

Introduction to SNLO software

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October 18, 2016

1. INTRODUCTION

The advent of powerful desktop computers has made it possible to automate calculations of the linear and nonlinear properties of crystals, and to perform detailed simulations of nonlinear mixing processes in crystals. The purpose of SNLO is to make these calculations available to the public in a free, user-friendly, Windows-based package, with the hope that this will advance the state of the art in applications such as optical parametric oscillators/amplifiers (OPO/OPA), optical parametric generation (OPG), frequency doublers, etc. There are three types of functions included in the SNLO menu, shown to the right. The first type help in computing the crystal properties such as phase-matching angles, effective nonlinear coefficients, group velocity, and birefringence. These functions are **Ref. Ind.**, **Qmix**, **Bmix**, **QPM**, **Opoangles**, **Ncpm**, and **GVM**. The second type, functions **PW-mix-LP**, **PW-mix-SP**, **PW-mix-BB**, **2D-mix-LP**, **2D-mix-SP**, **PW-cav-LP**, **PW-OPO-SP**, **PW-OPO-BB**, and **2D-cav-LP**, model the performance of nonlinear crystals in various applications, and the third set, **Focus**, **Cavity**, and **Help**, are helper functions for designing stable cavities, computing Gaussian focus parameters, and displaying help text for each of the functions. SNLO comes with preloaded examples. Mouse click anywhere on the menu form outside the buttons to access the examples. The capabilities of select functions are presented below.

2. CRYSTAL PROPERTY CALCULATIONS

2.1. Selecting angle-tuned crystals

The function **Qmix** is the best starting place for selecting a nonlinear crystal for your application. When you select a crystal from the list of 60+ crystals, the viewing area will display its properties, including the transmission range (as a plot if the information is available), references for Sellmeier data, nonlinear coefficients, damage thresholds, etc. Enter the wavelengths for your mixing process and push the 'Run' button to compute information

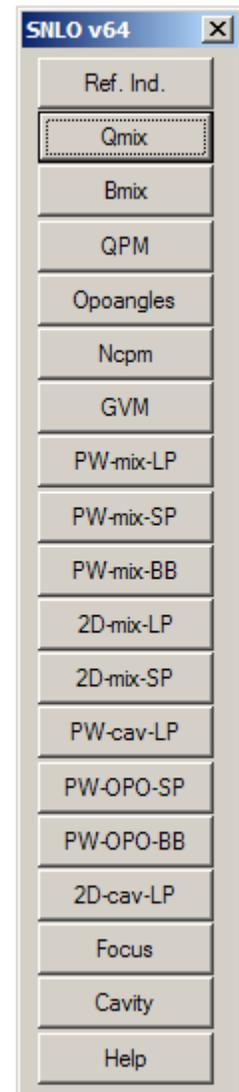


Figure 1: SNLO main menu

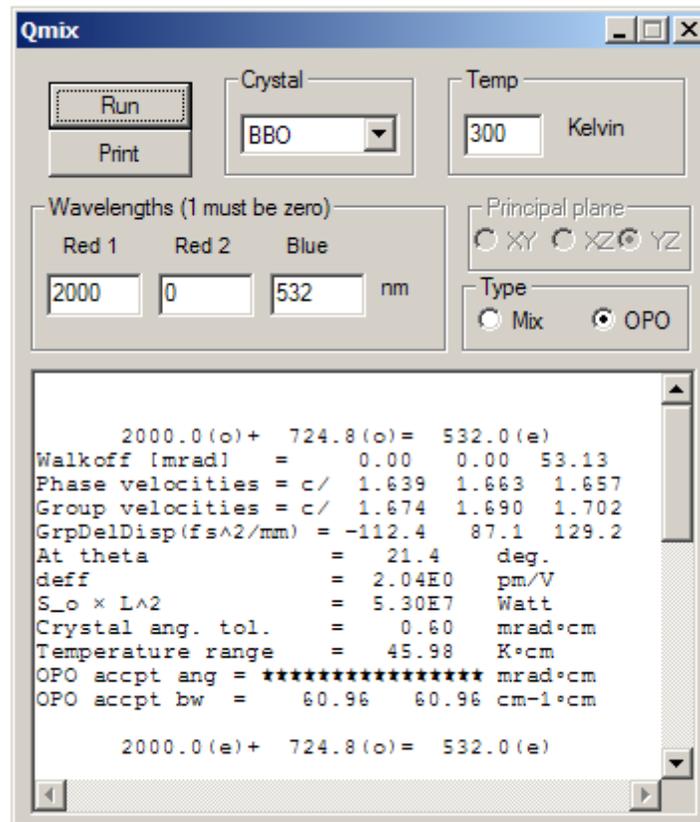


Figure 2: Qmix example.

specific to all possible phase-matched processes for the selected crystal at the specified wavelengths. Figure 2 shows one example. Note that for biaxial crystals only the principal planes are allowed in **Qmix**. If you are curious about a biaxial crystal's properties outside the principal planes, you can explore them using **Bmix**. Further information on crystal properties is available in the papers listed in the bibliography 'Crystals.pdf' available on the SNLO download website (<http://www.as-photonics.com/snlo>). It references over 600 papers relating to nonlinear optical crystals.

2.2. Selecting quasiphasematched crystals

The function **QPM** helps you find the right quasi phase matched poling period for any of the popular quasi phase matchable crystals. It also computes temperature and pump wavelength tuning properties for the crystal. You can chose the polarizations for your processes as well, although the zzz polarization is usually the one of practical interest.

2.3. Selecting angle-tuned OPO crystals

As shown in Figure 3, the function **Opoangles** displays a plot of the signal/idler wavelength versus crystal angle for a given pump wavelength. It also computes the nonlinear coefficient and the parametric gain versus angle. Comparing gain over the wavelength range of interest between different crystals and phase matching types gives a good indication of relative OPO performance. Note that this function permits non-collinear phase matching. Clicking on the 'pump tilt' edit box displays a diagram of the non-collinear angles. The signal is assumed to remain aligned to the cavity of an OPO, the pump is tilted by a fixed angle relative to the signal while the crystal and idler tilt by

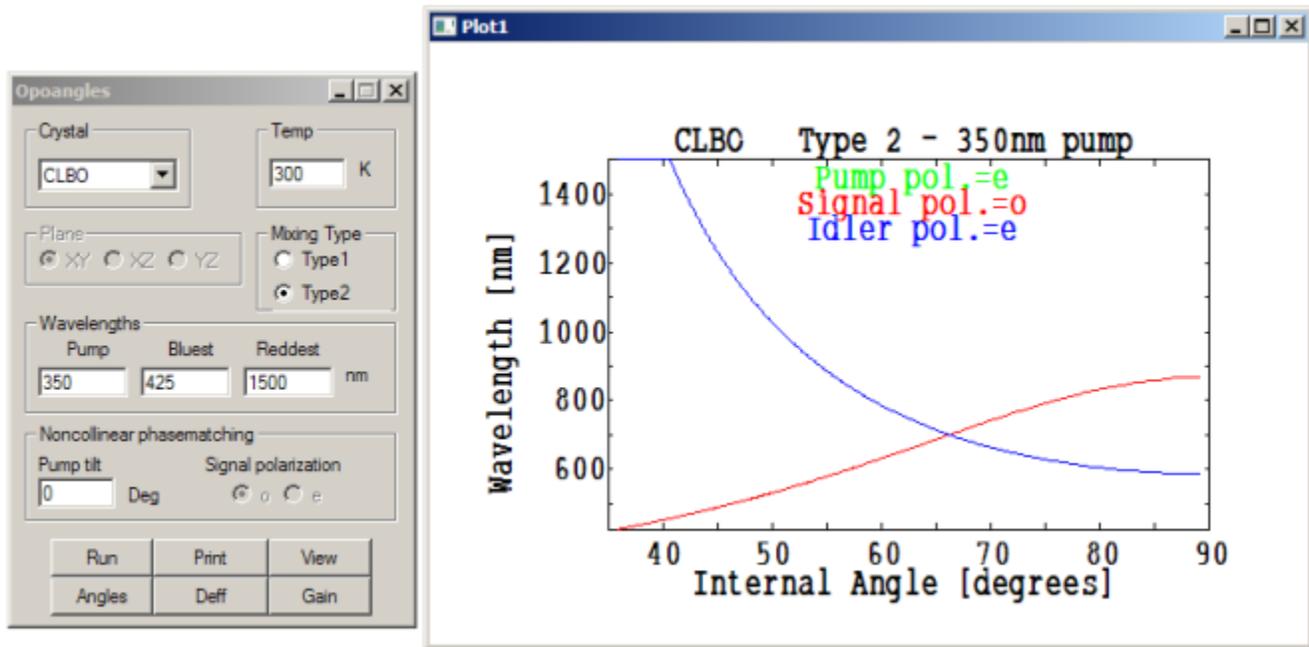


Figure 3: Opoangles example.

variable amounts to achieve phase match.

2.4. Selecting noncritically phase matched crystals

Ncpm computes all possible sets of the three wavelengths that achieve noncritical phase match in a selected crystal for a chosen propagation axis and mixing type.

2.5. Computing a crystal's linear optical properties

The function **Ref. Ind.** can be used to compute refractive indices, group velocities, group delay dispersions, and birefringent walk off for a given propagation angle, temperature, and wavelength. This is useful if you want to perform your own calculations of phase matching, group velocity matching, etc.

2.6. Computing group velocities in angle-tuned crystals

The function **GVM** computes the phase matching angles and effective group velocities for non-collinear phase matching. The slant parameter specifies the angle between the pump (bluest) wave's pulse envelope and its k-vector. All the pulse envelopes are assumed to have the same orientation so if they are all group velocity matched there is no temporal (longitudinal) walk off, but there is spatial (lateral) walk off. For a set of wavelengths and polarizations, the relative group velocities can be varied by changing the value of the slant. In many cases it is possible to achieve perfect group velocity matching in this way. This has obvious application in fs mixing, but it can also be used in mixing broadband light with temporal structure on a fs or ps scale.

3. NONLINEAR MIXING MODELS

The functions with ‘mix’ in their title handle single-pass mixing, as opposed to mixing in an optical cavity. The functions with the ‘PW’ prefix model plane-wave mixing, those with the ‘2D’ prefix include Gaussian spatial profiles with diffraction and birefringent walk off. The plane-wave models run much faster than the ‘2D’ models, so they can be used to arrive at an approximate set of conditions that can then be fine tuned with the diffractive models.

The functions with suffix ‘LP’ ignore group velocity effects and are appropriate for monochromatic ns and longer pulses, or for monochromatic cw beams. Functions with suffix ‘SP’ incorporate group velocity effects and are useful for ps and fs pulses. The suffix ‘BB’ indicates that the pulses are long but broadband so there is temporal structure on a time scale short enough to require inclusion of group velocity effects.

In the following sections we briefly discuss the mixing models.

3.1. PW-mix-LP

This model uses a plane-wave monochromatic approximation for single-pass mixing. It’s useful for approximating sum-frequency mixing, difference-frequency mixing, and parametric amplification for nanosecond to cw beams. Preloaded examples illustrate: cw difference-frequency mixing (example #16); cw parametric amplification (example #18); pulses parametric amplification (example #21); and cw sum-frequency mixing (example #22).

3.2. PW-mix-SP

This model uses a plane-wave approximation but includes group velocity and group delay dispersion effects for single-pass mixing of short pulses. [Figure 4](#) and [Figure 5](#) illustrate the input form and output. Preloaded examples illustrate: femtosecond pulsed sum-frequency mixing (example #1); chirped picosecond pulse sum-frequency mixing (example #2); and chirped picosecond pulse parametric amplifications (example #13).

3.3. PW-mix-BB

This model uses the plane-wave approximation and allows broad bandwidth for nanosecond pulses. It includes group velocity effects. [Figures 6, 7 and 8](#) show an example of an OPG calculation. The parameters are specified in the input form in [Figure 6](#), and the output time profile is show in [Figure 7](#) and the spectra are shown in [Figure 8](#). Preloaded examples illustrate: sum-frequency mixing of broadband nanosecond pulses (example #12); and optical parametric generation of a noise seed pulse (example #76).

	Red1	Red2	Blue
Wavelengths (nm)	528	528	264
Phase velocity index	1.674	1.674	1.674
Group velocity index	1.6	1.65	1.7
Group delay dispersion	0.00E0	0.00E0	0.00E0
Phases at input (rad)	0	0	0
n2 red1 (sq cm/W)	0.00E0	0.00E0	2.00E-15
n2 red2 (sq cm/W)	0.00E0	0.00E0	0.00E0
n2 blue (sq cm/W)	0.00E0	0.00E0	0.00E0
beta red1 (cm/W)	0.00E0	0.00E0	0.00E0
beta red2 (cm/W)	0.00E0	0.00E0	0.00E0
beta blue (cm/W)	0.00E0	0.00E0	0.00E0
Input face reflectivity	0	0	0
Output face reflectivity	0	0	0
Crystal loss (1/mm)	0	0	0
Pulse energy (J)	3.05E-7	3.05E-7	0
Beam diam. (fwhm mm)	0.5	0.5	0.5
Pulse duration (fwhm ps)	0.775	0.775	0.775
Pulse chirp (THz/ps)	0	0	0
Pulse delay (ps)	0	0	View
Crystal length (mm)	5	Run	Print
Deff (pm/V)	2	Iradiances	Norm Irr.
Delta k (1/mm)	0	Chirp	Phase
# of z integration steps	500	Spectra	>>
# time steps	256	<<	

In on-axis pk. irr. (W/sq cm)	= 1.305E8	1.305E8	0.000E0
In on-axis fluence (J/sq cm)	= 1.077E-4	1.077E-4	0.000E0
Out on-axis fluence (J/sq cm)	= 6.084E-5	6.084E-5	9.366E-5
Out on-axis peak irr.(W/sq cm)	= 7.735E7	8.008E7	1.163E8
So (W/sq cm)	= 4.398E7		

Figure 4: PW-mix-SP example.

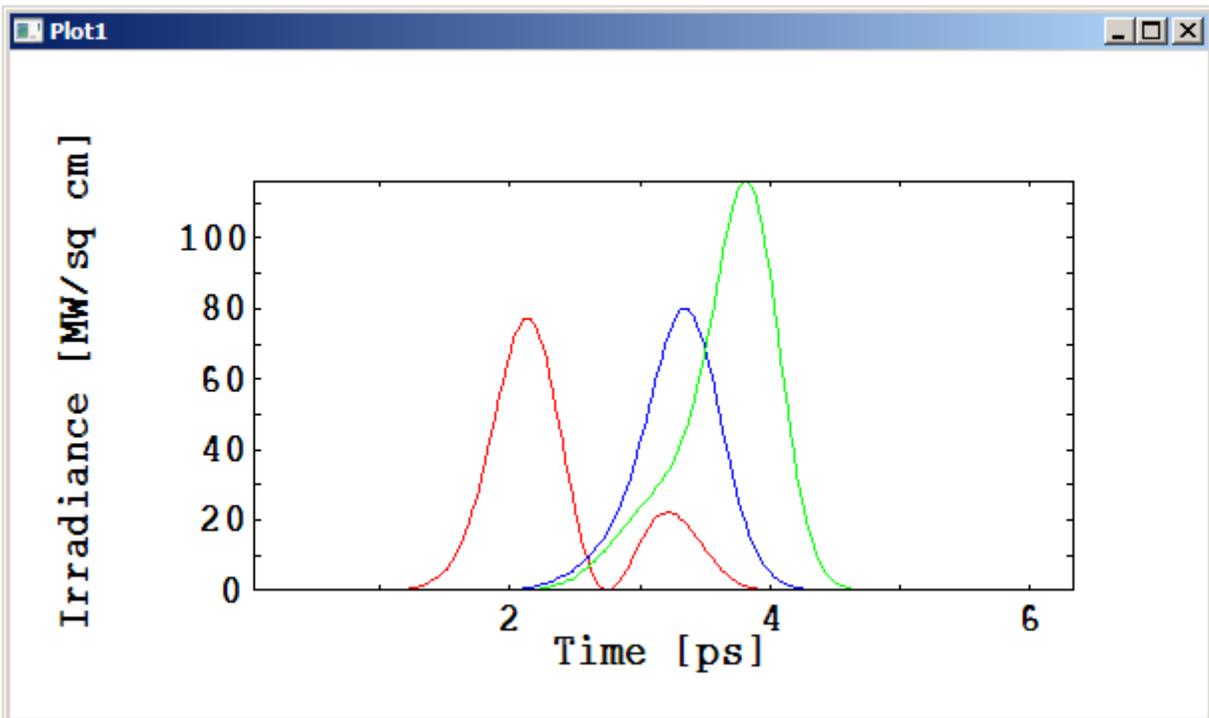


Figure 5: Output from **PW-mix-SP** example.

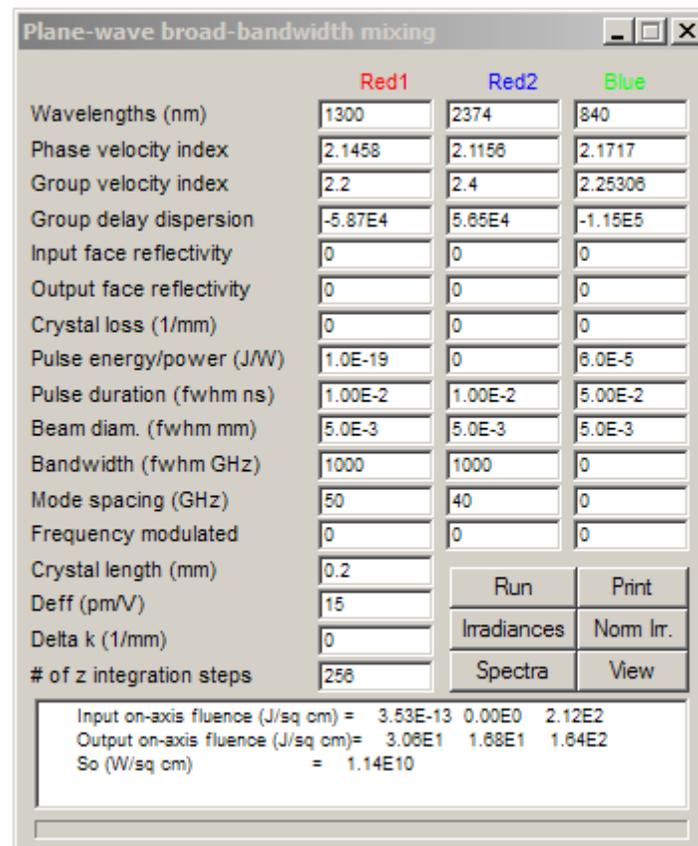


Figure 6: PW-mix-BB example.

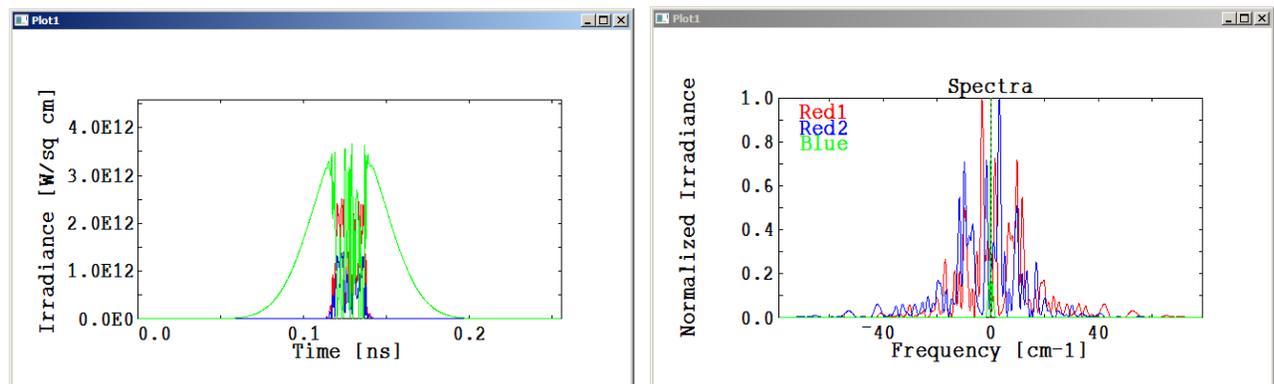


Figure 7: Output temporal irradiance profile from PW-mix-BB example. Figure 8: Output spectral profile from PW-mix-BB example.

3.4. 2D-mix-LP

This models single-pass mixing of long pulses or cw beams including Gaussian spatial profiles, diffraction and birefringent walkoff. The beams can be tightly focused or collimated. Preloaded examples illustrate: cw sum-frequency mixing of collimated beams including birefringence (example #14); cw sum-frequency mixing of focused beams (example #38); and cw sum-frequency mixing of focused beams with birefringence (example #58).

	Red1	Red2	Blue
Wavelengths (nm)	1560	1560	780
Indexes of refraction	2.23	2.23	2.23
Phases at input (rad)	0	0	0
ar coated (1=yes 0=no)	1	1	1
Crystal loss (1/mm)	0	0	0
Energy/power (J or W)	1.00E-4	1.00E-4	0.00E0
Pulse duration (fwhm ns)	10	10	10
Beam diam. (fwhm mm)	0.1	0.1	0.1
Supergaussian coeff.	1	1	1
n2 red1 (sq cm/W)	0.00E0	0.00E0	0.00E0
n2 red2 (sq cm/W)	0.00E0	0.00E0	0.00E0
n2 blue (sq cm/W)	0.00E0	0.00E0	0.00E0
beta red1 (cm/W)	0.00E0	0.00E0	0.00E0
beta red2 (cm/W)	0.00E0	0.00E0	0.00E0
beta blue (cm/W)	0.00E0	0.00E0	0.00E0
Walkoff angles (mrad)	0	0	20
Offset in wo dir. (mm)	0	0	0
Rad. curv. (mm/air)	9.80E1	9.80E1	1.00E2
# of integ/grid points	50	64	64
Crystal/grid sizes (mm)	10	0.65	0.4
Deff (pm/V)	2		
Delta k (1/mm)	0.3		
Dist. to image (mm)	0		
# time steps	50		

Accept

Suggested value = 20. Increase for greater time resolution.
(irrelevant for all cw beams).

Figure 9: Inputs 2D-mix-LP example.

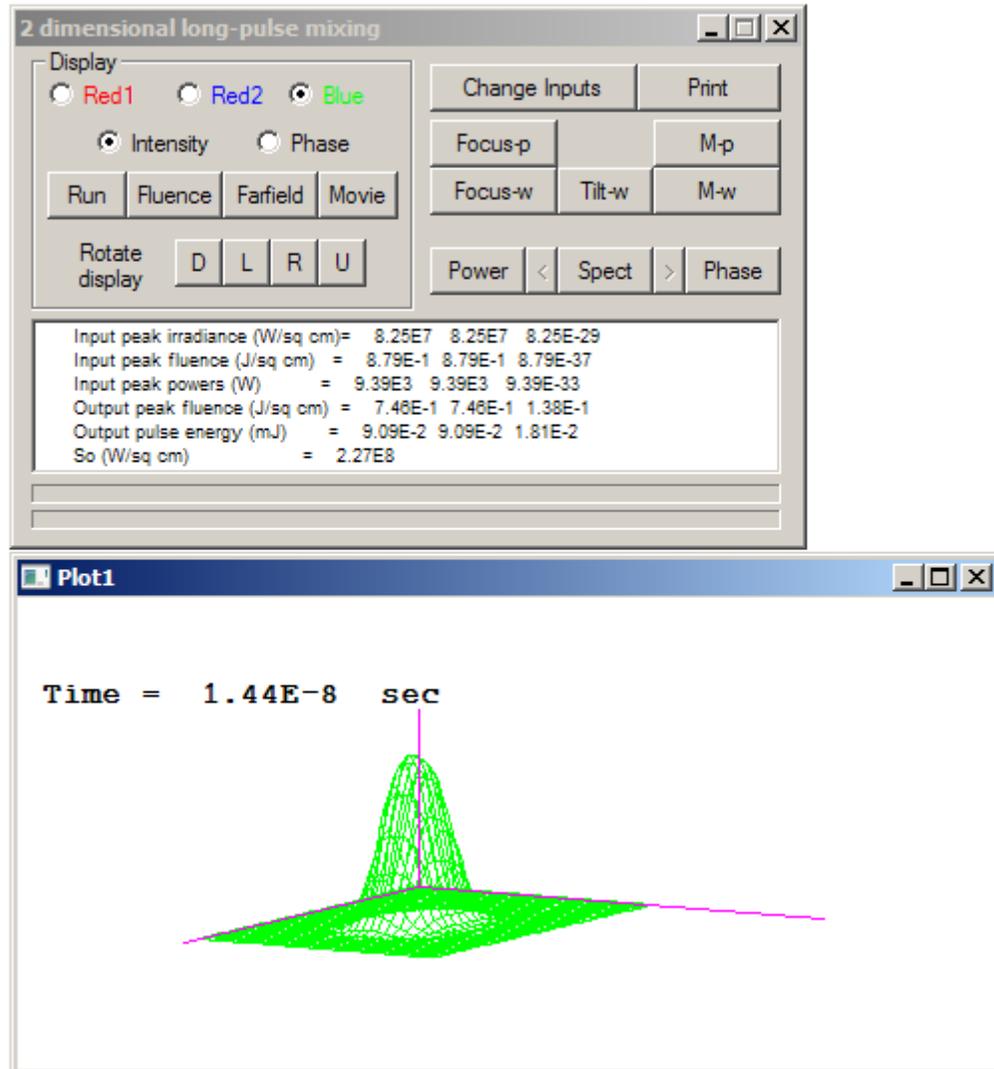


Figure 10: 2D-mix-LP example.

3.5. 2D-mix-SP

This models single-pass mixing including dispersion and diffraction for short pulse and Gaussian beams. Preloaded examples illustrate: sum-frequency mixing of focused beams with spatial and temporal walkoff (example #63); and sum-frequency mixing of group-velocity-matched collimated beams (example #66).

3.6. PW-cav-LP

This models intracavity mixing for long pulses in the plane-wave limit. Processes include intracavity sum-frequency mixing, intracavity difference-frequency mixing, and optical parametric oscillation. Preloaded examples illustrate: cw intracavity second harmonic generation (example #36); cw singly resonant OPO (example #51); cw doubly resonant OPO (example #46); cw pump-enhanced OPO (example #52); cw triply resonant OPO (example #55); and nanosecond singly resonant OPO (example #69).

3.7. PW-OPO-SP

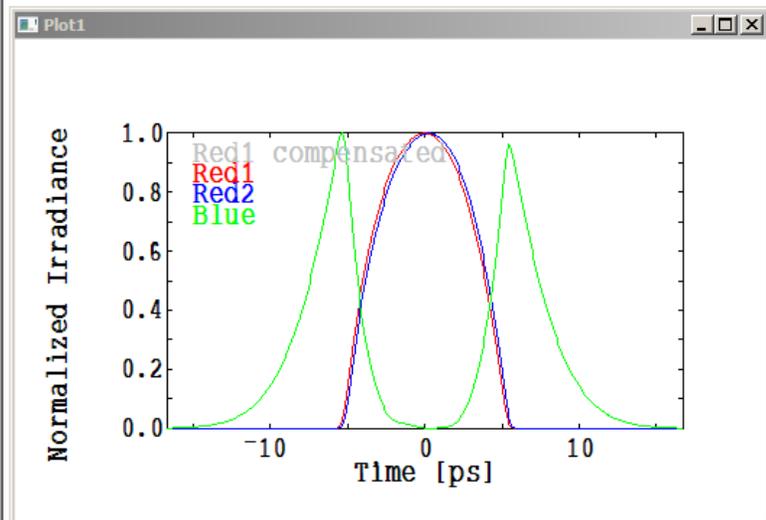
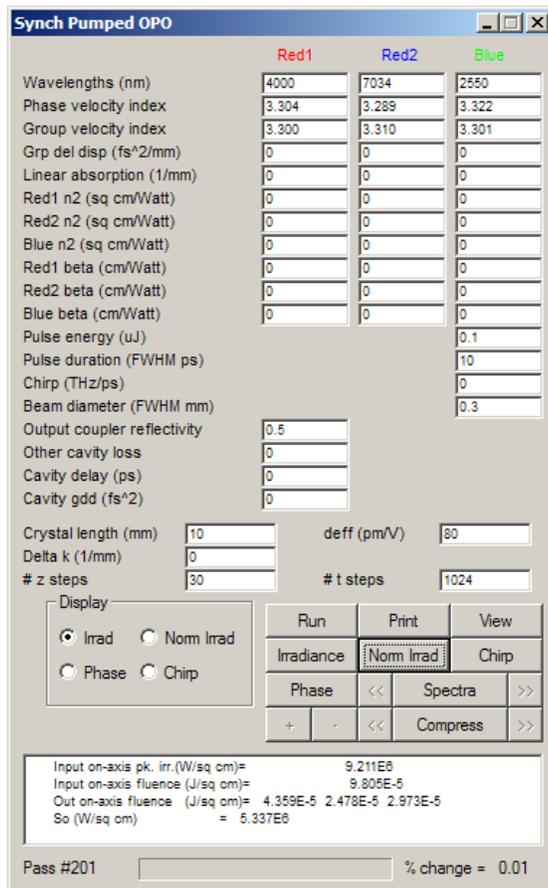


Figure 11: PW-OPO-SP example.

This models synchronously-pumped, singly resonant optical parametric oscillators in the plane-wave. Figure 11 illustrates an example. The model adds quantum noise to the signal and idler fields on each cavity pass. The OPO

starts from this noise. The model also includes group velocity and group delay dispersion adjustable compensation. Preloaded examples include #35 and #77.

3.8. PW-OPO-BB

This models broadband nanosecond optical parametric oscillators in the plane-wave limit. It includes group velocities, and allows the pump to be broadband as well as the signal and idler. You can specify a signal seed to study injection seeding of nanosecond OPOs. Preloaded examples include #48.

3.9. 2D-cav-LP

This models intracavity mixing of Gaussian beams for nanosecond to cw pulse lengths. Processes include sum-frequency mixing, difference-frequency mixing, optical parametric oscillation in stable or unstable optical cavities. Preloaded examples illustrate: cw intracavity sum-frequency mixing (example #37); cw optical parametric oscillator (example #42); cw doubly resonant optical parametric oscillator (example #45); nanosecond ring optical parametric oscillator (example #49); and cw pump-enhanced optical parametric oscillator (example #54).

4. AUXILIARY FUNCTIONS

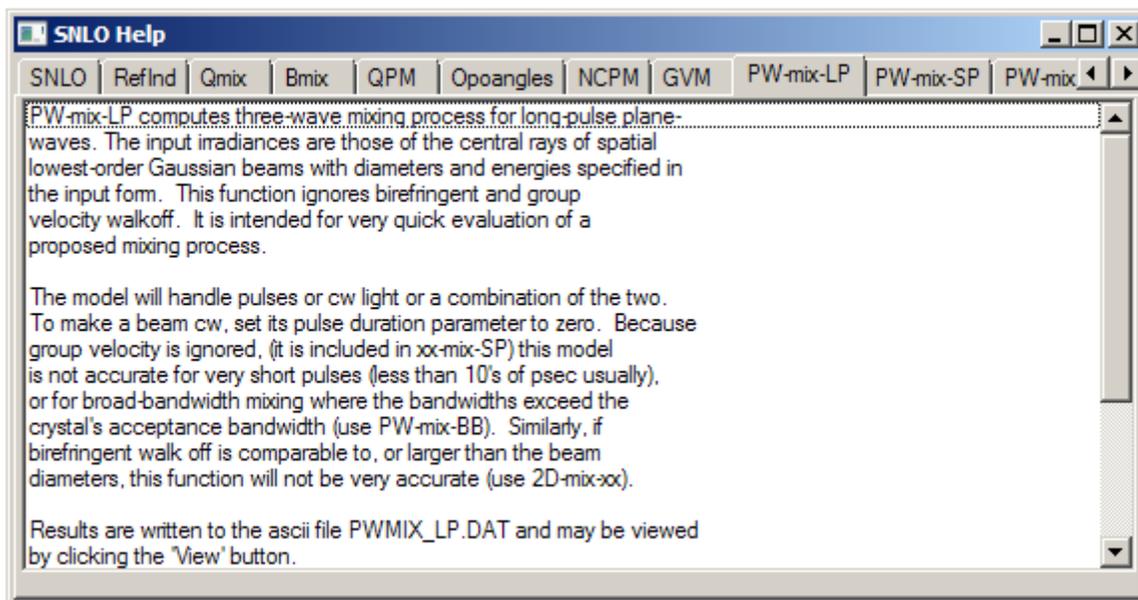


Figure 12: Help example.

Generally the mixing of low power beams is done in a stable cavity formed by focusing mirrors. Such cavities can be designed using the **Cavity** function which will also help you find the wavefront curvature of the input beams at the input mirror, and the cavity round-trip phase which must be known to achieve exact resonance in the cavity. This function operates much like **Focus** in that the outputs are updated automatically on any change of the input parameters. A help plot of the cavity pops up with this function to assist in setting the parameters.

The **Help** function offers a short description of each function along with hints on its use and a list of the output files written by each. One example is displayed in [Figure 12](#). The **Help** for each of the modeling functions usually lists several examples that illustrate the use of that function. The information in **Help** can also be found in `SNLO_help.pdf` included in the SNLO installation directory and available on the SNLO download website (<http://www.as-photonics.com/snlo>).

5. CONCLUSION

All of the modeling functions of SNLO are based on split-step integration methods. They are all-numerical to cover the widest possible range of applications. More details are available in references [1, 2, 3, 4]. I have carefully validated all of the modeling functions against analytical expressions and against each other. SNLO may be downloaded free of charge at web site <http://www.as-photonics.com/snlo>.

References

- [1] Smith, Arlee V. (2015). *Crystal nonlinear optics: with SNLO examples*. ISBN 978-0-692-40044-9.
- [2] A. V. Smith, W. J. Alford, T. D. Raymond, and M. S. Bowers, "Comparison of a numerical model with measured performance of a seeded, nanosecond KTP optical parametric oscillator," *J. Opt. Soc. Am. B* **12**, 2253-2267 (1995).
- [3] A. V. Smith, R. J. Gehr, and M. S. Bowers, "Numerical models of broad-bandwidth nanosecond optical parametric oscillators," *J. Opt. Soc. Am. B* **16**, 609-619 (1999).
- [4] A. V. Smith, and M. S. Bowers, "Phase distortions in sum- and difference-frequency mixing in crystals," *J. Opt. Soc. Am. B* **12**, 49-57 (1995).