SNLO Help

Arlee Smith[1]

[1] *AS-Photonics, LLC, 6916 Montgomery Blvd. NE, Suite B8, Albuquerque, NM 87109,*
arlee.smith@as-photonics.com

February 25, 2015

1 About SNLO

SNLO is written and maintained by Arlee Smith at AS-Photonics in Albuquerque, New Mexico. It is written in APL programming language. It is continuously updated with the latest version available online at http://www.as-photonics.com/SNLO

For a quick introduction to SNLO read the file SNLO.PDF that is in your SNLO folder, also available online at http://www.as-photonics.com/snlo_files/SNLO.pdf

Should you wish to reference SNLO in a publication please use: 'SNLO nonlinear optics code available from A. V. Smith, AS-Photonics, Albuquerque, NM'

Comments, questions, and suggestions are welcome. Send them to me at: arlee.smith@as-photonics.com

All *.DAT files in SNLO directory are output data files and may be deleted to recover disk space.

To print any of the help pages, double click anywhere in the text of that page. The file SNLO_HELP.PDF is a prettier version of this help. It is available on the SNLO download page.

Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

Additional crystal information is available in the 150 page bibliography CRYSTALS.PDF (in the SNLO directory, and available online), and from the file BETA_N2.pdf which includes tables of reported two-photon absorption cross sections and nonlinear refractive index coefficients. This file may be found in your SNLO folder.

2 Functions

2.1 Ref. Ind.

Ref.Ind. computes the refractive indexes, group velocities, group delay dispersion, and birefringent walkoff angle for uniaxial or biaxial crystals with any propagation direction. This function is useful if you wish to manually calculate phase matching or group velocities for situations not covered by SNLO functions QMIX, QPM, or Opoangles.

You specify the crystal, the temperature, the wavelength, and the propagation direction. The propagation direction is specified by θ (theta) and ϕ (phi) where θ is the polar angle measured from the z-axis and ϕ is the azimuthal angle measured from the x-axis toward the y-axis.

The calculated angle delta is the polarization angle for the eigenpolarization with hi refractive index. The angle is measured from the k-z plane in the clockwise direction as viewed along the propagation vector.

Walkoff is always toward the direction that would lower the refractive index at the highest rate. For negative uniaxial crystals the e wave walks toward $\theta = 90°$, while for positive uniaxial crystals it walks toward $\theta = 0$. The axis system I use for biaxial crystals makes the refractive indexes satisfy $n_x < n_y < n_z$. In biaxial crystals walkoff is in the same plane as the polarization. For the eigenpolarization associated with the hi refractive index, walkoff is in the plane defined by angle delta, while for the lo eigenpolarization walkoff is in the orthogonal plane.

For more information on the individual crystals you can run function QMIX. In QMIX, selecting a crystal will display basic information about that crystal.

2.2 Qmix

QMIX helps you quickly select the best crystal for your application from a list of over 60 crystals. It calculates all the possible phase-matching orientations for the crystal at the wavelengths specified, returning phase-matching angles, polarizations, refractive indexes, group velocities, group delay dispersion, effective nonlinearity, crystal tilt tolerance, acceptance angles, acceptance bandwidths, and acceptance temperatures. The three beams are assumed to have collinear propagation vectors. If the nonlinearity, d_{eff}, is zero, the other properties are not calculated. (If you want to find noncritical wavelengths, use function Ncpm.)

When a crystal is selected from the crystal list its transmission data (if available) is displayed in the plot and also written to the ASCII file CRYST_TR.DAT.

The values of d_{eff} for type 1 or type 2 mixing in uniaxial crystals are for crystals cut for the value of phi that maximizes d_{eff}. The value of phi can be determined from the form of the expressions for d_{eff} for (1 e wave) or (2 e waves) shown in the Qmix window when you select a uniaxial crystal.

For biaxial crystals, propagation is in one of the principal planes. When you choose a biaxial crystal the principal plane selector is activated. Select the plane of interest. I use the axis system in which the refractive indexes obey $n_x < n_y < n_z$. Be aware that this is not a universal convention. To calculate phase matching etc. for propagation that is not in a principal plane use the function BMIX.

Acceptance bandwidths, angles, and temperatures are ranges over which $(L\Delta k)$ varies from $-\pi$ to π. This is 13% greater than the full width at half maximum for the $\text{sinc}^2(\Delta kL/2)$ function that describes mixing efficiency.

The OPO acceptance bandwidth (abbreviated 'OPO accpt bw' and activated by selecting Type OPO) is that for the red1 and red2 waves, assuming the blue (pump) wavelength is fixed. That is, I assume that the red waves tune by equal amounts in opposite directions. The Mix acceptance bandwidths (activated by selecting Type Mix) are those of the red1 and red2. The left number is associated with the first wavelength on the first line of the output, the right number is associated with the second wavelength. I assume in calculating each bandwidth that the other red wavelength is fixed, so the blue wave tunes by the same amount as the specified red wave.

The OPO acceptance bandwidth in [cm^{-1}] for a one cm long crystal is given by $1/(gvi_s - gvi_i)$. The Mix acceptance bandwidths are given by $1/(gvi_3 - gvi_1)$ and $1/(gvi_3 - gvi_2)$ where gvi_x is the x wave group velocity index, related to group velocity by: group velocity $= c/gvi_x$.

Group delay dispersion (GDD) is the change in group delay with change in wavelength. I have chosen units of [fs^2/mm] to conform with common usage. To convert between GVD in [cm/sec $-$ cm^{-1}] and GDD in [fs^2/mm] use GDD $= -5.89 \times 10^{-4}$GVD gvi^2.

The OPO acceptance angles (abbreviated 'OPO accpt ang' and activated by selecting Type OPO) are those for the red1 and red2 waves assuming the blue wave is a plane wave at a fixed propagation angle. Thus the red waves must tilt in opposite directions so the transverse components of their k-vectors are equal and opposite. The Mix acceptance angles (activated by selecting Type Mix) are those of the red1 and red2 wavelengths. Each is calculated assuming the other is a plane wave of fixed angle so the specified wave and the blue waves must tilt in the same direction such that their transverse k-vector components are equal. The angles are internal to the crystal.

The OPO red1 acceptance angle in mrad for a one cm long crystal is given by $0.1 \times {}^{\lambda_1}/_{(n_1[wo_1 - wo_2])}$ where n_1 is the red1 refractive index, wo_1 is the red1 walk off in mrad, wo_2 is the red2 walkoff angle in mrad, and λ_1 is the red1 wavelength in nm. To find the red2 acceptance angle, exchange red1 and red2 in this expression. The Mix red1 acceptance angle in mrad for a one cm long crystal is given by $0.1 \times {}^{\lambda_1}/_{(n_1[wo_1 - wo_3])}$. To find the red2 acceptance angle exchange red1 and red2 in this expression. Diffraction defines the acceptance angle for angle noncritical mixing, but is not included in these acceptance angles. The angles are internal to the crystal.

Crystal angular tolerance indicates the amount of crystal tilt away from the phase-matching direction that makes $\Delta kL = 2\pi$. The individual beams are at fixed angles. Other folks sometimes call this the acceptance angle.

The quantity S_o listed in the Qmix output is defined by $S_o = (\epsilon_o c \lambda_1 \lambda_2 n_1 n_2 n_3)/(8\pi^2 d_{\text{eff}}^2 L^2)$. Divide the output value listed in Qmix by the square of the crystal length in cm to find S_o in [W/cm^2]. For that crystal (of length L), the parametric field gain can be written $\gamma L = \sqrt{S_3/S_o}$, where S_3 is the blue (pump) irradiance in [W/cm^2].

The values of d_{eff} listed are wavelength scaled (usually from those for doubling 1064 nm light). The wavelength scaling is based on Miller's rule, so it is only approximate. According to Miller's rule the value of d_{eff} is weakly wavelength dependent and is reduced at redder wavelengths. The d_{eff} values also include the correction due to the walk off angles.

The last-used QMIX input values are saved in the file MIX.SF. If you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store them. Copy the file back to MIX.SF to restore the settings.

2.3 Bmix

Bmix calculates the properties of biaxial crystals for propagation in any direction including out of the principal planes (in contrast to Qmix where propagation in a principal plane is assumed). Phase matching curves are computed along with the associated effective nonlinearity, walkoff, and acceptance angles. The purple circle on the phase matching plot indicates the location of the optic axes in the x-z plane. Parallel propagation directions (k vectors) are assumed.

All angles are in the optical frame defined by $n_x < n_y < n_z$. Phase matching angles theta and phi are customarily measured from the z axis toward the x-y plane for θ and from the x-z plane toward the y-z plane for ϕ. This is the case for Bmix only if the z-axis is selected as the rotation

axis. Unfortunately, with this convention, plots of the index matching loci are often double valued. To avoid this, select the x or y rotation axis. When x is selected, θ is measured from the x axis and ϕ is measured y-toward-z. When y is selected, θ is measured from the y axis and ϕ is measured z-toward-x. The information is the same no matter which axis is chosen but the display is easier to interpret if the plots are single valued.

The walkoff angles are specified for the two eigenpolarizations, lo and hi. Walkoff of each is in the direction of the eigenpolarization of the optical E field, so the lo and hi walkoff directions are orthogonal. The total walkoff is $\sqrt{\rho_{\rm lo}^2 + \rho_{\rm hi}^2}$. Walkoffs are not specified for the three separate wavelengths because they are approximately independent of wavelength. Ref: F. Brehat and B. Wyncke J. Phys. B: At. Mol. Opt. Phys. vol 22 p 1891 (1989).

The values of $d_{\rm eff}$ listed are wavelength scaled (usually from those for 1064 nm SHG) using Miller's rule. They also include the correction due to birefringent walkoff.

The group velocities are specified for the two eigenpolarizations, lo and hi.

The eigenpolarization directions for the lo and hi refractive indices are not specified here but could easily be added on request.

The range of ϕ is $-90^\circ - 90^\circ$ for $d_{\rm eff}$ plots rather than $0-90^\circ$ as it is for the other plots because $d_{\rm eff}$ can be asymmetric in ϕ, whereas the linear optical properties such as phase matching loci, acceptance angle, and walkoff are symmetric. The signs of $d_{\rm eff}$ require some interpretation. The abrupt sign changes that appear nonphysical are due to the abrupt changes in eigenpolarization directions when the propagation direction changes quadrants.

The results from running Bmix are saved in the ascii file BMIX.DAT in the format displayed by clicking the view button.

Last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

Acceptance angles and acceptance bandwidths can be calculated from the walkoff and group velocity data. See Qmix help for details.

2.4 QPM

QPM calculates properties of quasiphasematched materials including the poling, or domain reversal, period (always specified at room temperature), the temperature bandwidth, the frequency bandwidth, the group velocities, the group delay dispersions. In addition the tuning of phase matched red1 and red2 wavelengths due to blue (pump) tuning or crystal temperature tuning can be computed using the Pump Tune and Temp. Tune buttons. The Sellmeier equations are those referenced in Qmix when a crystal is selected. The temperature range and acceptance bandwidths are calculated as described in Qmix help.

The polarizations of the three waves are chosen in the Pol(s,i,p) list. The propagation direction is any of the directions x, y, or z that allows this polarization set. For example if Pol(s,i,p)=zzz the propagation direction can be x or y; if Pol(s,i,p)=xzx the propagation direction must be y.

QPM data is written to the ascii file QPM.DAT with the format displayed when you click the 'View' button. Temperature tuning and pump wavelength tuning data are written to the ascii files QPMT.DAT and QPMP.DAT.

If the temperature dependence of the refractive index is unknown, the temperature bandwidth and temperature tuning curves are not computed but the other properties are.

The values of $d_{\rm eff}$ listed are wavelength scaled according to Miller's rule. The factor $2/\pi$ appropriate for first order quasiphase matching is included in this value.

The last used input set is saved in the file MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store them. Copy the file back to MIX.SF to restore.

2.5 Opoangles

Opoangles computes OPO/OPA red1 and red2 wavelengths as a function of propagation angle in birefringent crystals assuming the blue pump wavelength is fixed. For biaxial crystals, propagation is in one of the principal planes of the crystal so the plane radio button is activated. Select the plane of interest. In biaxial crystals the angle θ (theta) is measured from the Z axis for propagation in the XZ and YZ planes. For propagation in the XY plane the angle ϕ (phi) is measured from the X axis toward the Y axis.

Noncollinear mixing is permitted and the angles are as diagrammed in the plot window when you click the mouse in the pump tilt input box. Noncollinear phasematching displays tuning vs. signal angle as is appropriate if the signal wave is the red wave that is resonated in a cavity and thus has a fixed angle. Pump tilt is measured relative to the signal wave. Noncollinear phasematching is useful in tuning via pump angle and also to control the bandwidth of the output. It is also of interest for tangential phasematching. Note that the tilts are assumed to lie in the critical (walkoff) plane of the crystal. In some cases the bandwidth can be large (at points where the phase matching curves are tangent to a vertical line). At these points the signal and idler have equal group velocities along the signal direction. The pump does not

usually have the same group velocity as the signal and idler, though, so this is not equivalent to matching all three group velocities as is desired for femtosecond mixing. Use function GVM for group velocity matching all three waves.

The d_{eff}'s calculated for noncollinear mixing are approximate because they do not account for the tilts of the three waves, but instead assume that all three waves propagate parallel to the signal wave. The d_{eff}'s do include Miller scaling for wavelength variation.

The 'Deff' and 'Gain' buttons display d-effective (d_{eff}) and parametric gain, where gain is defined as $gain = 0.172\, d_{\text{eff}}/\sqrt{\lambda_{\text{sig}}\lambda_{\text{idler}} n_{\text{pump}} n_{\text{sig}} n_{\text{idler}}}$ with λ's in [nm], and d_{eff} in [pm/V]. To find actual parametric gain in [cm^{-1}], multiply the gain by the square root of the pump intensity in [W/cm^2].

The ascii file OPOANGLE.DAT contains the results and may be viewed by clicking the 'View' button.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

2.6 Ncpm

NCPM (noncritical phase matching) helps you quickly search the crystal list for one that can noncritically phase match your wavelengths.

Noncricitcal phase match refers to collinear phase matching with no birefringent walk off. It is desirable for efficient mixing of weak, tightly focused beams, and for maintaining widest acceptance angle for all three beams. For uniaxial crystals the propagation direction is normal to the optic axis. For biaxial crystals the propagation direction is along one of the principal axes, X, Y, or Z.

For uniaxial crystals only mixing processes that involve a single e wave have nonzero d_{eff}. For negative uniaxial crystals the e wave is the bluest wave. For positive uniaxial crystals the bluest wave is o polarized and one of the two red waves is e polarized, the other is o polarized.

For biaxial crystals d_{eff} is sometimes nonzero only along two of the principal axes. When such a crystal is selected the appropriate radio buttons for the propagation axes are activated. Select the one of interest. Similarly, in some cases two polarization sets with nonzero d_{eff} are possible and the appropriate mixing type radio buttons are activated. Select the one of interest.

You can enter target wavelengths for one red wave and the blue wave. Horizontal and vertical gray lines will appear on the output plot at these wavelengths so you can conveniently adjust the temperature/mixing type/propagation axis to achieve noncritical phasematching at the desired wavelengths.

If the temperature dependence of the refractive indices for a crystal are unknown and the temperature is not set to 300K, when the Run button is clicked the temperature will be set to 300K.

Other crystal properties such as d_{eff}, group velocity, or gdd may be found using QMIX or Ref. Ind. once a noncritical phase match is found.

The computed phase matching data is written to the file NCPM.DAT.

2.7 GVM

GVM calculates group velocity (mis)match for noncollinear phase matching. The paper "Group-velocity-matched three-wave mixing in birefringent crystals," Optics Letters vol. 26, page 719 (2001) presents a description of the method of group velocity matching in birefringent crystals implemented in this function. This paper is available online at http://www.as-photonics.com/Publications.html

For a given crystal and set of wavelengths, and a specified slant of the pulse envelope, the propagation angles of the two redder beam relative to the blue (pump) beam are varied and the crystal phase matching angle theta is located. All angles are in the plane containing the optic axis of the crystal and the pump propagation vector in the case of uniaxial crystals, or in the selected principal plane in the case of biaxial crystals. The phase matching angles are plotted by the Angles button. The group velocity walkoffs (relative to the pump) parallel to the blue (pump) wave's propagation vector are displayed by the GVM button. Spatial walkoff perpendicular to the blue wave's propagation vector is displayed by the Walkoff button. Group delay dispersion (GDD) as measured along the blue wave's propagation vector are displayed by the GDD button in units of fs^2/mm (to convert to GVD in $\text{cm/sec} - \text{cm}^{-1}$ use $GDD = -5.89E-4\ GVD\ gvi^2$).

Slant angle is the tilt of the blue (pump) wave's pulse envelope relative to its propagation angle (k-vector direction). I assume that all three envelopes have the same alignment so they can overlap spatially. If the pump slant is 5°, the red1 slant relative to its k vector is 5° + Delta, and the red2 slant relative to its k vector is 5° − Gamma (see diagram that comes up when you select GVM). This means that if the group velocities are matched the envelopes stay overlapped in time (longitudinally), although they will walk off spatially (laterally).

In the plots, solid lines correspond to positive values of Delta and Gamma and dashed lines correspond to negative values of Delta and Gamma. Perfect group velocity matching occurs when the solid red, solid blue, and green curves coincide or when the dashed red, dashed blue, and green curves coincide. The curves are adjusted by varying the slant angle. Perfect velocity matching, if it can be

found, will occur at a certain value of Theta. The Angle button displays Delta and Gamma vs Theta permitting you to find the corresponding values of Delta and Gamma for each value of Theta. Likewise the spatial walkoff relative to the pump at that Theta can be found from the curves displayed by the Walkoff button. Envelope slant affects the group velocity dispersion. Net gdd is plotted by the GDD button.

When a set of wavelengths, a crystal, a temperature, and a plane (if the crystal is biaxial) are selected, all polarization combinations that can phase match with nonzero d_{eff} are enabled. Select the one of interest.

This function is useful in predicting the far-field ring angles for the two red waves in femtosecond OPG. It is also useful in preconditioning input pulses to slant their envelopes for optimum group velocity matching. For example, if group velocity matching can be achieved, the crystal length is not limited by group velocity walkoff. This permits the use of longer crystals with the result that two photon absorption and nonlinear refractive index effects can be minimized. Of course this requires beams large enough that walkoff is not dominant, which in turn requires sufficient pulse energy.

GVM data is written to the ascii file GVM.DAT with format displayed in the View window when you click the 'View' button.

The last used input set is saved in the file MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store them. Copy the file back to MIX.SF to restore.

2.8 PW-mix-LP

PW-mix-LP computes three-wave mixing process for long-pulse plane waves. The input irradiances are those of the central rays of spatial lowest-order Gaussian beams with diameters and energies specified in the input form. This function ignores birefringent and group velocity walkoff. It is intended for very quick evaluation of a proposed mixing process.

The model will handle pulses or cw light or a combination of the two. To make a beam cw, set its pulse duration parameter to zero. Because group velocity is ignored (it is included in PW-mix-SP), this model is not accurate for very short pulses (less than 10's of psec usually), or for broad-bandwidth mixing where the bandwidths exceed the crystal's acceptance bandwidth. Similarly, if birefringent walk off is comparable to, or larger than the beam diameters, this function will not be very accurate.

Results are written to the ascii file PWMIX_LP.DAT and may be viewed by clicking the 'View' button.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store and copy the file back to MIX.SF to restore.

PW-mix-LP examples: 16, 18-23, 27, 39. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.9 PW-mix-SP

PW-mix-SP computes three-wave mixing process for plane waves with irradiances equal to those of the central rays of spatial lowest order Gaussian beams with beam diameters and energies specified in the input form. It ignores birefringent walkoff but includes group velocity effects, so it is useful for modeling very short pulses. cw light is not allowed in this function. Pulses are Gaussian or Supergaussian in time at the input face. The three input pulses can have different durations and delays.

Clicking the Spectra button once gives the spectral irradiance on a THz scale. Clicking the Spectra button again gives the spectral irradiance on a nanometer scale.

A post run movie is available if "# z integration steps" input is set to zero. The Run button will turn into a Movie button after the run.

This function integrates Maxwell's equations using split-step methods for accurate simulation of group velocity effects. Nonlinear refractive indexes (n2's) and two-photon absorption (beta's) can be included. The n2 and beta values are not well known for most crystals, but some values and references are listed in the file BETA_N2.PDF in your SNLO folder.

Results for the fields are written to the ascii file PWMIX_SP.DAT and can be viewed by clicking the 'View' button. Results for the spectra are written to PWMIXSPS.DAT.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

PW-mix-SP examples: 1, 2, 6, 8, 11, 13, 17, 74. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.10 PW-mix-BB

PW-mix-BB computes three-wave mixing processes for plane waves with input irradiances equal to those of the central ray of lowest order Gaussian beams with energy and diameter specified on the input form. It ignores birefringent walkoff but includes group velocity effects. It is intended for modeling multi-longitudinal-mode pulses. The number of modes populated in each model run is sufficient to cover the specified bandwidth for each beam.

If the wavelength, duration, bandwidth, mode spacing, and fm inputs are identical for the red1 and red2 waves, they are assumed to be from the same source and will have identical starting spectra. This allows type 1 doubling. For type 1 doubling all entries for red1 and red2 should be identical and half the power/energy should be in each.

Unless the Frequency modulated input is set to one, the broadband light is chaotic, meaning the distribution of field amplitudes among the various modes obeys Gaussian statistics and the phase distribution is random. Some OPO's generate light that is more frequency modulated than chaotic, so the input 'frequency modulated' allows this type of light. Frequency modulated light has the specified bandwidth but the amplitude modulation is removed, leaving only frequency modulation.

Long pulses with broad bandwidths will require a large amount of computer memory and computation time. Often you can shorten the pulse duration without losing the important physics and in this way lessen the demands on your computer. Note that there is no input for nonlinear refractive index effects or for two-photon absorption. They can be added if there is sufficient interest.

Results are written to the file BBOPA.DAT and may be viewed by clicking the 'View' button.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

PW-mix-BB examples: 12, 59, 68, 76. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.11 2D-mix-LP

2D-mix-LP is similar to PW-mix-LP except it handles the full spatial profiles so it can realistically model circular or elliptical beams with Gaussian or Supergaussian transverse profiles. It includes diffraction, birefringent walkoff, displaced beams, etc. for pulsed or cw light. The light is assumed to be monochromatic, and the pulses are assumed to be long enough that group velocity effects are unimportant. Maxwell's equations are integrated using split-step methods to give true diffractive calculations. Modeling methods are described in detail in papers "Phase distortions in sum- and difference-frequency mixing in crystals," JOSA B vol. 12 p. 49 (1995), and "Comparison of a numerical model with measured performance of a seeded, nanosecond KTP optical parametric oscillator," JOSA B vol. 12 p. 2253 (1995). These papers are available online at http://www.as-photonics.com/Publications.html

The maximum size of the transverse grid depends on the amount of memory allocated to SNLO (see Readme.txt file about memory allocation). For 12 Mb, the grid can be as large as 128×128, for 180 Mb it can be up to 512×512. A 32×32 grid is usually adequate. I suggest you use the much faster PW-mix-LP first to find reasonable values for the input parameters.

Outputs include beam tilts in the walkoff direction (Tilt), time-dependent M^2 values in the walkoff direction and perpendicular to it (M-w and M-p buttons), time integrated M^2 values (written at top of plots of time dependent M^2), and wavefront curvature at the plane specified by the propagation distance input parameter. You should make sure these results are converged by increasing the grid density by factors of two until the answers stabilize. Usually a grid of 32×32 or 64×64 is adequate. Phases are plotted offset by $+\pi$ so the range is (0 to 2π) instead of ($-\pi$ to π).

The input pulses (if not cw) are all centered at t=0. Runs start at t=0 and progress to later time. Times $t < 0$ are not modeled because of the symmetry about t=0. The results are written to ascii files *_INT.DAT and *_PH.DAT, where the *_INT files (*_PH files) are irradiance (phase) out at each time step with columns x,y,irr(t1),irr(t2),.... The ascii files *_BEAM.DAT contain time, power, phase, M_x^2, M_y^2, X-curvature, Y-curvature, and X-tilt in columns $1 - 8$ (where X is the walkoff direction). The fluence is written to the ascii file FLUENCE.DAT with columns x, y, red1 fluence, red2 fluence, blue fluence at the propagation distance specified (from exit face of crystal). FLUENC_F.DAT is the relative far field fluence angular distribution with columns x-angle, y-angle, red1 fluence, red2 fluence, blue fluence. Actual x and y angles (in radians) are found by multiplying x-angle or y-angle by the wavelength (in meters) of the red1, red2, or blue wave. These distributions are Fourier transforms of the fields at the crystal exit face.

Noncollinear phase matching in the critical plane can be faked by using the walkoff parameter. For example, if the red1's true walkoff angle is 50 mrad and you want to propagate the pump along this direction, you would specify 50 mrad for both the red1 and blue beams. You must then compensate by adjusting the red2 walkoff to be $-50 \times \lambda_{idler}/\lambda_{pump}$. In other words, fake walkoff must be compensated to maintain phasematch, but real walkoff is not compensated. Of course, the tilts will not reflect the actual values for the fake walkoff but will be the deviation from the input beam tilt.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

2D-mix-LP examples: 9, 14, 24, 26, 38, 43, 44, 58, 60-62. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.12 2D-mix-SP

2D-mix-SP models single-pass mixing with diffraction, birefringent walkoff, group velocity walk off, and group velocity dispersion. This is a slow memory hog so try to select the best values for the time and spatial grids using the faster functions PW-mix-SP, PW-mix-LP, and 2D-mix-LP before running it. The maximum sizes of the spatial and temporal grids depend on the amount of memory allocated to SNLO (see Readme.txt file about memory allocation). A $32 \times 32 \times 128$ grid requires 35 Mb allocated to SNLO. This should be adequate for many situations.

The calculation is based on integrating Maxwell's equations using split-step FFT methods to give accurate diffractive and group velocity simulations. Methods are described in papers "Numerical models of broad bandwidth nanosecond optical parametric oscillators," JOSA B vol. 16 p. 609 (1999); "Phase distortions in sum- and difference-frequency mixing in crystals," JOSA B vol. 12 p. 49 (1995); and "Comparison of a numerical model with measured performance of a seeded, nanosecond KTP optical parametric oscillator," JOSA B vol. 12 p. 2253 (1995). These papers are available online at http://www.as-photonics.com/Publications.html

The phase velocity mismatch ($k_3 - k_1 - k_2$) refers to the carrier waves, i.e. the central frequencies and forward k vectors. The group velocity and group delay dispersion terms then account for phase mismatches at all other frequencies while the walk off angle accounts for the phase mismatches for all other k-vector directions. This is automatic, you do not have to worry about how all the frequency and tilts are phase matching among themselves.

Outputs include fluences at the detector and in the farfield, tilts in the walkoff direction, M^2 values in the walkoff direction and perpendicular to it (M-w and M-p buttons), integrated M^2 values (written at top of M^2 plots), and wavefront curvature at the detector. These are calculated vs time or vs spectrum. You should make sure these results are converged by increasing the grid densities by factors of two until the answers stabilize. The chirp of the output pulse is calculated by computing the chirp at each time and position and performing a spatial irradiance-weighted average over x and y to find chirp as a function of time.

On completion of a run the following ascii files are written: BEAM_3TS.DAT, BEAM_3TI.DAT, BEAM_3TP.DAT with columns in order time, power for red1/red2/blue beam in file with S/I/P in its name. BEAM_3WS.DAT, BEAM_3WI.DAT, BEAM_3WP.DAT with columns in order frequency, power for red1/red2/blue beam in file with S/I/P in its name. BEAM_3C.DAT with columns containing time, red1 chirp, red2 chirp, blue chirp FLUENCE3.DAT with columns x, y, red1 fluence, red2 fluence, blue fluence FLUENCE3F.DAT with columns x tilt, y tilt, red1 fluence, red2 fluence, blue fluence. Actual x and y farfield angles (in radians) are found by multiplying x-angle or y-angle by the wavelength (in meters) of the red1, red2, or blue wave. These angular distributions are the Fourier transforms of the fields at the detector.

Clicking the Save button writes ascii files SIG_INT3.DAT (red1), ID_INT3.DAT (red2), PMP_INT3.DAT (blue), SIG_PH3.DAT (red1), ID_PH3.DAT (red2), and PMP_PH3.DAT (blue) where the files with INT (PH) in their name contain irradiance (phase) with columns in order of x,y,int(t1),int(t2),...

Clicking the Process button computes beam parameters and adds the following columns to BEAM_3TS.DAT, BEAM_3TI.DAT, BEAM_3TP.DAT: M_x^2, $\langle M_x^2 \rangle$, M_y^2, $\langle M_y^2 \rangle$, X-curvature, Y-curvature, and x tilt (x is the walkoff direction). Clicking the Process button also adds the following columns to BEAM_3WS.DAT, BEAM_3WI.DAT, BEAM_3WP.DAT, M_x^2, $\langle M_x^2 \rangle$, M_y^2, $\langle M_y^2 \rangle$, X-curvature, Y-curvature, and x tilt (x is the walkoff direction). The units are the same as in the plots displayed by clicking the M-w, etc. buttons.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

2D-mix-SP examples: 63, 66. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.13 PW-cav-LP

PW-cav-LP models plane-wave mixing in cavities. Input irradiances are those of the central rays of lowest order Gaussian beams with diameters specified by the Beam diam. input values. You can model an OPO, cavity resonant SHG or any other cavity mixing process by specifying the input beams and the reflectivity of the mirrors. The crystal mixing is similar to PW-mix-LP. The cavity configuration can be standing wave or ring.

Each wave can be either cw or pulsed so both cw and pulsed devices, or devices with both cw and pulsed beams can be modeled. If the Pulse length input is set to zero, that beam is cw. If it is nonzero, a temporal Gaussian pulse is assumed.

For a ring cavity, the reflectivity of the third mirror is unity for all three waves. You can specify phase shifts in various parts of the cavity for each wave. This is useful in modeling OPO's that resonate more than one wave or for modeling seeded OPO's when the cavity is not exactly resonant with the seed. Usually the phases can be set to zero to model optimum OPO performance.

To model an OPO, it is easiest to supply a red1 or a red2 (not both) seed to either end of the cavity. If you

seed both red waves, you must be careful of phases. For approximate modeling of an unseeded OPO, use a vacuum level field (one photon per mode) to seed either red wave. This is approximately 10^{-9} watts. The exact value is not critical because the OPO behavior is usually not very sensitive to the seed power.

For strongly driven OPO's you might see bistable or even chaotic behavior of the output powers. This is normal and probably not due to numerical problems. It may not be very physical though, because real OPO's do not have plane waves and spatial averaging over irradiance profiles tends to eliminate this behavior.

The OPO output from the left and right ends are written to the ascii files PWOPO_R.DAT and PWOPO_L.DAT. They can be viewed by choosing the Right or Left radio button and then clicking the 'View' button.

If the number of starts input is set to 1, the time increment is the round trip time of the cavity. For a time resolution of half the round trip time, set the number of starts to 2. Higher numbers give still higher time resolution.

Batch mode is allowed on most inputs. Only one variable can be batched on any run. A batch run is automatically performed if the input box contains three numbers with space separating them. The format is: [starting value] [space] [ending value] [space] [increment]. If batch mode is used the output is written to sequential files named PWOPOR#.DAT and PWOPOL#.DAT where # is 0 for first run, 1 for second run, ... The last run in the batch also writes the files PWOPO_R.DAT and PWOPO_L.DAT as before. The file PWOPOLP.TXT contains copies of the output text box for each run. Open the file using Wordpad.

The last used input set is saved in the file MIX.SF, so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store. Copy the file back to MIX.SF to restore.

PW-cav-LP examples: 36, 40, 41, 46, 51-53, 55, 56, 69. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.14 PW-OPO-SP

PW-OPO-SP models a plane-wave, synchronously-pumped OPO. The irradiance of the plane pump wave is set equal to the central ray of a lowest-order spatial Gaussian whose beam diameter is specified in the input form under 'Beam diameter'. This function includes group velocity and group delay dispersion. The OPO cavity is a ring, with only the red1 wave is resonated. The blue (pump) pulse is a temporal Gaussian.

The modeling procedure is to propagate the three light pulses (red1, red2, blue) through the crystal, then apply any Compensator (see diagram in the plot window) changes to the signal pulse. The output pulses from that pass of the cavity are then plotted. For the next cavity pass, a new blue (pump) pulse is then used, along with the last reflected red1 pulse. This is repeated until the pulses stabilize. At the bottom of the PW-OPO-SP input form the pass number is indicated along with the % change in the red1 pulse on the last pass. When the % change is sufficiently small to indicate convergence (usually when the % change $< .05$) click the STOP button and the results of the previous pass are plotted and written to the ASCII output file PWOPO_SP.DAT which you can view by clicking the 'View' button. The 'Display' radio buttons can be used to display either the irradiance, normalized irradiance, frequency chirp, or phase. The display can be changed during a run.

Simulated quantum noise on the red1 and red2 beams is added on each cavity pass. The OPO starts from this noise. The quantum noise can be viewed by setting $d_{\text{eff}} = 0$ and selecting the 'Norm Irrad' radio button.

Stable operation of the OPO is not guaranteed. In some cases the OPO never turns on, perhaps because the cavity delay input is incorrect. In other cases the OPO turns on but never reaches stable operation.

After the run has stopped, you can click the 'Irradiance,' 'Norm Irrad,' 'Chirp,' 'Phase,' or 'Spectra' to view information about the last pass. Clicking 'Spectra' once will display the spectrum on a [THz] scale. Doing so again will display a [nm] scale. Compress adds a gdd to the red1 output. This is useful in testing the compressibility of the output pulse. Click the up or down arrow buttons repeatedly to find the best compression. The size of the up or down step can be adjusted by clicking the + or - button.

The last-run input set is saved in MIX.SF, so if you would like to save those settings for later recall, copy (do not just rename) MIX.SF to another file name to store them. Copy the file back to MIX.SF to restore settings.

PW-OPO-SP examples: 35, 71, 77. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.15 PW-OPO-BB

PW-OPO-BB models broad-bandwidth, nanosecond, plane-wave (actually the central ray of a spatial Gaussian) OPO's. It is similar to PW-OPO-LP except it allows for differing group velocities for the three waves. The mathematical methods are described in paper "Numerical models of broad bandwidth nanosecond optical parametric oscillators," JOSA B vol. 16 p. 609 (1999). These papers are available online at http://www.as-photonics.com/Publications.html This function permits studies of unseeded OPO's and the transition to seeding. It also models double resonance effects, or pumping

by multi-mode lasers. I suggest you narrow the range of input parameters using the much faster function PW-OPO-LP before you run this function because it is demanding on computer resources and user patience.

A built in noise model generates the startup quantum vacuum noise. The starting noise spectrum has a width greater than the crystal acceptance bandwidth which is proportional to $1/(gvi_1 - gvi_2)$. This is several times the actual OPO linewidth in most cases. The red1 and red2 noise is automatically added to whatever input light you specify. To make multiple runs with the same startup noise, you must set the New noise input to 0 on each run. It defaults to 1.

Phase shifts are specified for each side of the crystal. These are the phase shifts experienced by the carrier, or central frequency, for each of the waves. If it is single mode, the input light is assigned the frequency of the carrier. For example, if you wish to model seeding with exactly resonant red1 light you would set the red1 phases to zero, or more generally so the left and right phases add to a multiple of 2π. If the red1 seed is detuned from cavity resonance slightly, its round trip phase would differ slightly from 2π. This method of specifying phases allows you to model double resonance effects, cavity detuning from the seed, and double passing the pump with arbitrary reflective phase shifts, for example. Phase shifts in these situations can dramatically affect the OPO's output spectrum.

This function does not include group velocity dispersion, nonlinear refractive index, or two-photon absorption. These restrictions could be removed if there is sufficient interest.

Output fields are written to the ascii files BBOPOL.DAT and BBOPOR.DAT and may be viewed by clicking the 'View' button. Output spectra are stored in file BBSPECL.DAT and BBSPECR.DAT and start up noise is in NOISE.DAT.

The last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy (do not simply rename) MIX.SF to another file name to store and copy the file back to MIX.SF to restore.

PW-OPO-BB examples: 48, 70, 72. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.16 2D-cav-LP

2D-cav-LP is similar to PW-cav-LP except it handles the full spatial profiles so it can realistically model beams with Gaussian or Supergaussian transverse profiles. It includes diffraction, birefringent walkoff, displaced beams, etc. for pulsed or cw light. The light is assumed to be monochromatic and the pulses are assumed to be long enough that group velocity effects are unimportant. Modeling methods are described in detail in papers "Phase distortions in sum- and difference-frequency mixing in crystals," JOSA B vol. 12 p. 49 (1995), and "Comparison of a numerical model with measured performance of a seeded, nanosecond KTP optical parametric oscillator," JOSA B vol. 12 p. 2253 (1995). These papers are available online at http://www.as-photonics.com/Publications.html

Before running this model, I suggest you use the much faster PW-OPO-LP to find reasonable values for the input parameters. The function Cavity will help you if you wish to design a cavity with curved mirrors. The Guoy or focal phase shift is given by the Cavity function. You should compensate this by making the round trip phase of the OPO the same magnitude but opposite in sign. For example if the red1 wave is resonated and its phase shift calculated by the Cavity function is 1.3 radians, you should make the phase shift in the Phase L-C box in the red1 column -1.3 radians. You can check this by making sure this phase shift gives the best red1 resonance, or energy transmission by the cavity, for this phase shift with the gain set to zero (d_eff=0). If you don't use the correct phase the red1 resonance will be shifted, as you can see by looking at the red1 spectrum after the run (with gain turned on) is complete. For an OPO that resonates only the red1 wave the main effect of an improper shift is that the seed light will not be resonant with the cavity, weakening the seeding.

For modeling cw cases, the run-time display will include a '%change' value. When this is acceptably small, say 10^{-3}, click the 'Stop' button to end the run and display the results. For modeling pulsed cases, the run will automatically terminate at the end of the pulses. Note that running cw cases with very low cavity loss can take a long time because of the large number of passes required to allow transients to damp out. Patience will be rewarded by a good simulation.

The red1 and red2 input pulses (if not cw) can be offset in time from the blue pulse which is centered at t=0. The red1 wave is assumed to be reentrant after a pass of the cavity. That is, the cavity is aligned so the red1 wave, after traveling once around the cavity, is guaranteed to be centered on the incident red1 wave. Curved mirrors are also assumed to be centered on the red1 beam, as are both left and right grids. This means that if the red1 wave offset or walk off is different from those of the red2 or blue beams, the red2 or blue beams will not generally be centered on the mirror axis nor will they be reentrant. I suggest you run your case with d_{eff} set to zero to check the beam walk offs and offsets if you are in doubt about them.

Outputs include beam tilts in the walkoff direction (Tilt), time dependent (for the pulsed case) M^2 values in the walkoff direction and perpendicular to it (M-w and M-p

buttons), and wavefront curvature at the cavity mirrors. You should make sure these results are converged by increasing the grid density factors of two until the answers stabilize. Usually a grid of 32×32 or 64×64 is adequate.

The output fluences are written to ascii files FLU_NL.DAT (near field left), FLU_NR.DAT (near field right), FLU_FL.DAT (far field left), FLU_FR.DAT (far field right) with columns x-position, y-position, red1 fluence, red2 fluence, blue fluence. Actual x and y far-field angles (in radians) are found by multiplying x-angle or y-angle by the wavelength (in meters) of the red1, red2, or blue wave.

The output powers are written to ascii files PWR_L.DAT and PWR_R.DAT in format with colums time, red1 power, red2 power, blue power.

The output spectra are written to ascii files SPEC_L.DAT and SPEC_R.DAT with columns frequency in MHz, normalized red1 spectral fluence, normalized red2, normalized blue.

M_x^2, M_y^2, X-curvature, Y-curvature, and X-tilt are written in file BEAM_LO.DAT and BEAM_RO.DAT with time in column 1.

Noncollinear phase matching in the critical plane can be faked by using the walkoff parameter. For example, if the red1's true walkoff angle is 50 mrad and you want to propagate the blue beam along this direction, you would specify 50 mrad for both the red1 and blue beams. You must then compensate by adjusting the red2 walkoff to be $-50 \times \lambda_{red2}/\lambda_{blue}$. In other words, fake walkoff must be compensated to maintain phasematch, but real walkoff is not compensated. Of course, the tilts will not reflect the actual values for the fake walkoff but will be the deviation from the input beam tilt.

Last used input set is saved in MIX.SF so if you would like to save those settings for later recall, copy MIX.SF to another file name to store and copy the file back to MIX.SF to restore.

2D-cav-LP examples: 29, 34, 37, 42, 45, 47, 49, 50, 54, 57, 73, 75. Examples can be accessed by clicking the SNLO menu form anywhere outside the buttons.

2.17 Focus

FOCUS helps calculate the curvature of a Gaussian beam at a specific location that will give a certain waist size at a certain location. This information is needed in 2D-mix-LP and 2D-mix-SP if the beams are focusing (have curved wavefronts). To run this function simply change any of the input values and the output values are automatically updated. For example, if you want the beam to focus at the center of the crystal, use half the crystal length in the Dist. to focus input. Filling in the Waist input will then give the radius of curvature in air at the crystal input face and the beam diameter at the crystal input face that are necessary to focus at the crystal center with the specified beam waist.

2.18 Cavity

CAVITY helps design stable cavities in support of function 2D-cav-LP which can model curved mirrors. In order to mode match an input beam to a stable cavity, 2D-cav-LP needs as inputs the curvature of the input beams just inside the left curved mirror. This is found by setting the 'z' input of the Cavity function to a value slightly less than half of the 'Leg1' value. Mode matching also requires you to specify the beam size at the input mirror. This is also given by the Cavity function output 'Beam diameter @ z', again for a value of 'z' slightly less than half the 'Leg1' value. If an input beam in 2D-cav-LP is to be resonant with the cavity, you must also specify the round-trip phase shift due to focusing within the cavity. For example, for a ring cavity you can set the value of the input parameter 'Phase R-L' equal to the negative of the value given by the Cavity function output 'Round trip phase shift'. This makes the wave resonant in the cavity, maximizing the cavity enhancement of the field. When this is set correctly the spectrum of the resonated wave will peak at a frequency shift of zero. Click the Spectrum button after a run to check this. Note that the Leg1 length refers to the distance between curved mirrors on the leg containing the crystal, while Leg2 refers to the distance between curved mirrors on the other leg. Flat mirrors are unimportant and can be positioned in Leg1 or in Leg2. The latter is shown in the diagram.