

Plasma Formation and Self-focusing in Continuum Generation

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I. Abstract

This summer we managed to be the first group, to the best of our knowledge, to measure the rate of plasma growth and decay in sapphire (Al_2O_3). Having recorded this data we can proceed to attempt to relate it to laser beam self-focusing, yet another non-linear optical effect that contributes to continuum generation. Continuum generation (CG) is defined as the process by which white light is generated from a monochromatic light source due to non-linear optical effects in a non-linear medium. CG has a high potential since any part of its spectrum can be isolated as needed and thus be used as a tunable laser.

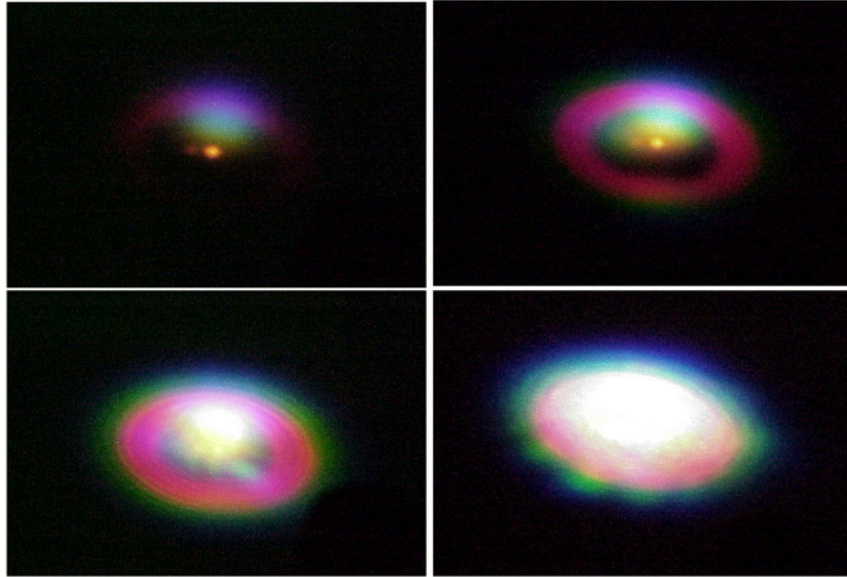


Figure 1: Pictures of Supercontinuum Generation at increasing intensity.

II. Introduction

In a perfect world, researchers of all types utilizing lasers in their respective areas of research would all have access to a single easily manipulated laser source such that the characteristics of the laser's emission could be changed as its user saw fit. This would suggest having access to a single laser system that could have its pulse width, output intensity, and perhaps most ideally, wavelength changed at will. However, there exists no such laser system that can meet all those criteria. It is possible, however, to isolate and use any of the several wavelengths of CG's spectrum (Figure 1). The problem with normal laser systems is that the light which they produce covers only a narrow spectrum. The CG process, however, results in light with a broader spectrum; in effect, researchers can use CG as a tunable short pulse laser light source with variable wavelengths.

CG has proven useful to researchers in practical applications such as optimizing ultra precise optical-clocks and providing broader bandwidth for optical coherence

tomography (a medical imaging technique), as well as having uses in fiber optics as a light source. Thus it is only a matter of time until CG is utilized more widely worldwide. However, CG cannot be optimally utilized just yet. There are many non-linear effects, such as four-wave mixing, self-focusing, self-phase modulation and plasma formation that contribute to CG. Each must be isolated and analyzed so that CG can be accurately modeled, and henceforth exploited. Currently our research is directed toward the isolation and analysis of both plasma formation and self-focusing.

Plasma is a state of matter in which atoms are ionized, or excited from the valence band into the conduction band, thus enabling the electrons to move around freely. Note that it takes an extremely large amount of energy to cause this phenomenon to occur in insulators (Figure 2). In sapphire for example, it requires ~ 8.8 eV to ionize electrons;

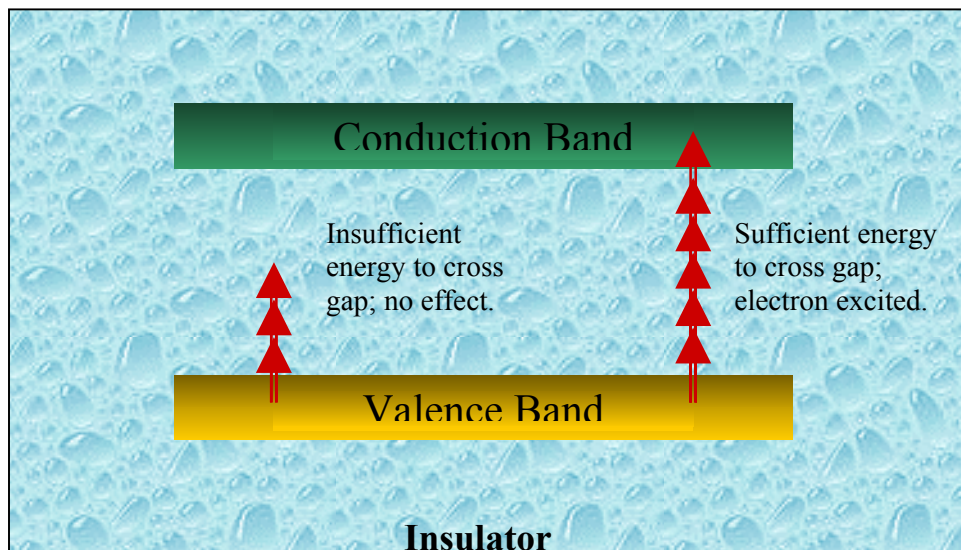


Figure 2: Ionization of electrons in an insulator. Plasma is formed in this way.

this is by no means a normal occurrence. However, when you have electrons moving around freely in an insulator, the characteristics of the insulator then begin to resemble those of metals and, as a result, plasma has the ability to reflect light. This allows us to

set up an experiment to measure plasma growth and decay in transparent media by measuring the amount of reflection we get off of any plasma present as a function of time.

Another contributor to CG is self-focusing. Self-focusing is a non-linear optical effect by which an intense laser beam propagating through a medium comes to a focus inside of the medium (Figure 3). This phenomenon can be explained physically. The total

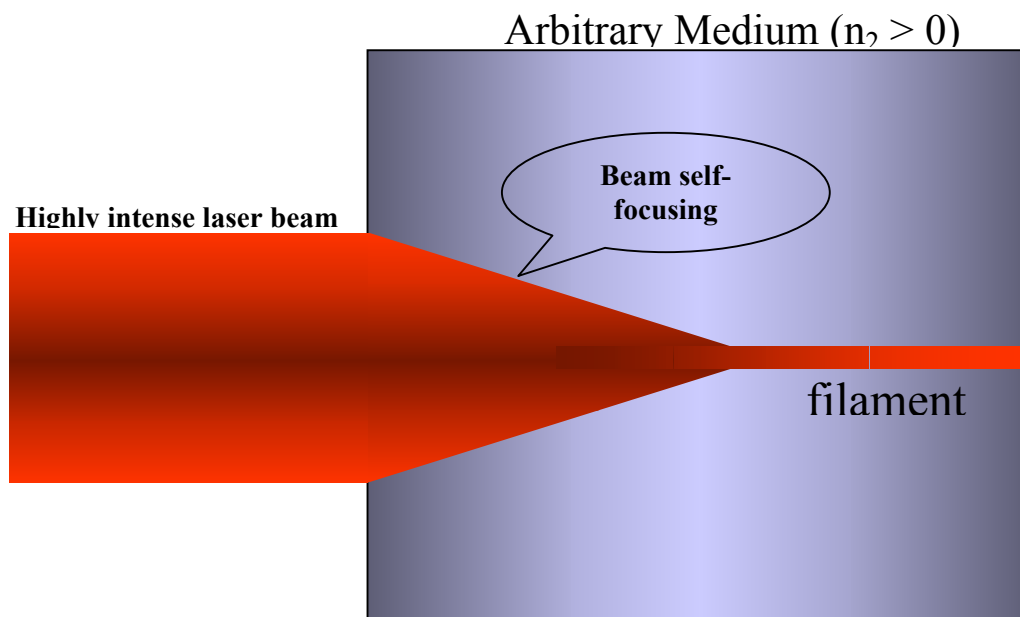


Figure 3: Self-focusing. The beam comes to a focus inside the medium due to a change in the index of refraction of the medium, which has become intensity dependant.

index of refraction of a medium is given by: $n_{\text{total}} = n_0 + n_2 \times I$, where "I" is the intensity of the beam, " n_0 " is the linear index of refraction and " n_2 " is a very small constant particular to the medium; for sapphire n_2 is of order $10^{-16} \text{ cm}^2/\text{W}$. As the beam enters the medium the index of refraction of the medium becomes dependant upon the intensity of the beam. Since the intensity of the beam is highest at its center and lowest at its edges, the index of refraction is also largest at the center of the beam, and lowest at the edges.

Therefore the edges of the beam travel ahead of the center, which is slowed down the most. The medium itself essentially acts as a lens, and the beam decreases to a focus inside the medium. Actually, the beam not only decreases to a focus but it remains at that minimum size for the remainder of the time it is inside the medium. This process is known as filamentation. The beam does not decrease indefinitely to zero however; there are processes occurring in the medium that counteract the self-focusing of the beam. One of these is diffraction. Diffraction is the tendency of a beam to diverge as it propagates. Another is an effect of the plasma formation itself. The plasma formed within the medium works to defocus the beam when it focuses down to a certain size. What we want to do is characterize the self-focusing of the beam inside the medium. That is, we want to know the beam's size as a function of the distance it traveled through the medium and possibly relate it to the rate of plasma growth and decay.

III. Experiment

We use a Ti:sapphire based laser system that provides us with extremely short-pulsed light (80 femtoseconds, i.e. 80×10^{-16} s) at 800 nanometers, which is near infrared (Figure 4). We then have the light undergo chirped-pulse amplification (CPA). Essentially, CPA is a process that takes a pulse, expands it (thereby reducing its intensity), amplifies it, then recompresses the pulse, resulting in a safely amplified short pulse. We then have the amplified pulse enter our apparatus, which utilizes a Mach-Zehnder interferometer to split and recombine the beam using two 50/50 beam splitters. The two pulses enable us to utilize a pump-probe technique. One of the two pulses, the pump, goes on to drive the continuum and generate plasma. The other, the probe, merely reflects off whatever plasma is present when it reaches the sample. In our experiment, the

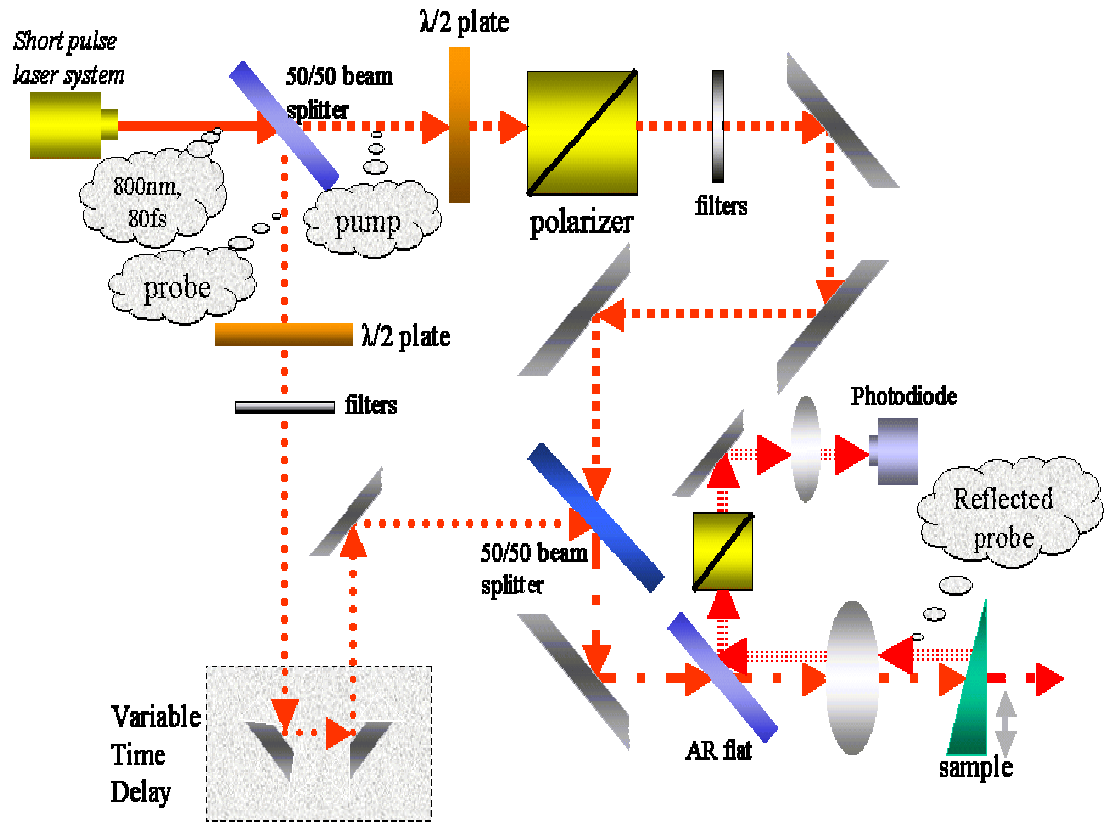


Figure 4: Schematic diagram of our experiment. It should be noted that the probe is too weak to perturb the CG or plasma formation.

probe undergoes a variable time delay before reaching the sample. It is also attenuated heavily so that it is too weak to contribute to the formation of plasma and CG itself. Using this apparatus we can vary the probe path length and have it reach the crystal before, after, or simultaneously with the pump. In this way we measure the reflected probe power as a function of delay between the pulses to measure plasma growth and decay.

There are several other important optics in our experimental setup which I will briefly mention. On the path that the pump follows there is a half-wave plate, a polarizer, and several glass filters. In tandem they have the effect of attenuating the pump so that it can drive the continuum without damaging the sample. In the probe path there is another

half-wave plate, which changes its polarization, and some heavier filtering. The filters attenuate the probe so that it does not contribute to the CG or plasma formation. We also have a polarizer on the path of the reflected probe. Its purpose is to pass only the reflected probe's polarization to the photodiode. Thus we can be assured that the diode, which is extremely sensitive, picks up only the reflected probe, and not any reflected pump light. Finally, our sample is placed near the focus of the lens before it. We have successfully used a sapphire (i.e. aluminum oxide: Al_2O_3) window to measure plasma growth and decay, however, to characterize self-focusing we have used and will continue to use a right angle prism. We will translate the prism up and down to simulate a beam going through varying propagation lengths. So far we have used fused silica as a medium, but we also plan on using sapphire, quartz, and calcium fluoride (CaF_2) as well.

We had to make major calibrations to our experiment in order to take accurate data. First off, we had to make sure that the probe aligned itself perfectly with the pump at the 50/50 beam splitter at the exit of the Mach-Zehnder interferometer. This was achieved by adjusting a mirror in the probe path. Furthermore, we had to make sure that the pump and probe beams were collinear. We did this by removing the sample and lens and spatially overlapping the beams some distance beyond. Making fine adjustments to the same beam splitter was all that was needed to assure this. Finally, and by far the most tedious and difficult calibration involved the time delay. It is not only necessary to overlap the two spatially, but they must also be overlapped in time. If the two are overlapped in space and time they will interfere with each other. Therefore, to be sure the two are overlapped in time we must look for an interference pattern, namely fringes. To do this we must first change the probe's polarization via the half-wave plate so that it has

the same polarization as the pump. Then we must adjust the variable time delay until we see the interference fringes. Finally we very slightly adjust the beam splitter so that we can see a perfect “bull’s-eye” pattern. This assures us that there is zero delay between the two pulses and that they are perfectly collinear.

IV. Data

Our latest plasma growth and decay data differs greatly from what current theory predicts (Figure 5). We used 800 nm, 80 fs pulses to drive the continuum and generate plasma in a 1 mm thick sapphire window. The resulting growth and decay of the plasma both took longer than expected. We measured a rise time of approximately 1 ps, and a

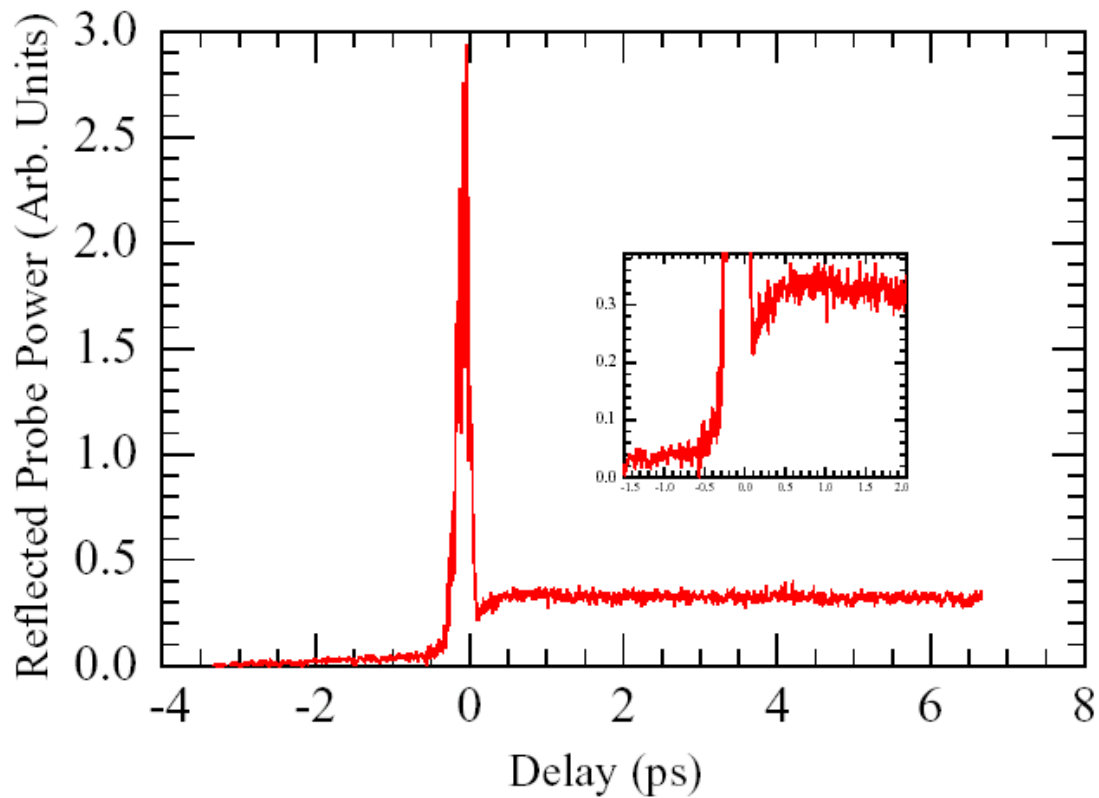


Figure 5: Our plasma growth and decay data using a 1mm thick sapphire window. The inset magnifies the plasma growth time.

decay time of approximately 80 ps. Current theory would predict a 100 fs rise time (10 times faster than we observed) followed by a 5 ps to 10 ps decay time—much faster than we observed. Therefore, though our data is consequently controversial it is also quite interesting as well.

Another notable aspect of our plasma data is the sharp peak that occurs right around zero delay between the pump and probe. This is due to some non-linear interaction between the pump and probe, probably four-wave mixing. Four-wave mixing is a non-linear phenomenon in which three waves interact inside a medium in such a way that a fourth wave is generated. Thus it is quite possible that at the exact moment which the two pulses coincide in space and time that four-wave mixing takes place, giving us a sharp peak at that time. This peak is not of interest to us in this experiment, however, it does have the unfortunate effect of partially obscuring the plasma rise time.

Our attempt to characterize self-focusing however was not quite as successful. We used a fused silica right angle prism in our preliminary attempt to record data. After realigning our collection optics to accommodate the prism in our apparatus it was only a matter of finding signal from the reflected probe to take data. However, we were unsuccessful in finding a good enough signal to perform data runs on. Exactly why this is, we are unsure. There are several possibilities. First, we were suspicious that it may be a problem of the right angle prism geometry. To test this we replaced the fused silica prism with a fused silica window, for purposes of working with a more familiar geometrical object. If suddenly get a good signal this way, then the problem would indeed be associated with the geometry of the prism. If not then the media itself may be the culprit. As it turned out, we still could not find signal. We now assume that there may

indeed be something about fused silica that is hindering our data collection.

Physically, fused silica is a type of glass and is amorphous. In other words, it has a random orientation. Prior to using the fused silica prism we had used sapphire, which has a fixed crystalline structure. Therefore the ionization rate in all of sapphire can be said to be more or less the same. However, in an amorphous material the gap between the valence and conduction bands is not as well defined. Thus the ionization rate in an amorphous material may well not be constant; it is unclear what effect this would have on our experiment. Another possibility is that there is indeed plasma growth and decay, but it is happening too quickly for us to see. This would seem unlikely. The lack of signal may indicate that some unknown physical process is suppressing or inhibiting plasma formation in fused silica. This is unconfirmed however, so this is little more than a possibility.

V. Future Work

Obviously there is still a lot of work to be done in characterizing self-focusing and attempting to relate it to plasma growth and decay. There are still a quite a few options for us at this point. One option is to switch to a blue probe. Replacing the half-wave plate on the probe's path with a frequency doubling crystal would do this for us. As a result we would have a 400 nm probe and an 800 nm pump. What this would do for us is get rid of some unwanted non-linear effects, particularly the four-wave mixing. This would hopefully give us a chance at collecting nicer, cleaner data. In addition, the blue probe would be slightly visible so as to make realignment much easier. However, we believe that the blue probe may have a longer pulse than that of the pump, preventing proper time resolution of the plasma dynamics. Also, it would become difficult to align the blue probe

and red pump temporally. Since the two would be at different wavelengths, we would not be able to do this by merely looking for fringes.

Another thing we can do is test whether or not the amorphous nature of fused silica is a problem. Since quartz is the crystalline form of fused silica, we can do this by switching to quartz and comparing the two, If all else fails, we can try using an even more sensitive diode. Perhaps the signal is there, just too weak for us to find using our current diode. In any case it is only a matter of labor in order to be on our way to characterizing self-focusing. If successful we can proceed to determine its relation to plasma formation, and thus be that much closer to accurately modeling CG.