GUIDE TO NOPAS

FROM
THE MCCAMANT GROUP
AT THE
UNIVERSITY OF ROCHESTER

Assembled by:
Kristina Wilson, PhD candidate in the lab of David McCamant in the Department of Chemistry at the University of Rochester.

Acknowledgements

Many of the materials in this guide were prepared by Barbara Dunlap, another graduate student in the same lab. Some were made by Randy Mehlenbacher, who is now a graduate student in the lab of Marty Zanni at the University of Wisconson. Barb, Randy and a current post doc, Reddy Challa, have all graciously contributed substantial amounts of time to figuring out the NOPA and getting it to work. Finally for the lab acknowledgements, I of course, must thank my adviser, Dave McCamant, who taught me everything I know about ultrafast (and many things that I have failed to absorb) and has somehow found time to help in lab as well as from the comfort of his office.

But the McCamant Lab's NOPA journey would never have come to such fruition without the help of Eberhard Riedle from BMO München, Giulio Cerullo from the Center for Ultrafast Science and Biomedical Optics at the Politechnico di Milano Departmento di Fisica, and Jake Brommage from the UR LLE. Our lab's understanding of NOPAs is a direct result of the knowledge and generosity of these colleagues in ultrafast spectroscopy.

Contents

Figures

Tables

A parts list is in an accompanying document.

INTRODUCTION

A myriad of interesting things happen to molecules on the femtosecond time scale. Titanium:Sapphire lasers and regenerative amplifiers give lots of eager scientists 100fs, 1 kHz rep rate, 800nm pulses with a milliJoule or two of power. But what if you want pulses that are visible, or that have bandwidths greater than 300 cm^{-1}, or that are just a few tens of femtoseconds long? Well then, you need a Non-Collinear Optical Parametric Amplifier (NOPA). We needed those things for our work on Two Dimensional Femtosecond Stimulated Raman Spectrsocopy. The endeavor proved surprisingly arduous, because while the basic theory and design are straightforward, the components are easily obtained and there are scores of academic papers describing functional NOPA designs, there exist precious few resources bridging the gap between all the optics arranged reasonably on your table and bright, broadband light.

FIRST AND FOREMOST: **ALWAYS WEAR PROPER EYE PROTECTION, AS THESE SEEMINGLY DIM PULSES CAN DAMAGE YOUR VISION PERMANENTLY**. When you go into the lab and start setting up your NOPA, you will be using large quantities of ultrashort 800nm pulses. We all know that 800nm beams are much more intense than they seem because we only perceive the scattering from them. However, you may not have considered that the lens on your eye focus these wonderfully high peak powers onto your retina, just like they do on your sample.

At any rate, we use goggles that are OD 6 at 766-860nm when working with strong 800nm (the 1mW portion of the fundamental generating the continuum is the only exception). For working with NOPAs we have found the goggles with OD 2 at 400-650nm and OD 1.5 at 650-700nm from LaserVision (we like frame F10 for protection from beams in your peripheral vision; the lens number is "00200.00"). These are particularly useful because they have attenuation across the visible spectrum but allow one to see the beam for alignment purposes.

In order for my notes to be helpful to you, you should be familiar with the following ideas and topics:

- handling ultrafast/broadband pulses
    - chirp
    - the transform limit
- geometrical optics
- some Non-Linear Optics:
    - SHG
    - OPA
    - supercontinuum generation

I strongly suggest that you read through this entire document before using any part of it.

THEORY

In order to give you something to map the following theoretical concepts onto, we'll start with what's already familiar: the basic set up of a functional NOPA.

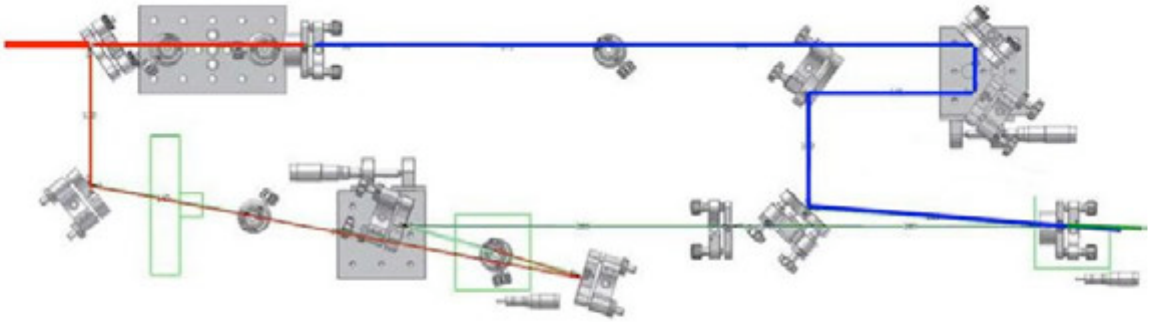


Figure 1: *The basics of a visible NOPA. 230 mW of the 800nm ti:sapph regen output is redirected through a 90%/10% beam splitter, with 10% going to white light continuum (WLC) and the bulk going to a BBO crystal cut for SHG.* ***WLC/seed:*** *The WLC is made by focusing the dim 800nm light into a 2mm sapphire crystal. The WLC is collimated, then directed into the NOPA BBO crystal.* ***SHG/pump***: *The bright red light passes though a doubling crystal, generating 400nm photons that are directed to the NOPA BBO crystal. The beams approach the NOPA BBO at a very particular crossing angle and are spatially overlapped in the crystal. Broadband light resulting from the non-linear mixing of the intense SHG with the weak WLC beam gives you a nice bright green pulse. CAD by Barbara Dunlap.*

What I provide as "theory" is the opposite of a rigorous treatment--it's just an assortment of useful notes. Refer to papers on NOPAs like those by Cerullo[1], Riedle[2], Kobayashi[3], or even a text on NLO[4] like Boyd's, if you crave a complete theoretical description of the concepts behind NOPAs.

Noncollinear Optical Parametric Amplification

Optical Parametric Amplification (OPA) is one of two types of Optical Parametric Generation (OPG), the other of which is Optical Parametric Oscillation (OPO). "The principle of OPG is quite simple: in a suitable nonlinear crystal, a high frequency and high intensity beam (the pump beam, at frequency ω_p) amplifies a lower frequency, lower intensity beam (the signal beam, at frequency ω_s); in addition a third beam (the idler beam, at frequency ω_i , with $\omega_i < \omega_s < \omega_p$) is generated. For the interaction to be efficient, momentum conservation (or phase matching condition),

$$\hbar\vec{k}_p = \hbar\vec{k}_s + \hbar\vec{k}_i ,$$

where $\mathbf{k}_p$, $\mathbf{k}_s$, and $\mathbf{k}_i$ are the wave vectors of pump, signal, and idler, respectively, must be fulfilled."[1]

This condition cannot be fulfilled in isotropic materials with normal dispersion, which is why we must use birefringent crystals like BBO. In fact, the nonlinear polarization of the crystal is what drives the amplitude variations in the propagating wave, which is what eventually allows intensity to be transferred from one pulse to another. In order to take advantage of this non-linear polarization, one must systematically vary the polarizations of the beams involved in phasemaching. There are numerous combinations of polarizations, depending on which non-linear process one intends to exploit, which wavelengths are involved and which crystal material is used; these are referred to as different "types" of phasematching. When the goal is OPA in the visible in BBO (a negative uniaxial crystal, so $n_e<n_o$), one employs Type I phasematching, or in other words, the following polarization scheme (described with respect to the ordinary and extraordinary axes of the crystal) is used:

$$o_s+o_i \rightarrow e_p$$

Thus, the pump is polarized perpendicularly to the seed (and therefore, the signal) and the idler.

In the crystal, efficient phasematching is achieved by utilizing the appropriate phasematching angle, or the angle between the wavevector of the propagating beams and the optical axis of the crystal.

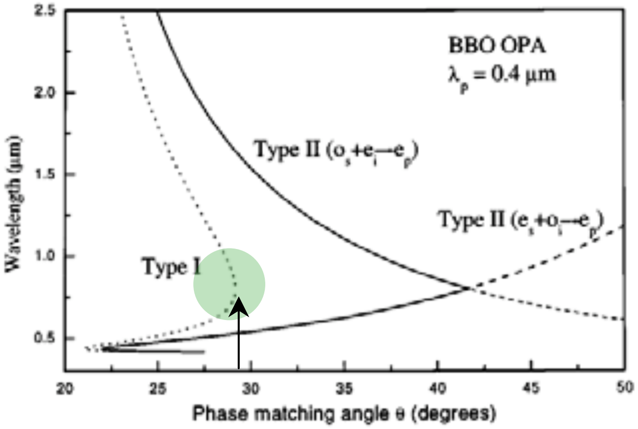


Figure 2. *Fig 4 from ref. 1. Angle tuning curves. The dependence of phasematching angle on phasematching type, the wavelengths involved (and of course the material) is shown in this graphic. Note that the angletuning shows why the phasematching angle for Type I phasematching of visible light is ~30°.*

This interplay is manifested physically in the cut angle of the crystal—it will be cut for a certain type of phasematching (see the Newlight Photonics webpage on BBO's[5]—it's chock full of valuable information, including Sellmeier equations for BBO). In practice, this angle will be within a degree of the phasematching angle you need, but not exactly what you wanted. We'll talk about dealing with that in the portion of the manual dealing with implementation.

The whole reason we've been talking about this is that we need to take advantage of wavelength and polarization-dependent indices of refraction in order to get our pulses to propagate through the crystal overlapped spatially and temporally—these n's basically put brakes on and redirect the pulses so they do that.

In order to talk about pulses traversing crystals, we must define the velocity at which a pulse travels through a crystal, or the group velocity:

$$v_g = \frac{d\omega}{dk}$$

In precise terms, we want to minimize Group Velocity Mismatch (GVM) between the interacting pulses. This is because, "**GVM between the pump and the amplified (signal and idler) pulses limits the interaction length over which parametric amplification takes place, while GVM between the signal and the idler beams limits the phase matching bandwidth**."[1]

So, we have these constraints—phasematching (a theoretical one governing the efficiency of the process) and GVM (a physical one that must be utilized properly in order to use your birefriengent, non-linear medium)—that we would like to satisfy simultaneously. Introducing another degree of freedom, i.e., making the OPA interaction have a non-collinear geometry, allows us to do so.

In terms of phasematching, the angle α is what facilitates broadband amplification of the signal; the pump wavelength and direction are constant, but for every wavelength in the WLC of the signal, an idler of a different wavelength is emitted in a different direction.

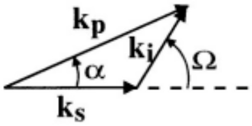


Figure 3. *Phasematching vectors in Non Collinear Optical Parametric Amplification.*[1] *This figure shows the compensation the idler can make for the different signal wavelengths in order to fulfill the phasematching condition for a pump of set wavelength.*

In terms of group velocities in the crystal, we can see how an angle between the signal and idler facilitates the amplification of broadband WLCs, because the different distances that the signal and idler must travel through the crystal minimize their GVM.

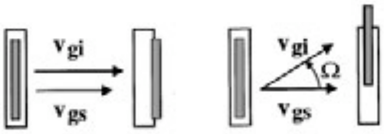


Figure 4. *GVM and Non Collinear Optical Parametric Amplification*[1]

Note, while the angle Ω is the angle that facilitates the small GVM in the crystal, because it is different for every combination of signal and idler wavelength, in practice we talk about α, as it is the angle physically set in the lab.

The Crossing Angle, α

It is important to realize that, because of the high index of refraction of BBO, the crossing angle inside even a 1mm crystal is substantially different than the angle outside of it. The internal angle is the one that is determined by the phasematching angle, the pump wavelength and the signal wavelength. The external angle is the angle that is set outside of the BBO crystal so that when the wavelength dependent index of refraction of BBO bends the pump and signal paths as they enter the crystal, they have the appropriate internal crossing angle, as determined by the following figure.

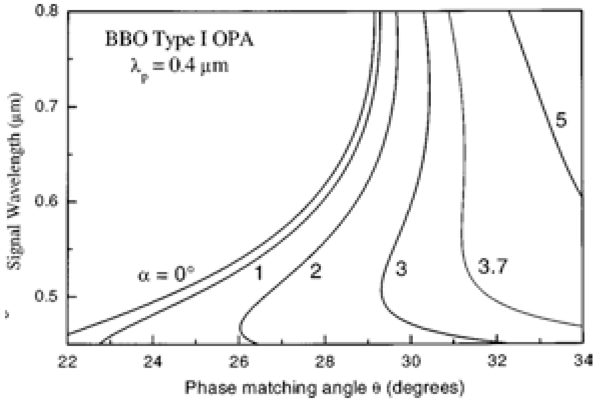


Figure 5. *Internal Crossing Angles. As you can see from the diagram, an average BBO cut at θ=31.2° for Type I phasematching of a 400nm pump with a 530nm signal internal angle of about 3.7°.*

Internal Angle: the crossing angle is determined by your pump wavelength and the wavelengths that you want to amplify. This is all assuming that you have purchased a BBO crystal cut for Type I phase matching, so cut at a 30-32° angle (the standard for amplifying visible light centered at 530nm). The diagram above is pretty handy for figuring out what that internal crossing angle, α, should be.

External Angle: this only takes a little geometry and Snell's Law. You can double check your work by checking out the external crossing angles in papers. Usually it's about 6° when amplifying a central wavelength of 530nm with a 400nm pump.

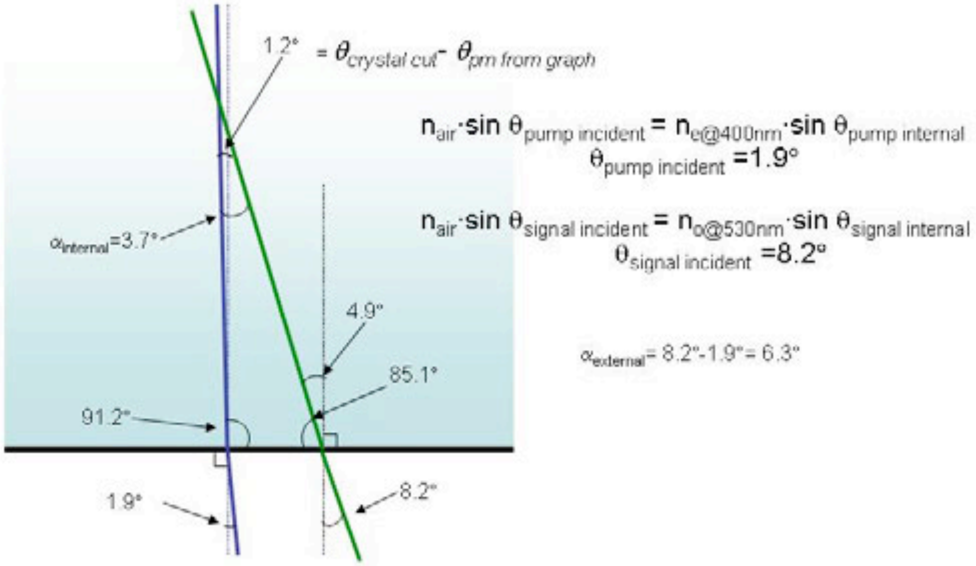


Figure 6. *Determining the external crossing angle, given an ideal internal crossing angle and the ordinary and extraordinary indices of refraction of BBO.*

Polarization

Polarizations are important, as NOPA is facilitated by BBO, a birefringent crystal. NOPAs in the visible use Type I phasematching, so the **pump and signal have perpendicular polarizations**. The signal and idler travel along the ordinary axis and the pump travels along the extraordinary axis. The plane formed by the intersection of the pump and signal beams must also be oriented along the plane formed by the ordinary and extraordinary axes of the BBO crystal.

Powers and Efficiency

OPA is not 100% efficient, so you have to set your average power and focal spot sizes carefully (below, there is a list of all of our parameters). In the lab, you'll get about 15-20% conversion efficiency from 400nm intensity. If you have a 1mm BBO crystal it works out nicely because when you approach 20% conversion, you also approach the damage threshold, which occurs at ~200 GW/cm^2. Attempting to exceed that will actually induce lower efficiencies, because the efficiency curve for OPA tops off at ~20% and then starts *decreasing*. See the nifty plot that Barb and I made.

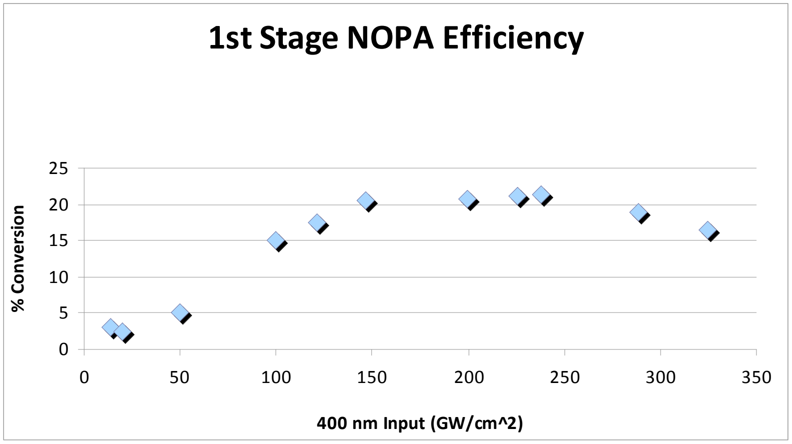


Figure 7. *OPA efficiencies. As you can when peak power exceeds ~200 GW/cm^2, OPA efficiency decreases. This is actual data that Barb and I took in the lab.*

White Light Generation In Sapphire: Easy, If Frequently Misunderstood.

There are plenty of papers that speculate on the mechanism of WLG but none of them tell you how to set one up in the lab. Lots of people seem pretty stumped by this, but setting up a stable continuum with a 100fs 800nm pulse in a sapphire is quite facile.

The functional understanding of WLG is as follows: when ultrafast pulses pass into a medium one must consider effects that do not occur in ordinary optics. The broad bandwidth of short pulses results in interesting phase effects, which occur even at low powers. "When pulses shorter than 100fs are focused on a transparent material, a strong spectral broadening starts because of self phase modulation. The newly created frequencies act as seeds for a large variety of higher order non-linear optical processes, such as wave mixing and parametric effects, resulting in a wide spectrum which spans from the near infrared to the near ultraviolet."[6] If you want to read more, I point you to Claude Rulliere's wonderful text "Femtosecond Laser Pulses".

As you can see in the figure in the "How to set up WLC" section below, the WLC is preceded by an iris and two NDF's. This is because generating a nice continuum is sensitive to irregularities in the mode of your laser and to very small differences in the intensity of the 800nm light going to generate it.

Moreover, notice that we choose to make our continua reflectively with spherical mirrors. Many other people use a lens as the first focusing optic if they seek pulses 20 fs or longer[2]. The advantage to a partly transmissive set up is that it uses less pathlength because it can be half-linear and astigmatism is somewhat avoided. The disadvantage is that chirp induced by the focusing lens on the 100fs beam ultimately limits the bandwidth of the WLC that is generated (and thus the possibility of <20fs pulses).

NOPA DESIGN AND ASSEMBLY

REMINDER: when you go into the lab and start setting up your NOPA, you will be using large quantities of ultrafast 800nm pulses. We all know that 800nm beams are much more intense than they seem because we only view the scattering from them. **ALWAYS WEAR PROPER EYE PROTECTION, AS THESE SEEMINGLY DIM PULSES CAN DAMAGE YOUR VISION PERMANENTLY.**

The most important parameters of your NOPA design are angles and powers.

Angles. The crossing angle must be ideal for the center wavelength you intend to amplify. Make things easier by keeping all beam paths through the entire NOPA at a constant height parallel to the optical table.

Powers. I assume that you'd like to use the laser power you have efficiently and that you'd like to get as much out of your BBO crystal as possible before damaging it (which will happen over time—Prof Cerullo has described them as basically disposable). In order to do that, you need to pay attention to the peak power of your SHG beam on the BBO crystal, which in turn necessitates that special care be taken when considering how much SHG power to use and how tightly to focus the beam on the crystal. (See Figure 5, above).

Polarization

Prof McCamant (wisely) prefers to have the plane that the pump and signal sweep out to be parallel to the plane of the table, that is, not going up into anyone's eyes. Therefore, the signal is horizontally polarized (with respect to the plane of the optical table) and the SHG, naturally, is vertically polarized.

Because these planes must be aligned, the rotation of the BBO crystal about the direction the seed propagates in must be set carefully. The rotation of the OPA crystal can be roughly set by sending the pump through and turning until the superfluorescence is maximized. If the crystal is not rotated properly, the birefringence of BBO will induce some ellipticity in the polarization of the signal. In order to set it precisely, use a polarizer to verify that the polarization of the seed is NOT twisted as it propagates through the crystal. This should be done without the pump on the crystal.

We've posted a parts list with a labeled CAD drawing of the NOPA. It actually goes with our Two Stage NOPA, but just use the parts from the first stage to get started. ☺

We've also included a list of NOPA parameters that have worked for us in the past.

<u>NOPA Stage 1</u>			
WLC	*3mW 800nm*		
M1 (100mm)-->sapph	sapph-->M2 (50mm)*	M2-->BBO	gaussian beam diameter @ BBO
100mm	50mm	325mm	.273 mm
SHG	*~27mW 800nm*		
focal length of lens	200mm lens-->BBO	SHG average power	gaussian beam diameter at BBO
200mm	249 mm	~10mW	.266 mm

* In the lab, this distance slightly deviates from the focal length of mirror 2 in order to set the focus far away at the BBO crystal (rather than recollimating), but the difference between exactly 50mm and what it was eventually set at was arrived at empirically, by checking beam diameters at the BBO crystal and translating M2 accordingly.

Table 1. *Parameters for the first stage of our two stage NOPA, which we only want ~1μJ of OPA output from. Please note that these parameters would be different if we planned to use only this stage in the lab, because we would want ~25 times the output power.*

At this point, you should be ready to take your design ideas to the white board or, even better, the CAD program. Physically assembling the NOPA and getting it to work is much more facile when all the optic placements and pathlengths are planned out to the cm before you put anything on the table.

HOW TO SET UP YOUR WLC:

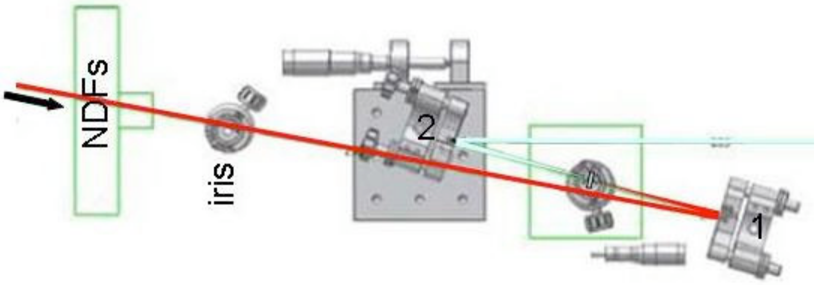


Figure 8. *A CAD drawing of one of our continuum designs.*

To avoid burning your sapphire crystal: use ≤2μJ total of 800nm for your continuum.

Place your optics on the table *except for the sapphire*. The 800nm beam should encounter the optics in the following order: iris, NDF's (one of which is on a rolling base), first focusing mirror, second focusing mirror, 750 nm short pass filter.
When placing the mirrors and the crystal, make sure that the crystal and the second mirror are on translation stages. To start, even though the crystal is not yet present, do place the crystal mount's translation stage for alignment purposes. This will provide the fine control needed in the future in order to place the crystal and set the focus of the WLC with accuracy.

Make the "z" of this path as flat as possible in order to minimize the effects of astigmatism from the focusing mirrors. For example, in the figure of our continuum above, it would have been ideal to have the white light pass closer to focusing mirror 1. It was not possible because of design issues down the line.

When all of the optics are in place and the "z" path is aligned, **place the sapphire crystal a little bit closer (maybe 1cm) to the first mirror than its focal length**, with the face of the crystal perpendicular to the 800nm incident beam (check with the back reflection—you may need an IR viewer to do this).

<u>Precision placement of the sapphire crystal:</u>

To avoid unwanted processes like multiple filaments emerging from the focus, it is best to focus **your 800nm light at the far side of the sapphire crystal, that is, the face of the crystal more distant from the first focusing mirror**.

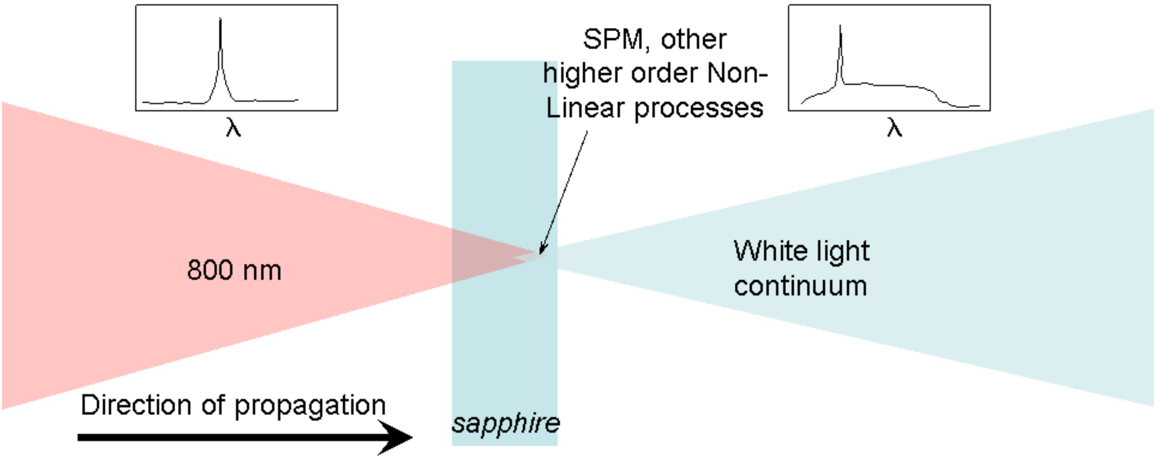


Figure 9. *A diagram indicating what to have in mind when setting the sapphire crystal in place for white light generation. The focus and CG should be as close to the exit side of the crystal as possible, in order to keep from generating multiple continua.*

When everything is set and aligned, open the iris all the way and roll the mobile NDF largely out of the way, letting ~ 2μJ through (in actuality, we put this number here so you don't burn your crystal because of our directions…you don't have to measure this quantity, just don't put all the light on the crystal).

What you *eventually* want is a pale blueish disc surrounded by a red ring. If there is a little too much power, the red ring will be very bright and there will even be a yellow ring around it. When this happens, roll the NDF to decrease the power until the output of the WLG is stable. Clean it up by closing the iris around the edges of the 800nm beam.

Initially, however, you'll probably get a crazy continuum—you will certainly be able to tell when you've gotten near the focus by very weird looking unstable stuff coming out of the crystal. If you don't get anything then adjust the mobile NDF to let more power on the crystal.

Once you get that bright, unstable output, decrease the power to the sapphire with the NDF until the continuum just disappears, then bring it back by translating the crystal closer to the focus of the first mirror, that is to say, by moving it closer to the focus. Go through the steps of decreasing the power and translating the crystal until you cannot bring back the continuum by translating the crystal anymore. Double check that this is about the expected focal length of your mirror.

I made a video of how to tweak a continuum with a colleague, Randy Mehlenbacher, who is now in Marty Zanni's lab at Wisconson. Please refer to it before attempting to set up your own continuum because a lot of this process is lost in a verbal description.

SHG delay and focusing

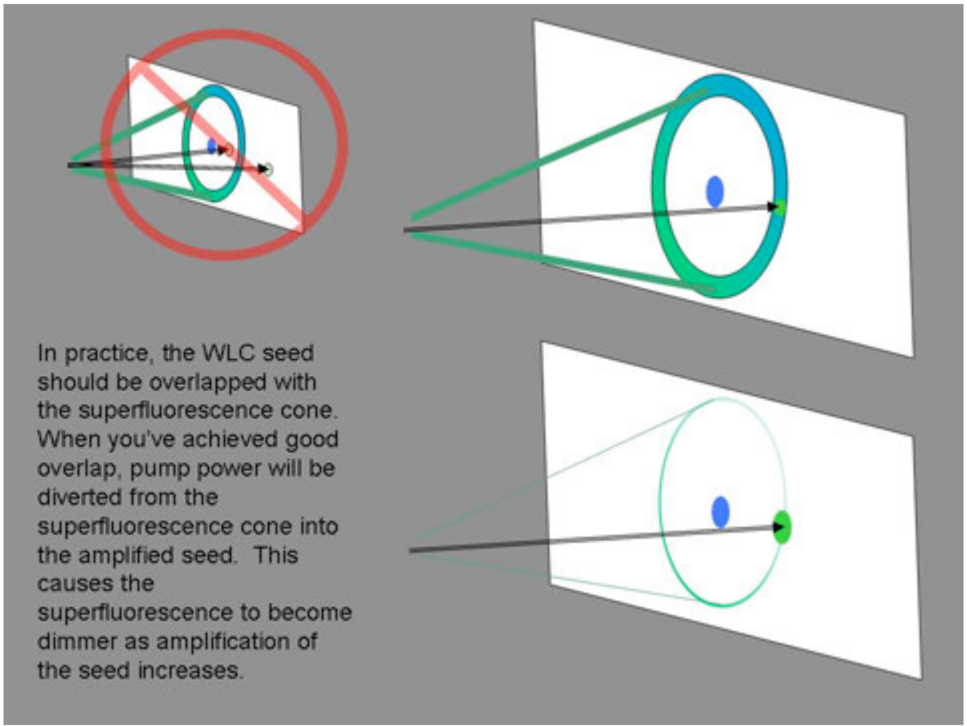
I will assume that you know how to set up SHG and a delay stage. Be careful to put your focusing lens in a spot where translating the SHG delay will not interfere with your focusing.

This is the part of the design in which you employ your knowledge of OPA efficiencies by carefully choosing average powers focal spot sizes. **Not exceeding reasonable peak powers has, in our experience, been the most crucial step towards a nice mode quality**.

How to set the Crossing Angle, α

First, set the angle as accurately as you can using geometry and regular old rulers. Assuming the angle is set somewhere close to α, the SHG passing through the BBO *without the WLC* will generate the superfluorescence cone, a greenish, speckled ring. If you've measured carefully, when the WLC is let through the BBO and is spatially overlapped with the SHG in the crystal, it should also be roughly overlapped with the superfluorescence cone.

Adjust the angle the SHG approaches the BBO at until the superfluorescence cone exactly overlaps the WLC. This will require iterations of moving the SHG beam's position on the last mirror before the BBO and then reestablishing spatial overlap of the pump and the WLG in the crystal. Use care to keep moving the SHG back onto the WLC in the crystal. As the angle incident on the crystal is adjusted, this sometimes drifts away. Also, there is no need to use full power when setting this alignment, so turn down your SHG crystal or put in some NDFs.



In practice, the WLC seed should be overlapped with the superfluorescence cone. When you've achieved good overlap, pump power will be diverted from the superfluorescence cone into the amplified seed. This causes the superfluorescence to become dimmer as amplification of the seed increases.

Figure 10. *The importance of seed/superfluorescence cone overlap*

Once you have a nice WLC, the right amount of SHG, your focusing optics are set up so that your peak powers are ideal and all of your pathlengths are appropriate, it's time to start looking for OPA ouput. You will, of course, not have measured your pathlengths to the femtosecond, so you'll translate your SHG delay until you see amplification. But what if you don't know what you're looking for?

Here’s what it looks like when you find it:

Figure 11. *A photo of green NOPA output and the blue leftover SHG.*

Watch a video of it on our group’s website (link coming soon)

On your first attempt at finding OPA light:

Translate the SHG delay; if you are very, very lucky, the amplified colors of the seed WLC will start to come in ROYGBIV order. If you are not using much SHG power or things aren't quite aligned correctly, the OPA output might be dim or sort of spread out around the circumference of the WLC spot. You may want to turn off the lights as you translate the SHG delay to be sure you'll see subtle changes in intensity. I also recommend that, when you are trying to find it at all, you roll the delay actuator back so that you can just push the stage for the whole delay rapidly with your hand, rather than turning the actuator knob. If you do it a little rapidly (and this is one of the things that is impossible to correctly communicate without a demo), the OPA light shows up more abruptly so you get more of a "flash" than you would translating. It can make a mild change in intensity more apparent AND you get the chance to say "laser disco party" when you find it.

DON’T BE FOOLED. You can see some amplification at non-ideal crossing angles. If α isn’t set well, though, it will be narrow bandwidth or be low intensity or both.

TROUBLESHOOTING

Things you should be absolutely sure of before you worry about details:

1) Translate the NOPA BBO close enough to the SHG focus that you get an easily visible superfluorescence cone, especially when trying to tweak from nothing. If you can see

that, you;ll be able to tell where the temporal overlap is even when the crossing angle (and spatial overlap, if you're using tons of power) is poorly set.

2) Double check your pathlengths and crossing angles.

3) Also double check the angle of rotation of the plane NOPA BBO about the WLC axis. If it's not pretty close, your polarizations will be wrong and you won;t find the signal. This, too, can be optimized by maximizing superfluorescence cone intensity as you rotate the crystal about the axis.

What to do if things are set up pretty well but you get almost no OPA output:

What you see is, you're looking at the WLC after the NOPA BBO, and as you translate the SHG delay, you'll see some blue SFG phasematched on the side of the WLC/SHG plane come in. Simultaneously some red DFG comes in pretty close to where the OPA output does, which is to say, almost overlapped with the WLC. Sometimes this is really bright and sometimes it's dim. I think it might have a slightly different dependence on the crossing angle than OPA, but I wanted to tell you it could be there. Don't worry if it's not, though. Just pretend I didn't say that and look for the familiar OPA output.

The (final) thing that we didn't think of when we were originally building NOPA:

…is the importance of beam diameters and peak powers, because OPA efficiency not only tops off at ~20%, but actually oscillates as you put in more SHG peak power with a modulation depth large enough that you could drive yourself down to like, ~10% if you go past an initial peak but not far enough to get to the next one. I also remember that the second OPA efficiency peak happens after the damage threshold for BBO, so you really want to be at the first sweet spot. Come to think of it, Barb and I made some nice plots of this stuff. If you think they would help, let me know and I'll get them to you.

If you still have problems, it would probably be best to send me a pic, or better yet, find a way to video conference.

References

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