2 the single frequency RISTRA models can provide accurate predictions for pump lasers that oscillate on multiple longitudinal modes such as unseeded Nd:YAG. Experience suggests this remains true for Ho:YLF even though its spectral bandwidth can be much greater than that of Nd:YAG [9, 10]. While pump bandwidth is an important consideration, of perhaps greater importance in our final example is the dependence of OPO performance on crystal length, especially when d_{eff} is large as it is for ZGP.

We've selected $\lambda_{\text{signal}} = 3800$ nm where the mixing is $2050(o) \rightarrow 3800(e) + 4451(e)$ with $\rho^{\text{signal}} = 11.22$ mrad, $\rho^{\text{idler}} = 11.23$ mrad, and $d_{\text{eff}} = 76.5$ pm/V. The polarizations are not ideal but for these wavelengths it's the only mixing available in ZGP. We selected these wavelengths because they are transmitted by sapphire, which facilitates fabrication of custom waveplates, and because the idler wavelength may be useful for applications such as IR countermeasures (IRCM). We begin with a one-crystal design, with the initial model inputs shown in Figure 12.

Note that the inputs in subsection 3.4 and subsection 3.5 were typical for OPOs pumped by commercial, research-grade Q-switched Nd:YAG lasers with rep rates of 10–30 Hz. The ZGP OPO we're modeling here uses lower pulse energy and a longer pump pulse of 30 ns which is more typical of Ho:YLF lasers pumped at 1.9 μ m by cw fiber lasers. Also, the beam profiles are lowest order Gaussian, where the extended wings limit the maximum beam diameter accommodated by the RISTRA mechanical assembly to about 3.6 mm (r_{1/e^2}), or $d_{FWHM} = 4.2$ mm.

Beginning with the inputs in Figure 12 and iterating to optimize performance we find $R_{\text{right}}^{\text{signal}} = 0.65$ and a crystal length of 12 mm provides 15.4 mJ at 3800 nm with $M_{\text{w}}^2 = M_{\text{p}}^2 = 1.77$. The M^2 values could

probably be lower but there is only a small amount of back conversion. The resulting pulse temporal profiles at the output coupler M2 are shown in Fig. 13a As usual we arrived at these specifications by adjusting crystal length and $R_{\text{right}}^{\text{signal}}$ to optimize energy but found that using a longer crystal reduced performance due to increased back-conversion. For example a crystal length of 15 mm results in 15.1 mJ with $M_{\text{w}}^2 = M_{\text{p}}^2 = 1.96$, a reduction in signal energy and beam quality. The pulse temporal profiles for the 15 mm crystal are shown in Fig. 13b. Increasing the crystal length for this OPO is clearly couterproductive.

For a two-crystal ZGP RISTRA we retain $R_{\text{right}}^{\text{signal}} = 0.65$ and set $R_{\text{right}}^{\text{pump}} = 0.99$, and after testing various combinations of crystal lengths find C1 = 8 mm and C2 = 15 mm give the best performance with signal energy of 21.4 mJ, pump depletion of 81.2%, and M_w^2 and $M_p^2 = 1.85$. The difference in crystal lengths is almost a factor of two, but with walkoff angles of ~ 11 mrad this shouldn't complicate operation of the OPO. Also, the pump depletion is very high, even for a two-crystal RISTRA, but does it represent a realistic value? In an attempt to answer this question we approximate a real device by setting $R_{\text{crystal}} = 0.01$ for all three wavelengths (somewhat lousy AR coatings), and also set $R_{\text{left}}^{\text{idler}} = R_{\text{left}}^{\text{pump}} = R_{\text{right}}^{\text{idler}} = 0.01$ because real mirrors don't have R = 0, and we also include crystal loss $\alpha = 0.008 \text{ mm}^{-1}$ at $\lambda_{\text{pump}} = 2050 \text{ nm}$ (α obtained from Inrad's data sheet for ZGP, http://www.inrad.com/pages/crystals.html). These changes result in signal energy of 18.2 mJ, pump depletion of 79.6%, and $M_w^2 = M_p^2 = 1.86$. Of course we don't accurately know the values for the various surface reflections, but barring other unforseen loss mechanisms, our estimates suggest the high performance predicted by the model is reasonable. Figure 14 shows pulse temporal profiles for the two-crystal ZGP RISTRA



Figure 6: Output from SNLO's QMIX for flux grown KTP and for BBO with a 532 nm pump and 800 nm signal. Note that the temperature is 300 K. The refractive index temperature derivatives are large for certain crystals so using the correct temperature is important. See text for additional details.

Qmix Contraction Contraction	Qmix
Run Crystal Temp Print KTA_1 300 Kelvin	Run Crystal Temp Print KTA_1 300 Kelvin
Wavelengths (1 must be zero) Principal plane	Wavelengths (1 must be zero) Principal plane
Red 1 Red 2 Blue C XY @ XZ C YZ	Red 1 Red 2 Blue C XY @ XZ C YZ
1550 0 1064 nm Type C Mox © OPO	1550 0 1064 nm Type C Mix © OPO
Temperature range = 112.38 K*cm OPO accpt ang = 4.33 1.91 mrad*cm OPO accpt bw = 56.33 56.33 cm-1*cm 3393.4(e) + 1550.0(o) = 1064.0(o) Walkoff [mrad] = 14.88 0.00 0.00 Phase velocities = c/ 1.810 1.776 1.787 Group velocities = c/ 1.903 1.803 1.819 GrpDelDisp(fs/2/mm) = -513.7 56.7 139.6 At theta,phi = 79.6 0.0 deg. deff = -3.12E0 pm/V S_o × L^2 = 1.04E8 Watt E Crystal ang. tol. = 12.60 mrad*cm Temperature range = 28.05 K*cm OPO accpt ang = 12.60 5.86 mrad*cm OPO accpt bw = 9.92 9.92 cm-1*cm	<pre>deff = 0.00E0 pm/V</pre>
▲ ▶	↓ ◆ >

Figure 7: Output from SNLO's QMIX for *xz*-cut KTA for $1064(o) \rightarrow 1550(e) + 3393(o)$ at $\theta = 41.6^{\circ}$ and $1064(o) \rightarrow 1550(o) + 3393(e)$ at $\theta = 79.6^{\circ}$. See text for additional details.

	C		
Manufacture (con)	Signal	Idler	Pump
Wavelengths (nm)	800	1588.1	532
Indexes of refraction	1.817	1.738	1.79
Crystal left reflectivity	0	0	0
Crystal right reflectivity	0	0	0
Crystal loss (per mm)	0	0	0
Enrgy/Pwr left (J/W)	1.0E-12	1.0E-12	0.1
Enrgy/Pwr right (J/W)	0.001	1.0E-12	
Pulse duration (ns)	0	10	8
Pulse delay (ns)	0	0	
Beam diameter (FWHM mm)	2	6	6
Supergaussian coefficient	1	4	4
Walk off angle (mrad)	47.65	0	0
Beam offset (mm)		0	0
Left mirror reflectivity	0.99	0	0
Right mirror reflectivity	0.7	0	0
Phase L-C (radians)	0	0	0
Phase C-R (radians)	0	0	0
Phase R-L (radians)	0	0	0
Grid numbers z x	30	32	
Crystal/grid sizes (mm)	15	10	
deff (pm/V)/delta k (1/mm)	3.21	0	Accept
Sig/ld swap (1=yes;0=no)	0		
Pump must be bluest wave. Signal and idler designations are into Signal wave by default is perfectly Other beams will not be if they walk	erchangeable. aligned in cavity.		

Figure 8: The input GUI for the RISTRA model for KTP with $532(o) \rightarrow 800(e) + 2588(o)$.

One-Crystal RISTRA		_ 🗆 🗙	
Display O Signal O Idler @ Pump	Beams C Left	• Right	
	Focus-p Anal	yze M-p	
Rotate D L R U	Focus-w Tilt	-w M-w	
Run Movie Fluence	Power	NormPower	
Change Inputs Print		ua	
Right input (W J -) = 1.00E-3 1.00E-12 Left input (W J J) = 1.00E-12 1.00E-12 1.00E-1 Left output energy (J) = 5.54E-4 1.00E-12 1.21E-81 Right output energy (J) = 2.37E-2 1.22E-2 6.38E-2			

Figure 9: The output GUI for the one-crystal RISTRA model for KTP with $532(o) \rightarrow 800(e) + 2588(o)$ corresponding to the inputs in Figure 8. See text for additional details.



Figure 10: (a) OPO pulse temporal profiles for the RISTRA model inputs in Figure 8 but with pump energy increased to 200 mJ and $R_{\text{right}}^{\text{signal}}$ reduced to 0.60. The KTP crystal length is 15 mm, the signal energy is 45.9 mJ, and the pump depletion is 35% Note the sudden decrease in amplitude for the depleted pump in (a), followed by a sudden recovery. This is the signature of parametric back-conversion. (b) The crystal length was decreased to 12 mm to reduce back-conversion so the signal energy increased to 51.4 mJ. The pump depletion is now 39%. From the parameters in Figure 8 the model tells us this one-crystal RISTRA OPO is unlikely obtain high conversion efficiency, where pump depletion would exceed 50%. The temporal profile for the undepleted pump is generated by setting $d_{\text{eff}} = 0$ in the model, as indicated in Equation 1. The plots of pulse profiles shown here are not generated by the RISTRA model but were plotted using data in the model generated file R1PWR_R.DAT. See text for additional details.



Figure 11: (a) OPO pulse temporal profiles at right mirror (output coupler) for the two-crystal RISTRA model using inputs in Figure 8 but with pump energy increased to 200 mJ and crystal lengths of 7 mm and 14 mm. The signal and idler are normalized relative to the undepleted pump at the left mirror (pump exit) for proper power scaling. (b) Pulse temporal profiles at left mirror. The signal and idler pulse heights are exaggerated so they don't overlap the profile for the depleted pump. In (a) note the absence of back conversion due to the short crystal, and in (b) note the near 100% depletion of the pump in the second half of the pulse. These are signatures of a very efficient nanosecond OPO, where the signal energy is now 98.7 mJ and the pump depketion is 72%. The temporal profile for the undepleted pump is generated by setting $d_{\text{eff}} = 0$ in the model, as indicated in Equation 1. The plots of pulse profiles shown here are not generated by the RISTRA model but were plotted using data in the model generated files R2PWR_R.DAT and R2PWR_L.DAT. See text for additional details.

One-Crystal RISTRA				
	Signal	Idler	Pump	
Wavelengths (nm)	3800	4451.4	2050	
Indexes of refraction	3.148	3.144	3.148	
Crystal left reflectivity	0	0	0	
Crystal right reflectivity	0	0	0	
Crystal loss (per mm)	0	0	0	
Enrgy/Pwr left (J/W)	1.0E-12	1.0E-12	0.05	
Enrgy/Pwr right (J/W)	0.001	1.0E-12		
Pulse duration (ns)	0	35	30	
Pulse delay (ns)	0	0		
Beam diameter (FWHM mm)	2	4	4	
Supergaussian coefficient	1	1	1	
Walk off angle (mrad)	11.22	11.23	0	
Beam offset (mm)		0	0	
Left mirror reflectivity	0.99	0	0	
Right mirror reflectivity	0.6	0	0	
Phase L-C (radians)	0	0	0	
Phase C-R (radians)	0	0	0	
Phase R-L (radians)	0	0	0	
Grid numbers z x	30	32		
Crystal/grid sizes (mm)	10	18	A	
deff (pm/V)/delta k (1/mm)	7.65	0	Accept	
Sig/ld swap (1=yes;0=no)	0			
Pump must be bluest wave. Signal and idler designations are inter Signal wave by default is perfectly a Other beams will not be if they walk	rchangeable. Iligned in cavity. off			

Figure 12: RISTRA model inputs for single-crystal ZGP with $2050(o) \rightarrow 3800(e) + 4451(e)$.



Figure 13: (a) OPO pulse temporal profiles at right mirror M2 (output coupler) for a one crystal ZGP RISTRA using inputs in Figure 12 but with $R_{\text{right}}^{\text{signal}} = 0.65$ and crystal length increased to 12 mm. The signal energy is 15.4 mJ and the pump depletion is 58%. The signal and idler are normalized relative to the undepleted pump for proper power scaling. (b) Same as (a) but with crystal length increased to 15 mm. The longer crystal reduces the 3800 nm signal energy slightly from 15.4 mJ to 15.1 mJ and increases M_w^2 and M_p^2 from 1.77 to 1.96. The pump depletion is now < 57%. See text for additional details.



Figure 14: (a) OPO pump-pulse temporal profiles at left mirror M4 (pump exit mirror) and signal and idler pulses at mirror M2 (output coupler) for a two crystal ZGP RISTRA using the model inputs for the one-crystal version in Figure 12 but with C1 and C2 lengths of 8 mm and 15 mm, respectively. The signal energy is 21.4 mJ and the pump depletion is 81.2%. The signal and idler are normalized relative to the undepleted pump for proper power scaling. (b) Same as (a) but with $R_{crystal} = 0.01$ for all three wavelengths, $R_{left}^{idler} = R_{left}^{pump} = R_{right}^{idler} = 0.01$, and crystal loss $\alpha = 0.008 \text{ mm}^{-1}$ at $\lambda_{pump} = 2050 \text{ nm}$. Attempting to mimic the losses in a real OPO reduces signal energy to 18.2 mJ and reduces pump depletion to 79.6%. See text for additional details.

4 Thermal effects



Figure 15: Coefficients of thermal expansion along principal axes for (a) biaxial and (b) uniaxial crystals.

4.1 Introduction

Optical parametric oscillators do not have intrinsic heating like optically pumped lasers or Raman oscillators. However, it is not unusual to have absorption of one or more of the waves in the nonlinear crystal. Because the waves are not equally absorbed, the heating is nonuniform along the length of the crystal. Heating is also nonuniform in the transverse dimension because it mimics the transverse beam profiles. Such nonuniform heating can cause disruption of phase matching along the longitudinal and transverse directions. It also can cause thermal lensing which disrupts the cavity mode profiles.

The steady state temperature profile can be computed from the heat deposition profile and from the crystal thermal conductivity, and thermal boundary conditions. If we assume the crystal has a square $d \times d$ cross section, a length L and is cooled on one side, as is usually true for a RISTRA, the temperature rise (ΔT) at the center of a beam of radius r is roughly equal to

$$\Delta T pprox rac{\langle Q/L
angle}{Kd}$$

where $\langle Q/L \rangle$ is the time averaged heat absorbed per unit length, and K is the thermal conductivity. There will be a thermal lens created by the thermo optic effect which has a focal length of roughly

$$\mathrm{FL} = \frac{2\pi r^2 K}{L} \left[\left\langle \frac{Q}{L} \right\rangle \times \frac{\mathrm{dn}}{\mathrm{dT}} \right]^{-1}$$

AS-Photonics, LLC

Because the cooling is asymmetric there will also be a thermally induced beam tilt, at an angle

$$\delta = \frac{\langle Q/L \rangle}{2Kd} \frac{\mathrm{dn}}{\mathrm{dT}}$$

Note that all three effects are inversely proportional to K. For crystals, K is a tensor with two principal values for uniaxial crystals or three principal values for biaxial crystals. The values of K vary by a large amount from crystal to crystal but the multiple principal values are approximately equal for any particular crystal. Figs. 16a and 16b show the principal values for several popular nonlinear crystals. Conductivities vary from 46 W/m-K for GaAs to less than 2 W/m-K for several crystals.

A high thermal conductivity does not ensure minimized thermal effects because thermal lensing and tilt are inversely proportional to the thermo optic coefficient dn/dT. This coefficient also varies by large amount among crystals, and it depends on wavelength. Its value can be computed using the SNLO function Ref. Ind. by computing the refractive index for the chosen wavelength at two different temperatures.

4.2 **RISTRA** specific

Thermal tilt is not usually an important issue for the RISTRA. We explain elsewhere that small mirror tilts do not destroy the optical axis of the cavity but merely shift the angle and location of the axis slightly. The same is true of small thermally-induced tilts in the crystal. The maximum allowed tilt is limited by the shift in beam position that can be tolerated. It is typically ~ 1 mrad which causes a shift in the axis location of approximately 100 microns.

However, because the beam diameters are typically quite large in a RISTRA, the beam quality of the resonated wave can be strongly affected by even weak thermal lensing. AS-Photonics has developed thermal models that can quickly compute the thermal profile inside the crystal based on the heat deposition profile and the crystal thermal conductivity. We are also developing self consistent models of RISTRA OPOs that include thermal effects. The RISTRA OPO model is iterated with the thermal model, and the computed temperature profile is used in propagating the beams through the crystal on the next iteration of the OPO model. This modeling allows us to predict beam quality for the OPO, assuming the absorption and thermal properties of the crystal are known with sufficient accuracy. Note that the method of cooling the crystal has little influence on thermal lensing. Lensing depends on the transverse gradients of the temperature, and these gradients are determined by the transverse profile of the heat deposition and the crystal conductivity. The gradient depends weakly on the net temperature rise at the beam center.

The cooling conditions can, however, strongly affect the disruption of phase matching along the length of the crystal. The thermal conductivity of the aluminum crystal mounting plate is ~ 250 W / m-K, or about 100 times the conductivity of most nonlinear crystals. Assuming good thermal contact with the mounting plate and good conductivity of heat out of the mounting plate, the temperature rise at the beam center is determined primarily by the crystal conductivity and absorptivity, as expressed above in the introduction. As a rough estimate, with good thermal contact between the plate and crystal and between the rotation shaft and its housing, the temperature rise of the crystal where it contacts the mounting plate is ~ 0.7 K per watt absorbed. Thermal contact between the plate and crystal can be improved by using a thermal paste or a thermal pad between crystal and plate. Pads and pastes typically have conductivities in the range 1-10 W/m-K, and because they are only 100 microns or so thick, their thermal resistance is negligible compared with the crystal resistance. AS-Photonics offers thermal pads

and thermal pastes suitable for crystal mounting. Heat removal from the RISTRA crystal mounting plate is by conduction along the rotating shaft holding the plate. This shaft is designed with a small clearance to the body of the rotation stage, so good heat removal can be achieved by using thermal paste in this gap. Ordinarily this is omitted but it can be added at the customers request, or the customer can add the paste - in which case, we recommend contacting AS-Photonics for advice on how to do so.

4.3 Higher order thermal effects

The only thermal effect discussed above was the thermo optic effect which is usually the dominant effect. However, the thermal profile causes optical distortions via other effects as well. For example, nonuniform thermal expansion caused by nonuniform temperature profiles can cause slight bulges in the end faces of the crystal centered on the beams. This adds or subtracts from the thermal lensing due to the thermo optic effect. Other higher order effects include refractive index changes due to thermal expansion via the strain optic effect, via the electro optic effect due to electric fields induced by thermal expansion and the inverse piezo electric effect or fields induced by the pyro electric effect. Changes caused by these higher order effects are usually of order 10 times smaller than the thermo optic changes, but in some circumstances they must be considered as well.

5 Assembling the RISTRA OPO

The RISTRA OPO is simple to assemble. However, the cavity mirrors, waveplates, and crystals it contains must be treated with care by individuals acquainted with the proper handling of delicate optical components. One fingerprint on a crystal like BBO – which can't be cleaned with common solvents such as methanol or acetone – will ruin your day.

The RISTRA is delivered fully assembled minus the optical components. Final assembly requires attaching mirrors and gluing crystals and waveplates in place. Procedures for carrying out these steps are described below. Note that the order of assembly given here is optional and should be changed to accommodate your particular application. It may help to read through subsection 5.1 - subsection 5.3 before you begin assembly to determine what will work best.

The optical components must adhere to the specifications outlined in Appendix A. An example of a mirror set is listed in Appendix C.

5.1 Installation of cavity mirrors

- *Tools required:* Small screwdriver for 0-80 shoulder bolts, fiber tipped tweezers such as Techni-Tool 758TW0304, cavity mirror installation jig (see Figure 17), blower-duster (preferably N₂, CO₂, or rubber bulb air blower). *Optional* – powder-free nitrile gloves, reading glasses or jeweler's loupe.
- Materials required: Cavity mirrors

The cavity mirrors are attached to flat faces on the RISTRA's cylindrical body by spring-loaded retaining rings, where three points on the rings align with three points on each face to define a plane. Without a ring to hold it in place a mirror will slide off the face unless the face is horizontal. When assembled and mounted on its baseplate none of the RISTRA's mirrors are horizontal, so the easiest



Figure 16: Thermal conductivities along principal axes for (a) biaxial and (b) uniaxial crystals.

Figure 17: Cavity mirror installation jig.

way to attach the mirrors is to first remove the crystal rotation assemblies from the cylindrical body and mount it on the cavity mirror installation jig described in Appendix D. To attach the mirrors follow these steps:

- Remove the 0-80 shoulder bolts that hold the retaining rings to the cylinder. Be careful handling the springs as they are easily lost.
- Decide which faces will hold M1–M4 and mark the cylinder with a pencil if necessary. You should also use a hard pencil to mark the sides of all of your mirrors with M1–M4 for future reference
- Mount the cylinder to the jig. To do so, insert the dowel pin into one of the holes on the jig's plate, and secure it with #2-56 screw in the other hole. Because the mirror retaining rings overhang the flat face on the side with the shorter waveplate holder assembly and prevent the cylinder from mounting flush on the mirror jig, the mirrors should be mounted to the longer side first.
- Use tweezers to pick up the correct mirror with its high-reflecting side down (away from the tweezers) and check for any dust that may be on the coating. Very carefully remove the dust by blowing gently with a blower duster. Do not use any pressurized duster whose contents can condense and stick to the mirror coating. Dry N_2 is best if available. Second best is probably a rubber bulb air blower.
- Carefully set the mirror on the horizontal face on the cylinder
- Pick up a mirror retaining rig with the tweezers. Note that the bolt holes are not uniformly spaced so line the ring up to the hole pattern on the cylinder in advance. Set the ring over the mirror. Make sure the three tabs where the bolts pass through the ring are all in contact with the backside of the mirror.
- Pick up a bolt with a spring on its shoulder and drop it through the ring and thread it into the cylinder. The bolt can be dropped it place using the tweezers but you can also use you fingers if you're comfortable doing so but try not to touch the mirror, even if you're wearing gloves. Install all of the bolts. Tighten the bolts until the bolt shoulders are tight against the RISTRA body then back them out one turn to avoid binding of the retaining ring.
- Remove the cylinder from the jig and remount for installation of the next mirror. Repeat above steps until M1–M4 are in place.

5.2 Installation of nonlinear crystals

- *Tools required:* Small mixing pan and sharp tipped tool for applying epoxy. For two-crystal cavities a film polarizer, lined paper, and a microscope slide, for determining the direction of birefringent walkoff in a crystal. *Optional* – fiber tipped tweezers such as Techni-Tool 758TW0304, powder-free nitrile gloves, reading glasses or jeweler's loupe.
- *Materials required:* Crystal(s), Low-outgassing optical epoxy such as opto-packaging epoxies from Epoxy Technology.

If thermal conductivity is not a concern, crystals are glued to rotation platters in the rotation assemblies using high quality low-outgassing optical epoxy. As shown in Figure 18 the surface of a rotation platter is cut with small trapezoidal shaped flutes to retain glue and form a strong bond. Nonlinear crystals are almost always prepared with frosty sides and this is obviously a requirement for attaching them using epoxy.

Crystals should be glued to the platter near the center, and not on each end, to reduce the chance of inducing stress in the crystal. For the $10 \times 10 \times 15$ mm³ in Figure 18 glue would be applied to the two flutes in the center of the platter. In principle high quality optical epoxies will shrink very little during curing but it is still a good idea to avoid inducing unwanted stress. Always apply just the minimum amount of glue required to form a strong bond. Excess glue serves no purpose. A very small screwdriver or other sharp tipped tool

Figure 18: Rotation assembly

such as a scribe works well for applying small drops of epoxy. Note that the nominal aperture size for crystals used in the RISTRA is $10 \times 10 \text{ mm}^2$ so they can usually be handled without tweezers. However it is a good idea to wear powder-free nitrile gloves.

For two-crystal cavities it is usually a good idea to orient the crystals so the direction of birefringent walkoff is reversed in C1 and C2. This will improve efficiency by increasing spatial overlap of the pump and resonated waves, and if the resonated wave is *e*-polarized, obtain propagation closer to the geometric central ray of the cavity.¹¹ Figure 19 shows one of two orientations for reversing walkoff, and includes a diagram and instructions for determining the direction of birefringent walkoff in a crystal.

5.3 Installation of intra-cavity waveplates

- *Tools required:* A needle for applying glue, fiber tipped tweezers such as Techni-Tool 758TW-0304, UV source for curing UV glue, blower-duster (preferably N₂, CO₂, or rubber bulb air blower). *Optional* powder-free nitrile gloves, reading glasses or jeweler's loupe.
- *Materials required:* Waveplate(s), UV curing glue.

¹¹Because the cavity is singly resonant and there are two mirror reflections between crystals we can ignore the orientation of the d-tensor in the second crystal, as discussed in Ref. [15].

Figure 19: (a) Reversal of walkoff in two-crystal oscillators. In this example the resonated *e*-wave is displaced toward the outside of the cavity, but displacement in the opposite direction works as well. (b) Determining the direction of walkoff in a birefringent crystal. Place the crystal so a straight reference line can be viewed in transmission. Clean paper with a fine line is acceptable for this purpose, but to minimize collecting particles on the crystal a clean microscope slide can be set on the paper. If handled carefully the dielectric coatings on the crystal will not be damaged from contact with the microscope slide or with the paper. Now rotate the film polarizer to selectively view the *o*- and *e*-waves as shown. The *e*-wave will be displaced from the reference line as viewed through the crystal (dashed line). Observing *e*-wave displacement for crystals with small walkoff angles may require magnification. Try a jeweler's loupe. *Important note:* You are viewing light scattered back through the crystal toward your eye from the surface below, so the direction of walkoff for a wave propagating forward through the crystal (away from your eye) is opposite to the direction of displacement you view for the *e*-wave. In other words, we saw the line move to the right, so going into the page a ray would walk off to the left. It is a good idea to use a hard pencil to identify the crystal, and also to mark the direction of birefringent walkoff.

The intra-cavity waveplates are glued into their holders using UV curing glue. It is very important to use as little glue as possible, and to use a high viscosity flexible-curing glue such as Norland 68, otherwise capillary action can carry the glue around the perimeter of the waveplate inside its holder. If the glue is cured with complete contact the waveplate can be difficult to remove, in case that becomes necessary.

The axes of the waveplates must have the correct orientation relative to the polarized light in the cavity. The orientation is obtained by marks on the waveplate holder at 0° for two-crystal cavities, and at 22.5° for one-crystal cavities (see Fig. 20). Aligning to the marks is inexact so the waveplate mount allows $\pm 10^{\circ}$ of rotational adjustment. Unmounted stock half-waveplates usually have a flat ground on their side that is parallel to their slow axis. This flat is used for orientation. For some single-crystal applications the RISTRA can use stock multiple-order plates while two-crystal designs require custom double- $\lambda/2$ plates for the pump and resonated wave. For broader tunability zero-order plates composed of two or more multiple-order plates may be necessary, and these also have flats, or some other mark, indicating their orientation. Note that the custom waveplates required for most two-crystal cavities may not have a flat ground on their side unless it is requested when they are ordered.

For a one-crystal cavity you will need to decide in advance where to install the waveplate because the two wavelplate holders have different lengths. For most applications the waveplate will be located

Figure 20: Intra-cavity waveplate holder. Note the markings at 0° and 22.5° .

between M2 and M3 (WP1 in Figure 5). However, sometimes it makes sense to put it between M4 and M1, at the location of WP2. For example, in a 2 μ m pumped ZGP RISTRA with a resonated wavelength $\lesssim 3.7 \mu$ m and idler wavelength $\gtrsim 4.5 \mu$ m with propagation direction M1 \rightarrow M2 \rightarrow M3 \rightarrow M4, you could eliminate idler absorption in a waveplate made from sapphire by placing it between M4 and M1.¹² In choosing this location we're assuming the cavity is singly-resonant and therefore any remaining idler is weak following three mirror reflections – a reliable assumption. We're also assuming identical *s*- and *p*-reflective phase shifts on M3 and M4, as described in section 2. If for some reason M3 and M4 are not identical mirrors, it's OK to use two waveplates oriented at 0° in a one-crystal cavity.

The following procedure is suggested for installing the waveplates. Note that steps for optimizing linear polarization purity can be omitted if a suitable test laser is unavailable. Although less rigorous, optimization of waveplate orientation is possible by monitoring output energy near the oscillation threshold.

- Place a waveplate holder on clean flat surface and gently drop in a waveplate using fiber-tipped tweezers.
- Visually align the flat on the plate so that the appropriate alignment mark is in the middle of the flat. Rotate the plate by gently pushing on the exposed edge of the waveplate.
- Apply a very small amount of UV glue to the edge of the plate at just one point. Use a needle for applying the glue. Cure the glue with the UV light source.
- Install the plate in the RISTRA's cylinder and install the appropriate mirrors for testing orientation of the polarization.
- Repeat all steps but the preceding one if you have a two-crystal cavity.

- The following steps can be omitted if you don't have a suitable test laser.

¹²Unfortunately there aren't many birefringent materials suitable for making waveplates with sufficiently high damage thresholds for $\lambda \ge 4.5 \ \mu$ m. Sapphire is a good choice if it can be used.

- For a one-crystal cavity:

- The RISTRA should be completely assembled so that it can be mounted on the optical table or a breadboard.
- Remove M2. The wavleplate can be installed between M2 and M3, or between M4 and M1 as discussed previously.
- Inject linearly polarized laser light at the resonant wavelength through the opening for M2 along the path M2 \rightarrow M3. It can be *s* or *p*-polarized, but will preferably have the polarization of the resonated wave as it leaves C1 in lower leg.
- After aligning the beam to the cavity, use a polarizer aligned to transmit one polarization component as the light exits along the path M1 \rightarrow M2.
- Rotate the waveplate as necessary to extinguish, or at least minimize, the unwanted *s* or *p*-polarization component.

- For a two-crystal cavity:

- Install M3 alone and the wavelplate between the locations of M2 and M3
- Install the polarizing beam-splitter cube holder described in Appendix D with a PBS cube in place to extinguish one polarization component.
- Inject linearly polarized laser light at the resonant wavelength through the opening for M2 along the path M2 \rightarrow M3. It can be *s* or *p*-polarized, but will preferably have the polarization of the resonated wave as it leaves C1 in lower leg.
- Rotate the waveplate between M2 and M3 as necessary to extinguish, or at least minimize, the unwanted polarization component for light exiting through the hole for M4.
- Now install M4 and M1 and the waveplate between M4 and M1.
- After aligning the beam to the cavity, use a polarizer aligned to transmit one polarization component as the light exits along the path M1 \rightarrow M2.
- Rotate the waveplate between M4 and M1 as necessary to extinguish, or at least minimize, the unwanted polarization component.
- Lock the adjuster(s) for orientation angle and remove the waveplate(s). If you were able to adequately adjust the orientation of the wavelplate(s) then add two more very small drops of UV glue and cure the glue.

If you didn't have a test laser available for the previous steps, waveplate orientation can optimized by maximizing output energy near the oscillation threshold. The signature of optimized polarization will likely be difficult to observe for higher pump fluence, so oscillation near threshold is strongly suggested.

5.3.1 Adjusting the angle of incidence for the waveplates

The waveplate holders also allow adjustment of tilt about an angle of incidence near 0° . This adjustment was included because waveplates often behave like étalons even though we don't want them to. Because the resonated light passes through the intra-cavity waveplates many times during a pump

pulse, a small loss associated with étalon transmission can reduce the efficiency. This effect can be observed in broadly tunable cavities, resulting in periodic oscillation of output energy as the wavelength is changed, and it can also affect performance of single-frequency oscillation. For broad tuning little can be done except to get waveplates with very good anti-reflection coatings. However for single-frequency oscillation at a fixed wavelength, output energy can be optimized by adjusting the angle of incidence of the waveplates. After oscillation in a single-frequency RISTRA OPO has been optimized – pump beam well aligned and $\Delta k = 0$, as described in subsection 6.2 and subsection 6.3 – try tilting the angle of incidence to see if it influences output energy. The fringe signal for the seed laser might also indicate maximum étalon transmission. It will probably be easiest to optimize transmission while scanning the seed laser frequency, or cavity length, with the servo loop open.

6 Use of the RISTRA OPO

In subsection 6.1–subsection 6.3 we describe how to safely use the RISTRA OPO and how to carry out initial optical alignment. We also describe in detail how to injection seed the RISTRA for applications requiring single frequency oscillation.

6.1 Eye safety with nonplanar geometry

Exposure to the high power laser radiation emitted by nanosecond OPOs, and by the Class-IV Q-switched lasers that pump them, poses a significant ocular hazard. Unfortunately these hazards are increased by the nonplanar geometry of the RISTRA cavity, in particular for one that contains two crystals. If the pump wave is *o*-polarized M4 will likely be the pump-beam exit mirror for two-crystal designs, with M1 the input coupler. For this configuration the pump beam leaves the cavity at an angle of approximately 65° with respect to horizontal and therefore posses a significant hazard. Because peak intra-cavity irradiance can easily exceed 100 MW/cm² the beam for the non-resonant wave, and leakage of the cavity mode through high-reflecting mirrors, also pose significant hazards. When using the RISTRA OPO always use the utmost care to locate all stray beams exiting the cavity and use beam dumps or some form of enclosure to capture them.

To reduce the hazard posed by a high power pump beam that exits through M4, AS-Photonics offers a beam dump assembly that attaches to the RISTRA body that blocks this beam. This assembly also incorporates a mirror that redirects beams exiting through mirror 4 so that they propagate parallel to the optical table. One use for this mirror is to separate the resonated wave from the pump beam to observe cavity fringes for a lock signal when a PZT mirror assembly is attached at the location of M3. See Appendix D for this assembly and other accessories.

6.2 Pump beam delivery and alignment

Aligning the pump beam to the RISTRA cavity is relatively simple but unlike a typical open cavity, the pump must propagate within the round bores of the RISTRA's cylindrical body. Given it's a solid chunk of metal with apertures formed by mirror retaining rings and waveplate holders, it's important to begin alignment using very low pulse energy. A misaligned high-energy beam that strikes metal and forms a plasma can damage expensive optics and crystals. Some high-energy Q-switched lasers suitable for

pumping the RISTRA offer pulse energy control, but if this is not available we suggest the optical setup shown in Figure 21.

Figure 21: Alignment of the pump beam. If your pump laser lacks energy control use a half-waveplate and thin film polarizer to attenuate the beam during initial alignment. The turning mirrors labeled HR 45° should be selected for s(p)-polarization when M1(M2) is the input coupler. For large beam diameters (≥ 7 mm flat-top, ~ 5 mm $1/e^2$ Gaussian) pump-beam alignment can be critical for the RISTRA cavity because the beam must pass through the bores of the cylindrical body without clipping and must clear the apertures formed by mirror retaining rings and waveplate holders. $\lambda/2$ = halfwaveplate; HR = high reflector.

With any alignment procedure you should use two mirrors to facilitate "walking in" the beam, as shown in Figure 21. And because the RISTRA's removable base is indexed, you can pre-align the pump beam to the center of the cavity bore without the cavity in place. You might also consider compensating in advance for the vertical offset at M1, or the horizontal offset at M2, depending on where the pump enters the cavity. This correction can be important for high-index IR substrate materials such as ZnSe or ZnS when a small diameter pump beam must overlap an injection-seeded cavity mode, or if a large diameter beam fills most of the input coupler's clear aperture. You should also pay attention to the walkoff displacement for an *e*-polarized pump wave when its diameter is ≥ 6 mm for a flat-topped spatial profile. For Gaussian pump beam profiles be aware of the extent of the wings. For a true lowest-order Gaussian the maximum diameter is about 5 mm $(1/e^2)$ or < 3 mm (FWHM).

Following initial alignment – and before you increase the pump energy – you might be able to *carefully* observe the position of the pump beam on the cavity mirrors. For a one-crystal RISTRA only two mirrors are involved but with two crystals the pump impinges on all four mirrors, with two being high reflectors. Weak scatter from high reflectors might be observable from the backside of the mirrors, but some coatings, notably ion-beam sputtered coatings, can have such low scatter that the beam spot is difficult to see. This is especially true for IR pump beams. If the pump enters through M1 and exits trhough M4 you can also test alignment by comparing the positions of the reflected and transmitted spots on the RISTRA's base plate. For an injected seeded pump laser an interference fringe pattern may be observable below M1, indicating the pump is reasonably well aligned. Note however that the positions of the pump-beam spots on mirrors, or a fringe pattern below M1 on the baseplate, indicate approximate, but not final alignment. After it's safe to increase pump energy, final alignment is obtained by optimizing output energy near the oscillation threshold. For two crystal cavities it's best to optimize energy after both crystals are rotated to have the same phase matching angle. For injection

seeded cavities the seed wavelength provides a reference for $\Delta k = 0$, whereas free running oscillation places less constraint on the phase matching angles. Additional details for injection seeded operation are given in subsection 6.3.

Finally, for two-crystal cavities with an *e*-polarized pump beam pure *o*-tilt (vertical) or pure *e*-tilt (horizontal) in the lower crystal C1 results in a combination of *o*- and *e*-tilt in the upper crystal C2. This consequence of nonplanar geometry may be confusing at first but you'll get used to it. Just make adjustments to pump beam tilt in small increments and re-optimize crystal rotation angles as necessary.

Here are a few things to remember when aligning the pump beam:

- Begin alignment with very low pulse energy
- Don't rush and damage expensive optics or crystals
- Install a thin film polarizer and half-waveplate to control pulse energy if your pump laser lacks energy control
- If possible set beam height and propagation direction before installing the RISTRA assembly in the beam path. This step will result in a pump beam that is fairly well aligned to begin with. The center of the lower bore of the RISTRA is 2.25" above table, and it is laterally centered on the base plate.
- Use two mirrors to walk-in the pump beam as shown in Figure 21
- Exercise caution when observing beam spots on the back sides of high reflecting cavity mirrors, or the positions of beams exiting the cavity.
- And finally, for two-crystal cavities with an *e*-polarized pump beam, be aware that pure *o* or *e*-tilt in the lower crystal C1 results in a combination of *o and e*-tilt in the upper crystal C2.

6.3 Injection seeding for single frequency oscillation

When a singly-resonant nanosecond OPO is injection seeded by a cw laser and pumped by a single frequency laser, it can generate temporally transform limited pulses at the seed laser wavelength. Despite some claims to the contrary, using a broadband pump laser and an injection seeded OPO will usually not obtain a true transform limited bandwidth. This is the case for a pump pulse with strong amplitude modulation – a characteristic common to homogeneously-broadened solid-state gain media such as Nd:YAG. With an amplitude modulated pump the resonated spectrum will consist of a strong carrier at the seed laser frequency accompanied by weak AM sidebands. For many applications the spectral narrowing obtained for broadband-pumped injection-seeded oscillation will be sufficient but it's unlikely to be temporally transform limited. Under these conditions the spectrum of the unresonated wave can also be narrowed slightly but it largely retains the broadband character of the pump.

Injection seeding a ring cavity, even a nonplanar cavity like the RISTRA, is relatively easy. A ring geometry often allows injecting a seed beam through a partial reflector like the output coupler without inserting a beam splitter in high power beams as they leave or enter the cavity. OPO cavities also circulate light at all times because they don't contain active or passive Q-switches, so robust cavity locking techniques that generate a continuous error signal such as first derivative dither-lock (i.e., traditional

phase-sensitive detection), or Pound-Drever-Hall (PDH) [11, 12], are simple to implement.¹³ Although discrete sampling techniques such as cavity build-up time or feed-forward approaches such as rampand-fire can be used with nanosecond OPOs, continuous error correction usually provides a tighter lock and better frequency stabilization.

The laser that is used to injection seed the OPO must oscillate on a single longitudinal mode, and the injected beam must have little wavefront aberration and be well collimated. Although a lowest-order Gaussian spatial profile works well for seeding, it is not mandatory. Other profiles are useful for special applications such as pulsed injection seeding, where the seed-beam spatial profile can be selected to strongly influence the spatial profile of the OPO's resonated wave [13]. For most seeding applications the beam that emerges from a single-mode polarization-maintaining fiber, following collimation, provides an excellent spatial profile. The optical power required for seeding can be as low as a few μ W, or even lower, but should be sufficient to generate an error signal that is well above the baseline electronic noise in the detector, and in the electronics comprising the servo system.

Owing to its nonplanar design initial alignment of the seed beam to the RISTRA cavity may seem a bit daunting, but you'll find it's relatively straight forward. When the seed beam is initially injected, dithering the seed-laser frequency, or equivalently the OPO cavity length, will reveal a resonated wave that usually has little resemblance to a cavity mode. The spatial profile for leakage from a high reflector may consist of an interference pattern containing tens to hundreds of spots. At this point focusing the light onto a detector and looking for cavity fringes on an oscilloscope in xy-mode is usually of little use. The best way to proceed is to view the weak leakage using a beam profiler and "walk-in" the seed beam until the number of spots diminishes and modes begin to appear. A lens can then be used to focus the light onto the active area of a detector, typically a Si or InGaAs PIN photodiode, and look for fringes on an oscilloscope. Adjustments will continue until the fringe pattern observed on the scope consists entirely of the one-time-around mode described in subsection 2.2. Initial alignment can be simplified using the seed-beam propagation direction indicated in Figure 22 for a beam injected through the output coupler M2 that circulates in the direction M1 \rightarrow M2 \rightarrow M3 \rightarrow M4, and Figure 23 shows typical optical setups for seeding one- and two-crystal RISTRA OPOs. Figure 24 shows typical evolution of the seed beam's spatial mode from initial to final alignment, and Figure 25 shows seed-beam cavity fringes at various stages of alignment.

The electronics and additional optics required to frequency stabilize an OPO are not too expensive and consist of standard optical and RF components. Depending on the application the seed laser might be locked to the OPO, or the OPO locked to the seed laser. If your application requires single-frequency oscillation but the exact wavelength is not critical, then the laser can be locked to a standard RISTRA cavity. An example application might be high efficiency sum-frequency generation, where the OPO's output pulse is mixed with the pulse from an injection seeded pump laser [14]. If instead your application requires that a specific wavelength falls within the spectral bandwidth of the OPO's pulse, then the OPO must be locked to the laser. This configuration requires that a cavity mirror be mounted on a piezoelectric transducer (PZT) to control cavity length. For this configuration AS-Photonics sells a PZT

¹³There may be some confusion about what constitutes PDH locking. If the low-amplitude first-order modulation sidebands (modulation index \ll 1) lie within a cavity resonance this is traditional phase-sensitive detection, even if the modulation frequency is several hundred MHz. Following demodulation and low-pass filtering the error signal will be the familiar first derivative. If the first-order sidebands lie outside the resonance, and following demodulation you retain a high bandwidth for error correction, then this is true PDH. The high bandwidth is usually unnecessary for stabilizing ns OPOs, and sidebands outside the one-time-around resonance of the RISTRA may cause problems as they could couple to the vortex modes described in subsection 2.2.

Figure 22: Alignment of the injection seeding beam through cavity mirror M2 for propagation in the direction $M1 \rightarrow M2 \rightarrow M3 \rightarrow M4$. Begin by aligning the seed beam parallel to the flat surface of the RISTRA assembly's base plate. Then use a protractor to set the incident angle on M2 as shown. This is a common configuration for one- and two-crystal cavities. If the direction of propgation is reversed, $M4 \rightarrow M3 \rightarrow M2 \rightarrow M1$, with M1 the output coupler and and M2 the input coupler, it's easiest to inject the seed beam through M3. Approximate initial alignment helps reduce the complexity of the interference pattern shown in Figure 24(a).

Figure 23: Two typical optical setups for injection seeding the RISTRA OPO cavity. (a) One-crystal cavity. (b) Two-crystal cavity. The nonplanar RISTRA cavity is projected onto the page as a rectangle with mirrors M1–M4 indicated. In these examples we're assuming a spectroscopic application where the OPO cavity must be stabilized to a specific seed wavelength and therefore requires piezo-electric transducers (PZTs). If an exact wavelength is not required the seed laser can be locked to the cavity and the PZT's are not needed. In that case the servo amplifier sends a correction signal to the laser controller instead of to the cavity mirror PZT. In either case we prefer to generate an error signal by modulating the laser frequency rather than slowly dithering the cavity length. See Figure 26 for information on electrical components required for cavity stabilization and see text for additional details. RF = radio frequency, LO = local oscillator, $\lambda/2$ are half-wave retardation plates.

Figure 24: Weak leakage of the resonated wave through a high-reflecting mirror of the RISTRA cavity during seed-beam alignment. In these examples the laser frequency, or the cavity length, is being swept over at least one free spectral range so that (a) and (b) represent "snapshots" of patterns that otherwise evolve in time. (a) During initial alignment image-rotating cavities can produce very complicated patterns. (b) As the seed beam is "walked in" patterns suggesting actual cavity modes begin to appear. At this point the light can collected with a lens and focussed on a detector to observe fringes on an oscilloscope. (c) Well aligned seed beam exiting the cavity through a high reflector. The upper right corner in (a)–(c) contains a weak secondary reflection.

Figure 25: Typical fringes observed during alignment of the seed laser to the RISTRA cavity. When the spatial mode pattern in Figure 24(b) is initially focused onto a detector the corresponding fringe pattern (not shown) might initially resemble a sine wave but following small adjustments will begin to display recognizable fringes. (a) The cavity is poorly aligned with the two- and four-times modes described in subsection 2.2 easily observed. (b) Cavity alignment is better but the amplitude of the redand blue-shifted four-times modes is still too large. (c) The cavity is well aligned so that only one-time modes are observed. Note that there may always be a small amount of coupling of the seed laser to the off-axis modes but this will not result in any significant admixture to the one-time mode once the cavity it locked because they are non-degenerate in frequency with shifts ± 0.25 free spectral range.

assembly that attaches to the RISTRA's cylindrical body using the threaded holes for a mirror retaining ring. Figure 26 illustrates locking the OPO to the laser, where a servo amplifier sends a correction signal to a PZT. To lock the laser to the OPO, the servo amplifier would instead supply a correction signal to the laser controller. For either locking method we prefer modulating the laser light rather than slowly dithering a cavity mirror. For example, modulating the current in semiconductor lasers can produce a phase modulated seed spectrum that works well for phase sensitive detection, although it will contain a small amount of residual AM (RAM). Following demodulation, the DC offset that occurs from RAM is easily eliminated by adjusting the DC input-offset on most servo amplifiers.

Regardless of how the seed laser remains resonant with the OPO cavity – adjust the seed frequency or adjust the cavity length – we recommend using phase-sensitive detection for stabilization. This technique is robust, simple to implement, and electrical components such as balanced mixers, voltagecontrolled oscillators (VCOs), and low-pass filters are available in convenient coaxial packages that are small and inexpensive. An expensive lock-in amplifier is not necessary. Figure 26 shows a block diagram using discrete components for cavity length stabilization using phase sensitive detection. As discussed in a previous footnote this is sometimes referred to as PDH stabilization, but in our examples we're assuming the low-amplitude first-order modulation sidebands (modulation index $\ll 1$) lie within the OPO's cavity resonance. For true PDH stabilization the modulation frequency exceeds the cavity resonance width, but will be less than the cavity's free spectral range. Applying this technique to the RISTRA is unnecessary and might unintentionally excite the RISTRA's vortex modes, as described in subsection 2.2.

After the OPO can be locked – and remain locked barring major perturbations such as pounding on the optical table or changing the crystal rotation angle a significant amount - you must rotate the crystal(s) to locate $\Delta k = 0$ for the seed laser wavelength. This can be done by pumping just above the threshold for unseeded oscillation and observing OPO pulses using a scope and detector that each have bandwidths \gtrsim 200 MHz. While the crystal is rotated to change the phase matching angle the OPO pulse energy will increase significantly when $\Delta k \approx 0$. This technique works well if you know that the crystal is rotated close to the correct angle to begin with and requires only minor adjustments. If instead the error in the phase matching angle is larger than a few degrees, you may need to simultaneously compare the seed laser wavelength and the wavelength(s) for unseeded oscillation.¹⁴ You can use a pulsed wave meter to observe the separate wavelengths, but if your seed wavelength is already accurately known then a secondary absolute measurement using an expensive instrument is unnecessary. A good alternative is an inexpensive grazing-incidence grating followed by a lens with focal length \gtrsim 1 m to observe the spectrum in the far-field using a video camera. Each crystal angle is then rotated until its wavelength, and the wavelength for the seed laser, coincide. Note that rotating the crystals through large angles may force the cavity out of lock so large angle tuning may be easier with an open servo loop. Independent of the initial technique to find $\Delta k \approx 0$, final crystal-angle adjustments can be made by maximizing OPO pulse energy with the pump set just above the threshold for seeded oscillation. Of course with a seed wavelength longer than about 2 μ m video cameras are scarce and expensive so the initial search for $\Delta k \approx 0$ may be restricted to observing OPO pulse energy, and may therefore be more tedious.

A few final comments are in order. Even if you have experience with injection seeding of nanosecond OPOs, or with alignment of stable build-up cavities, the geometry of the RISTRA can present a few

¹⁴If your OPO contains two crystals you will likely observe three wavelengths: The seed laser and one wavelength for each crystal. How may wavelengths you observe and how easily they can be observed will depend on how hard the OPO is pumped.

Figure 26: Block diagram showing discrete, inexpensive electronics for cavity length stabilization using phase sensitive detection. This example uses a distributed feedback (DFB) or distributed Bragg reflector (DBR) semiconductor laser as the seed source. When available these lasers are convenient because their frequency stability and linewidth are adequate for seeding low finesse OPO cavities, and their packaging sometimes includes SMPM fiber pigtails with FC/APC connectors. Optical phase modulation is achieved through the laser driver's RF input. In this example the OPO cavity is locked to the seed laser using a low-voltage PZT stack for cavity length stabilization. To lock the laser to the cavity the PZT assembly is removed and the dashed line marked "Servo in" supplies a correction signal to the laser driver's servo input. Note that the phase shifter may be optional as small changes in the VCO frequency may obtain the correct phase for demodulation. AS-Photonics can suggest vendors for many of the components shown here. Definitions: IF = intermediate frequency; LO = local oscillator; RF = radio frequency; PZT = piezo-electric transducer, SMPM = single-mode polarization-maintaining; FC/APC = FC-angle polished connector; TV = tuning voltage; VCO = voltage controlled oscillator.

unexpected pitfalls, so here are a few things to keep in mind. Don't saturate the fringe detector, and start out by scanning slowly through at most about three free spectral ranges. If the one-time around fringe saturates the detector, the relative height of the four-times-around fringes – the ones you're trying to eliminate – will be exaggerated, and it might appear that you can't achieve good seed-beam alignment. Most PIN photodiodes can accommodate about 1 V into 1 M Ω before they begin to saturate, although it's generally a good to keep their output voltage much lower. Also, be sure to maintain complete spatial overlap of the cavity leakage with the fringe detector's active area. As shown in Figure 24(b) spatial separation between lobes for the various modes of this cavity can result in missing information unless the entire leakage beam impinges on the fringe detector. If you use a fiber-coupled detector it goes without saying that you shouldn't try to use a single mode fiber. Finally, the RISTRA mechanical assembly may be rock-stable due to its quasi-monolithic design but most mirror mounts are comparatively flimsy. When making fine adjustments to the turning mirrors used for seed beam alignment, lightly touch and then release the knobs on mirror mounts. When you touch a mirror mount during alignment you may find the fringe pattern changes abruptly upon contact.

6.3.1 Injection seeding improves beam quality

Although nanosecond OPOs are usually injection seeded for applications requiring single frequency oscillation, seeding can also improve beam quality. For a nonplanar cavity like the RISTRA, broadband oscillation can allow simultaneous oscillation of off-axis modes such as the four-times-around vortex modes described in subsection 2.2. How many of these modes might oscillate and with what fraction of the total pulse energy depends on the cavity Fresnel number \mathcal{F} , the mixing parameters for a given crystal, and the pump beam spatial profile, with the latter sometimes enhancing excitation of these modes. For example, some diffractively-coupled Nd:YAG laser oscillators produce donut-like beam profiles that can excite the vortex modes at the expense of the one-time-around mode. An admixture of these modes reduces beam quality because they remain hollow at all propagation distances, they have helical wavefronts that combine with flat wavefronts to produce highly structured interference patterns, and they have comparatively large far-field divergence angles. Fortunately these modes can be eliminated almost entirely by injection seeding the higher gain one-time-around mode. If you have no choice but to use a donut-like pump-beam, the overall conversion efficiency may be lower than anticipated, but seeding will dramatically improve the beam quality for the resonated wave, and even for the unresonated wave, in most cases. If your application requires the best possible beam quality, especially for higher output energies, you might consider the extra effort, and cost, of injection seeding the cavity – even if you have a near-perfect pump beam profile.

Appendices

A Dimensions and specifications for the RISTRA OPO

Table 1 contains the dimensions for the RISTRA OPO mechanical assembly and for its optical components. Not included are specifications for small hardware and other minutiae.

Cylindrical body	Length = 50.017 mm	OD = 37.64 mm
Cavity	Physical length $\approx 109 \text{ mm}$	Cavity Bore ID = 10 mm
Cavity Legs	$Long \approx 31.925 \text{ mm}$	Short = Long/ $\sqrt{2} \approx 22.575$ mm
Beam height	Center of lower bore at 2.25 in.	
Max. beam diameter	Flat-topped \approx 7 mm	Gaussian $\approx 5 \text{ mm} (1/e^2)$
Base dimensions	3.75×2.75 in.	1/4-20 hole pattern 3.0×2.0 in.
Assembly height	One-crystal = 3.51 in	Two-crystal = 4.31 inch
Crystal apertures	Max width = 10 mm	Height = 10 mm

Table 1: Dimensions and specifications for the RISTRA OPO

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Crystal length	Nominal max 15 mm	Absolute max 17–18 mm for $10 \times 10 \text{ mm}^2$ aperture
Crystal rotation	Range $\pm 10^{\circ}$ for $10 \times 10 \times 15 \text{ mm}^3$ crystal	Resolution $\approx 20.4 \text{ mrad } (1.17^{\circ})$ per actuator turn
Cavity mirrors	Dia = 0.5 + 0.0, -0.010 in	Thick = 0.125 ± 0.010 in
Angle of incidence	All mirrors $\approx 32.765^{\circ}$	
Waveplates	Dia = 0.5 + 0.0, -0.010 in	Max thickness $\approx 3 \text{ mm}$
PZT assembly	Total displacement = 15μ m	Midpoint voltage = 50V

Note: Be sure to order mirrors which do not have beveled edges on the outward-facing side. To minimize strain on the mirrors, which would affect the beam quality, the mirrors are secured only by three short clips on the mirror-retaining ring. These clips might not securely fasten a mirror with beveled edges.

B Example configurations and performance specifications

Previous uses of the RISTRA OPO include remote sensing platforms and prototype development for various applications. Some published and un-published examples are described below. Wavelengths are in nm unless otherwise stated. Table 2 provides a brief overview of specifications for a few applications. Detailed descriptions follow below in the same order.

Configuration	Mixing & Crystal(s)	Pump beam	Output (mJ)
two-crystal 803 nm resonant injection seeded	$532(o) \rightarrow 803(e) + 1576.4(o)$ xz-cut KTP (2) 10 × 10 × 15 mm ³	6 mm dia. flat-top duration 10 ns	14 at 803 nm
intra-cavity SFG 803 nm resonant injection seeded	$532(o) \rightarrow 803(e) + 1576.4(o)$ xz-cut KTP, $10 \times 10 \times 15 \text{ mm}^3$ $532(o) + 803(e) \rightarrow 320(e)$ type-II BBO, $10 \times 10 \times 10 \text{ mm}^3$	6–7 mm dia. flat-top duration 10 ns	140 at 320 nm
two-crystal 1550 nm resonant injection seeded	$1064(o) \rightarrow 1550(o) + 3993.4(e)$ xz-cut KTA (2) $10 \times 10 \times 17 \text{ mm}^3$	5 mm dia. 2nd-order super-Gaussian duration ≤ 10 ns	170 at 1550 nm

 Table 2: Example performance specifications

one-crystal 3400 nm resonant unseeded	$\begin{array}{c} 2050(o) \rightarrow 3400(e) + 5163(e) \\ \text{ZGP} \\ \text{length 10 mm} \end{array}$	4.0–4.5 mm dia. $(1/e^2)$ Gaussian duration > 14 ns	10 at 3400 nm
two-crystal 1627 nm resonant unseeded	$1064(o) \rightarrow 1627(0) + 3074.8(e)$ xz-cut KTP $10 \times 10 \times 14 \text{ mm}^3$ $10 \times 10 \times 17 \text{ mm}^3$	6 mm dia. semi donut profile duration ≤ 7 ns	100 at 1627 nm

Application: Demonstration of very high conversion efficiency and very high beam quality using pulsed injection seeding

Configuration: Two-crystal 803 nm resonant with pulsed injection seeding (self seeded) *Mixing:* $532(o) \rightarrow 803(e) + 1576.4(o)$

Crystals: Aperture $10 \times 10 \text{ mm}^2$, length 15 mm, *xz*-cut KTP, $\theta = 58.4^\circ$, $\phi = 0^\circ$

Output coupler: R = 0.7 at 803, *R* > 0.98 at 532, *R* < 0.04 at 1576.4

Waveplates: Two. Custom multi-order double $\lambda/2$ for 532 and 803

Pump beam: Injection seeded Nd:YAG 2ω , 6 mm diameter flat-topped spatial profile, duration 10 ns.

Seed beam: Pulsed 50 μ J–1 mJ, 6 mm diameter flat-topped spatial profile

Output: Maximum energy (at 803 nm) \sim 14 mJ

Pump depletion: Measured with high accuracy at 90%

Beam quality: M^2 not measured. Approximately 60% of 803 nm energy within diffraction limited spot in far field

Reference: Opt. Lett 31, 380–382 (2006)

Comments: Designed for low energy output but very high pump depletion. Developed before we appreciated using unequal length crystals. Higher pump depletion may be possible. Flat-topped 803 nm beam in near field not well characterized by M^2 .

Application: High energy UV generation at 320 nm for prototype ozone DIAL system using intracavity sum-frequency generation

Configuration: Two-crystal, 803 nm resonant with pulsed injection seeding (self seeded) Mixing for OPO: $532(o) \rightarrow 803(e) + 1576.4(o)$ Crystal for OPO: Aperture $10 \times 10 \text{ mm}^2$, length 15 mm, *xz*-cut KTP, $\theta = 58.4^\circ$, $\phi = 0^\circ$ Mixing for SFG: $532(o) + 803(e) \rightarrow 320(e)$ Crystal for SFG: Aperture $10 \times 10 \text{ mm}^2$, length 10 mm, type-II BBO, $\theta = 48.2^\circ$ Output coupler: R = 0.85 at 803, R > 0.98 at 532, R < 0.04 at 1576.4, R < 0.02 at 320 Waveplates: Two. Custom multi-order double $\lambda/2$ for 532 and 803 Pump beam: Injection seeded Nd:YAG 2ω , 6–7 mm diameter flat-topped spatial profile, duration 10 ns.

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Seed beam: Pulsed $\sim 400 \,\mu$ J, 6–7 mm diameter flat-topped spatial profile

Output: Maximum 803 nm energy not known, maximum UV energy \ge 140 mJ

Pump depletion: Not accurately measured

Conversion efficiency: 532 to 320 approximately 33%

Beam quality: Not known for 803 nm, poor for UV

References: SPIE **5710**, 1–8 (2005); IEEE J. Sel. Topics Quantum Electron. **13**, 721–731 (2007)

Comments: Pump passes through SFG crystal first. Conversion efficiency and beam quality degraded by two-photon absorptive heating in BBO SFG crystal. Extra-cavity SFG to generate 320 nm was also demonstrated using the OPO described in Opt. Lett **31**, 380–382 (2006). Using post amplification of the OPO's 803 nm beam to an energy of ~ 100 mJ, then SFG with additional 532 nm pump, 320 nm energy reached 190 mJ. Extra-cavity SFG conversion efficiency also suffered from absorptive heating in BBO.

Application: Demonstration of high energy eye-safe source at 1550 nm

Configuration: Two-crystal 1550 nm resonant with cw injection seeding Mixing: $1064(o) \rightarrow 1550(o) + 3993.4(e)$ Crystals: Aperture $10 \times 10 \text{ mm}^2$, length 17 mm, xz-cut KTA, $\theta = 79.6^\circ$, $\phi = 0^\circ$ Output coupler: $R \approx 0.7$ at 1550, R > 0.98 at 1064, $R \approx 0.04$ at 1576.4 Waveplates: Two. Custom multi-order double $\lambda/2$ for 1064 and 1550 Pump beam: Injection seeded Nd:YAG 1 ω , approximately 2nd-order super-Gaussian with $\sim 5 \text{ mm} (1/e^2)$ diameter, duration $\leq 10 \text{ ns}$. Seed beam: cw, spatially filtered, $\sim 2 \text{ mm} (1/e^2)$ diameter Output: Maximum energy (at 1550 nm) $\sim 170 \text{ mJ}$ Pump depletion: Highest conversion efficiency $\sim 55\%$ Beam quality: $M_{\parallel}^2 \approx 3.8$, $M_{\perp}^2 \approx 4.2$, (\parallel denotes in direction of walkoff) Reference: SPIE **5337**, 71–80 (2004) Comments: Undesirable ooe mixing dictated by small d_{eff} for oeo mixing in KTA. One KTA crystal had refractive index inhomogeneities resulting in reduced conversion efficiency and

Application: Prototype 3.4 μ m source for laser ultrasonic testing

Configuration: One-crystal 3400 nm resonant unseeded Mixing: $2050(o) \rightarrow 3400(e) + 5163(e)$ Crystal: Aperture NA, length 10 mm, ZGP, $\theta = 55.8^{\circ}$ Output coupler: $R \approx 0.5$ at 3400, R not reported for 2050 and 5163 Waveplates: One. Multi-order $\lambda/2$ for 3400 Pump beam: Broadband Ho:YLF 1 ω , lowest-order Gaussian with 4.0–4.5 mm (1/ e^2) diameter, duration > 14 ns. Seed beam: unseeded

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reduced beam quality.

Output: Maximum energy (at 2400 nm) > 10 mJ *Pump depletion:* ~ 35% *Beam quality:* M^2 not measured but far-field divergence indicates $\leq 1.8 \times$ diffraction limited *References:* SPIE **6875**, 687507-(1–10), (2008); Opt. Express **15**, 14404–14413 (2007) *Comments:* This repetition rate for this system was as high as 500 Hz. At 100 Hz, following post amplification in another ZGP crystal, the power output was 30–40 W.

Application: Remote sensing source at 1627 nm

Configuration: Two-crystal 1627 nm resonant unseeded

Mixing: $1064(o) \rightarrow 1627(0) + 3074.8(e)$

Crystals: Aperture $10 \times 10 \text{ mm}^2$, length 17 mm, *xz*-cut KTP, $\theta = 72.9^\circ$, $\phi = 0^\circ$

Output coupler: $R \approx 0.55$ at 1627, R > 98% at 1064, R < 4% at 3074.8

Waveplates: Two. Custom multi-order double $\lambda/2$ for 1627 and 1064

Pump beam: Broadband Nd:YAG 1 ω , semi donut profile (not dark in center), 6 mm diameter, duration \leq 7 ns.

Seed beam: Unseeded

Output: Maximum energy (at 1627 nm) \sim 100 mJ for 450 mJ pump energy

Pump depletion: Not measured

Beam quality: M^2 not measured but far-field divergence indicates substantial admixture of vortex modes. At least $4 \times$ diffraction limited, probably worse.

References: Not published

Comments: This is a good example of why the eye-safe region is a challenge, resulting in low conversion efficiency and poor beam quality. An idler near 3000 nm allows use of KTP rather than the more expensive KTA, but we are still forced to choose *ooe* mixing with larger d_{eff} and very small walkoff rather than *oeo* mixing with larger walkoff and lower d_{eff} . The pump laser was a Continuum Inlite – which was not designed for pumping OPOs – but is attractive to lidar developers owing to its small ruggedized package. It has a donut-like profile, which for unseeded oscillation in the RISTRA enhcances excitation of vortex modes.

C Example cavity mirror specifications

The example model results in section 3 determine output coupler reflectivity with high accuracy but use somewhat idealized reflectivity values for the pump and un-resonated wave. Typically in nanosecond OPOs the middle wavelength is resonated so actual specifications for the idler can be relaxed because it has the longest wavelength and will generally achieve high transmission through "thin" coatings designed for the two blue waves. What we want is a cavity that is singly-resonant, and with four mirror reflections that can be achieved rather easily for the un-resonated wave. Consequently, mirror specifications should give the thin film coater some room to adjust the design to achieve the best performance while retaining adequately high optical damage thresholds. Both of the example specifications shown below for a 532 nm pumped KTP RISTRA cavity are similar to those used in Ref. [5], and they reflect this concept, where $R_{idler} \leq 4\%$, although some of the values for R_{pump} and R_{signal} may be optimistic. In

contrast the model inputs in section 3 assume $R_{idler} = 0\%$, but even if we had set it to 1%, this is lower than required in a four-mirror cavity and for some coating designs may be difficult to achieve. Note that for the one-crystal specifications M3 is identical to M4 with side 1 unpolarized, and to reduce the number of coating runs we use the AR coating from side 2 of M2 on side 2 of M3 and M4. We begin with specifications for the mirror substrates, followed by required damage thresholds for the optical coatings. Mirror specifications are then given for two-crystal and one-crystal cavities.

Note: Be sure to order mirrors which do not have beveled edges on the outward-facing side.

SUBSTRATE SPECIFICATIONS

Diameter = 0.5 + 0.0, -0.010 in (12.7 + 0.0, -0.254 mm) Thickness = 0.125 ± 0.010 in $(3.175 \pm 0.254$ mm) Wedge ≤ 1 arc minute Transmitted wavefront: $\lambda/10$ at 633 nm over $\geq 80\%$ of clear aperture Surface quality: Super polish, if applicable for selected substrate material Material: Fused silica

PUMP LASER SPECIFICATIONS AND DAMAGE THRESHOLDS

Laser: Nd:YAG 2 ω , $\lambda = 532$ nm, Pulse length = 10–15 ns, Repetition rate = 10 Hz, Spatial profile: Approximately flat-topped with diameter ≈ 6 mm. Peak power ≤ 200 MW/cm², peak fluence ≤ 2.0 J/cm²

Optical damage thresholds: $\geq 4 \text{ J/cm}^2$ for $\lambda = 532 \text{ nm}$, $\geq 2 \text{ J/cm}^2$ for $\lambda = 800 \text{ nm}$, $\geq 2 \text{ J/cm}^2$ for $\lambda = 1588 \text{ nm}$

MIRROR SPECIFICATIONS FOR TWO CRYSTAL CAVITY

All angles of incidence are $\theta = 32.8^{\circ}$ Nonlinear mixing: $532(o) \rightarrow 800(e) + 1588(o)$

Mirror 1: (Input coupler)

Side 1 (inside): R < 0.25%, $\lambda = 532$ nm, *p*-polarization (best effort: R < 0.5% acceptable) $R \ge 99\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

Side 2 (outside): R < 0.25%, $\lambda = 532$ nm, *p*-polarization $R \le 0.25\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

Mirror 2: (Output coupler)

Side 1 (inside): $R \ge 99\%$, $\lambda = 532$ nm, *s*-polarization

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 $R = 70\% \pm 2\%$, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *s*-polarization

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *s*-polarization R < 0.25%, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *s*-polarization

Mirror 3:

Side 1 (inside): $R \ge 99\%$, $\lambda = 532$ nm, *s*-polarization $R \ge 99\%$, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, unpolarized

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *s*-polarization R < 0.25%, $\lambda = 800$ nm, *p*-polarization R < 4%, $\lambda = 1588$ nm, unpolarized

Mirror 4: (Pump exit)

Side 1 (inside): $R \le 0.25\%$, $\lambda = 532$ nm, *p*-polarization (best effort: R < 0.5% acceptable) $R \ge 99\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *p*-polarization $R \le 0.25\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

MIRROR SPECIFICATIONS FOR ONE CRYSTAL CAVITY

Note: All angles of incidence are $\theta = 32.8^{\circ}$ Nonlinear mixing: $532(o) \rightarrow 800(e) + 1588(o)$

Mirror 1: (Input coupler)

Side 1 (inside): R < 0.25%, $\lambda = 532$ nm, *p*-polarization (best effort: R < 0.5% acceptable) $R \ge 99\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *p*-polarization $R \le 0.25\%$, $\lambda = 800$ nm, *s*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *p*-polarization

Mirror 2: (Output coupler and pump exit)

Side 1 (inside): R < 0.25%, $\lambda = 532$ nm, *s*-polarization (best effort: R < 0.5% acceptable) $R = 70\% \pm 2\%$, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *s*-polarization

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *s*-polarization R < 0.25%, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *s*-polarization

Mirror 3:

Side 1 (inside): R < 1%, $\lambda = 532$ nm, unpolarized $R \ge 99\%$, $\lambda = 800$ nm, unpolarized $R \le 4\%$, $\lambda = 1588$ nm, unpolarized

Side 2 (outside): $R \le 0.25\%$, $\lambda = 532$ nm, *s*-polarization R < 0.25%, $\lambda = 800$ nm, *p*-polarization $R \le 4\%$, $\lambda = 1588$ nm, *s*-polarization

Mirror 4: Mirror 4 is identical to mirror 3

(a) Corner Cube

(b) Beam dump

(c) Piezo mirror adjustment

Figure 27: RISTRA Accessories

Figure 28: Bearing retainer spanner tool.

D Accessories for the RISTRA OPO

Beam block assembly and turning mirror for pump beams that exit at M4: See Fig. 27b. For two-crystal RISTRA OPOs that use M4 as the pump exit mirror we offer an assembly that attaches to the RISTRA cylinder that provides a beam block and an optional turning mirror to redirect the beams parallel to the optical table. The redirection mirror can be wavelength selective to separate the pump beam and resonated wave. This simplifies observation of cavity fringes as required for cavity length stabilization. Can be used in conjunction with the PZT assembly described below when the PZT is attached at the location of M3.

Polarizing beam-splitter cube holder: See Fig. 27a. A diagnostic tool for two-crystal RISTRA cavities with the propagation direction $M1 \rightarrow M2 \rightarrow M3 \rightarrow M4$ that simplifies adjusting the orientation of the intra-cavity waveplates to achieve high linear polarization purity. Attaches temporarily to the RISTRA cylindrical body near M4.

PZT assembly for single frequency oscillation: See Fig. 27c. If you need to stabilize the OPO output to a specific wavelength then you'll need to lock the OPO cavity to a seed laser. This can be done using a PZT assembly that can be attached at the location of M3 or M4, as shown. The PZT is a low-voltage stack with midpoint voltage of 50V and total displacement of 15 μ m. The cavity mirror must be glued to the PZT assembly with precision alignment. AS-Photonics offers this service with the purchase of the PZT assembly.

Cavity mirror installation jig: See Fig. 17. Cavity mirrors for the RISTRA OPO can be expensive so don't risk damaging them during installation. This jig holds the cylindrical body so that the plane for the cavity mirror is horizontal. Having both hands free facilitates placement of the cavity mirrors and retaining rings to reduce the risk of scratching a mirror during installation. This jig is included in all RISTRA purchases at no extra cost.

Bearing retainer spanner tool: See Fig. 28. When assembling the rotation housing, a small nut used to secure the rotation shaft in place. The nut, which threads into the rotation body, is tightened by a spanner tool. The two pins on the spanner tool fit into holes on the nut. This tool is included in all RISTRA purchases at no extra cost.

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