Noncollinear Phase Matching in Optical Parametric Chirped-Pulse Amplification

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Summary

Optical parametric chirped pulse amplication (OPCPA) is a method used to generate high-powered laser pulses. In this process, energy from a "pump" pulse is used to amplify a signal "seed" pulse. A computer program based on an analytical model was written and used to demonstrate the influence of noncollinearity, a condition in which the pump and seed are not parallel, and crystal tilt on the signal seed pulse. The investigations showed that maximum signal amplification is achieved when the crystal is slightly detuned.

1. Introduction

Energy is required to do work, and therefore is essential to the sustenance of life. With the energy supplies of the last century rapidly draining away, scientists seek new sources of energy to power the advanced technologies that make modern human civilization possible. One possible avenue is fusion power. Scientists at the University of Rochester Laboratory for Laser Energetics (LLE) hope to make fusion power a viable energy source. The fusion of nuclei can generate a massive amount of energy. Certain conditions, however, must be met if fusion is to occur. High temperatures give the nuclei energy to overcome the strong nuclear forces that exist between them, and high densities increase the probability that the nuclei will collide. At LLE, these conditions are met by inertial confinement fusion (ICF). A fuel pellet, approximately 1 mm in diameter, holding deuterium and tritium isotopes, is uniformly irradiated by 60 amplified laser beams[1]. The lasers cause the outer shell of the pellet to vaporize and ablate, or become explosively torn free at a tremendous force. According to Newton's Third Law, an equal and opposite force is directed into the pellet, creating the high temperatures and densities needed for fusion to occur. When the nuclei of the tritium and deuterium isotopes fuse, energy is given off as alpha particles and neutrons. Some of this energy is deposited in unreacted fuel, allowing the fusion reaction to continue and more energy to be generated as a result. This phenomenon is called ignition. Researchers hope to maximize the energy yield from implosions.

Increasing the power of the laser can help maximize the energy yielded in the fusion reaction. Scientists at LLE are designing a new petawatt laser system, which will allow them to amplify a low-energy signal seed pulse, while maximizing its bandwidth. Optical parametric chirped pulse amplification (OPCPA) is a method which can produce the high-power laser pulses needed, and is being considered for the next generation of laser systems at LLE.

Numerous variables influence the effectiveness of signal seed amplification in the OPCPA process. Although a collinear interaction between the pump and the signal seed has been analyzed in great detail, scientists have discovered that the amplified signal seed pulse can be extracted more easily from the process if the seed is not collinear with the pump. A computer program based on an analytical model is written and used here to calculate the effect of noncollinearity on the intensity and spectrum of the amplified signal seed pulse. This model illucidates that the crystal must be tilted in order for maximum amplification to occur. By calculating the total intensity integrated over time for a range of crystal tilts, I was able to calculate the crystal tilt that will maximize the total energy of the signal pulse. I was able to prove that this angle was slightly less than the angle needed to achieve the degenerate phase-matching condition. The model also simulates the parametric fluorescence that is generated simultaneously as the pump passes through the crystal.

2. OPCPA generates a short, high-intensity laser pulse

OPCPA can begin by stretching a Gaussian-shaped signal seed pulse in time, as shown in Fig. 1. Diffraction gratings stretch the pulse by bending different frequencies at different angles. As a result the individual frequencies become separated creating a chirped signal seed pulse. According to the conservation of energy, the total energy of the stretched pulse remains unchanged. Since the energy is stretched over a longer period in time, the pulse power at a specific time is reduced. The stretched signal seed and a pump pulse are then sent into the optical parametric amplifier (OPA). The OPA used is a lithium triborate (LBO) crystal. This crystal has two indices of refraction, a property known as birefrigence. Because it has different

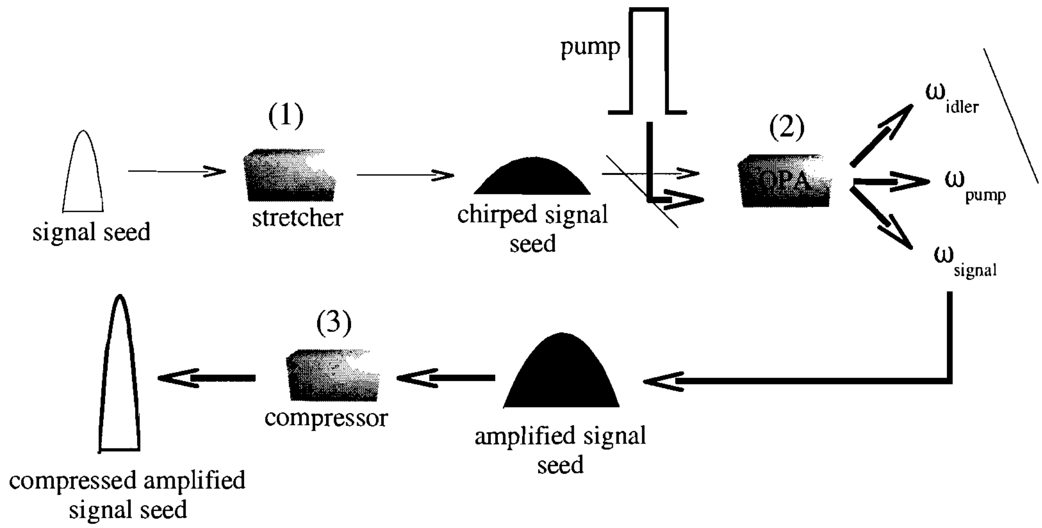


Figure 1. A graphical illustration of optical parametric chirped pulse amplification (OPCPA). (1) A Gaussian-shaped signal seed pulse is stretched into a chirped pulse. (2) The stretched seed and a pump are sent into an optical parametric amplifier (OPA). The OPA allow the signal and pump to interact, creating an idler pulse and allowing for the amplification of the signal. The OPA used consisted of lithium triborate (LBO). (3) The amplified signal is compressed into a short, high-intensity pulse, whereas the pump and idler are blocked from further use.

indices of refraction, light will travel at different speeds as it passes through the crystal from different directions.

When two pulses pass through the crystal, energy from the pulses excite the molecules within the crystal. Because of the nonlinear properties of the crystal molecules, the energy is reradiated as idler pulses. Amplification of the signal pulse is only possible when there exists an idler. My simulations assumed a small signal regime. In this type of interaction, the relative energy of the signal to the pump is low enough that any change in pump energy is considered negligible. Therefore, a small signal regime assumes that the energy of the pump remains undepleted, even though energy is being lost to the seed. OPA follows Equation 1 for the small signal regime. In reality, the changing pump energy affects how much energy is transferred to the signal seed.

$$E_{signal}(z) = \left[E_{signal}(0)\left(\cosh gz - \frac{i\Delta k}{2g}\sinh gz\right) + \frac{\kappa_{signal}}{g} E_{idler}{}^*(0)\sinh gz\right] e^{i\Delta kz/2}$$

$$\kappa_{signal} = \frac{8\pi\, i\, \omega_{signal}{}^2\, d\, E_{pump}}{k_{signal}\, c^2}$$

$$g = [\kappa_{signal}\kappa_{idler}{}^* - (\Delta k/2)^2]^{1/2}$$

$$E_{idler}(z) = \left[E_{idler}(0)\left(\cosh gz - \frac{i\Delta k}{2g}\sinh gz\right) + \frac{\kappa_{idler}}{g} E_{signal}{}^*(0)\sinh gz\right] e^{i\Delta kz/2}$$

$$\kappa_{idler} = \frac{8\pi\, i\, \omega_{idler}{}^2\, d\, E_{pump}}{k_{idler}\, c^2}$$

Equation 1. The undepleted pump approximation was used to calculate parametric intensities. **E** represents the electric field. The intensity of a pulse can be determined from $|\mathbf{E}|^2$. Because we assumed a small signal regime, the energy of the pump remained constant. **z** represents the distance the pulse passes through the crystal. Because we want to calculate the intensity at the end of the crystal, **z** represents the length of the crystal, or 25 mm. Notice that when $\mathbf{\Delta k}$ equals zero, the intensity of the signal and idler are maximized.

In a related situation, the reradiated energy is used to generate fluorescence at a wide range of wavelengths and at numerous angles, depending on the phase-matching conditions within the crystal. Fluorescence results from interactions with photons, acting as signal pusles.

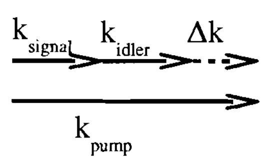
As a result of this energy exchange process, a third pulse is generated called the idler pulse. In a type I interaction, both the signal and the idler are ordinary waves, and the pump is an extraordinary wave. The electric field of an ordinary wave is perpendicular to the crystal's optic axis; therefore, the indices of refraction of the two ordinary waves, the signal and the idler, are not dependent on the angle at which they propagate through the crystal. The electric field of an extraordinary wave has a component along the optic axis; therefore, the index of refraction of an extraordinary wave, such as the pump, can vary depending on the angle of propagation of the pump in relation to the optic axis.

After the three pulses pass through the crystal, the amplified signal seed pulse is compressed into a short, high-intensity pulse. Compressors, like stretchers, involve diffraction gratings; however, the diffraction gratings in a compressor bend the frequencies of a chirped pulse so that the frequencies become mixed once again. While the pump and idler are blocked from further use, the compressed amplified signal is sent toward the target. The fluorescence that is generated can affect the spectrum of the amplified signal seed pulse, thereby decreasing the pulse contrast ratio and exacerbating the prepulses in the compressed signal.

3. Energy transfer differs in collinear and noncollinear interactions

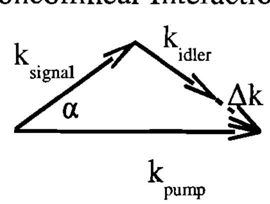
In a collinear interaction, the signal seed and the pump are sent into the crystal at the same angle; as a result, the idler pulse generated is parallel to both the signal and pump. Because the signal and the idler have the same direction of propagation and the same polarization, it is difficult to separate the signal seed pulse, which will later be compressed, from the unwanted idler. By sending the signal seed at an angle to the pump, this issue is eliminated, because in a noncollinear interaction the signal and idler propagate at different angles through the crystal. In a noncollinear interaction, Δk can be derived based on the geometry of a triangle.

Collinear Interaction



$$\Delta k = k_{pump} - k_{signal} - k_{idler}$$

Noncollinear Interaction



(Eq. 2) $$\Delta k = \sqrt{k_{signal}^2 + k_{pump}^2 - 2k_{signal}k_{pump}\cos(\alpha)} - k_{idler}$$

Figure 2. In a collinear interaction, the k-vectors of the signal, idler, and pump are parallel to one another. In a noncollinear interaction, the k vectors form a triangle. α represents the angle of noncollinearity between the signal and the pump. When the endpoint of k_{idler} and the endpoint of k_{pump} coincide, so that Δk equals 0, energy transfer is maximized. The equation for Δk in a noncollinear interaction was derived from the law of cosines.

An expression derived from the law of cosines (Eq. 2) shows that Δk depends on the angle between the signal and the pump in a noncollinear interaction. Because the Δk expression differs between collinear and noncollinear interactions, energy transfer must differ between them as well.

4. How the spectrum and intensity of a pulse can be changed

4a. Wavelength

Because the signal seed is a chirped pulse, it contains a range of wavelengths that are uniquely spaced out in time. As the wavelength of the signal changes, the wavelength of the generated idler must vary, and the k-vector mismatch, or Δk, must change as well. Consequently, for the range of wavelengths in a chirped signal pulse, there must exist a corresponding range of values for Δk. The relationship between Δk and wavelength of the signal pulse is approximately parabolic, and the minimum Δk value occurs at or near the central wavelength of the signal seed pulse. The spread of Δk values and the wavelength(s) for which Δk equals zero will determine the spectrum of the amplified signal seed pulse. The signal used in these investigation was a 200 fs Gaussian seed pulse, stretched in time to 1 ns, with a central wavelength of 1054 nm.

4b. Angle of Noncollinearity

When the angle between the pump and the signal increases, the Δk associated with all wavelengths will increase (see Eq. 2). As seen in Fig. 3, the entire plot of Δk, as a function of wavelength, will be pulled downward and the spectrum of the signal pulse will be changed. When the Δk plot is tangent to the x-axis, there exists one signal wavelength for which Δk equals zero (see Figure 3a). When this condition exists, the signal is said to be degenerate. This configuration correlates to a single peak intensity in the Gaussian-shaped signal pulse spectrum. When the Δk plot is pulled below the x-axis, by increasing the angle of noncollinearity, there exist two wavelengths for which Δk equals zero, corresponding to two peak intensities (see Figure 3b). As the angle of noncollinearity continues to increase, the two intensity peaks will be pulled farther apart[2].

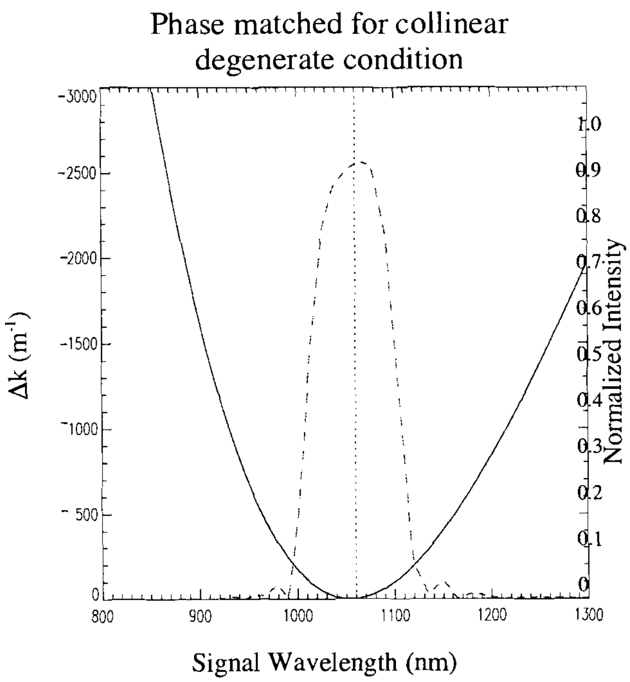
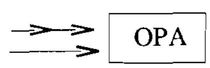


Figure 3a.



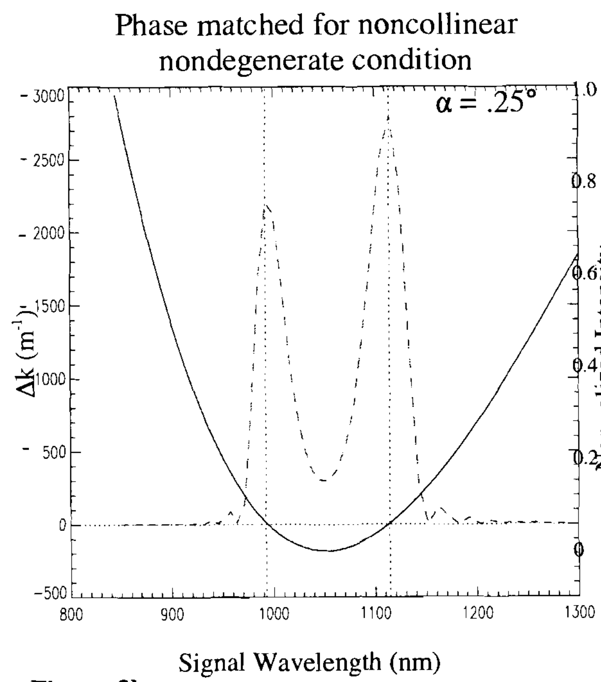
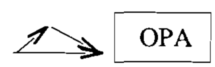


Figure 3b.



In these diagrams, the solid curve illustrates Δk and the dashed line represents the normalized intensity. When the angle between the signal and the pump (α) is increased from the collinear (α = 0) degenerate (wavelength of signal = 1054 nm) condition to an angle of noncollinearity of .25°, while keeping the crystal tilt constant, the entire plot of Δk is pulled downward, such that there now exist two locations where Δk equals zero, or two intensity peaks.

Phase matched for noncollinear slightly-nondegenerate condition by tilting crystal

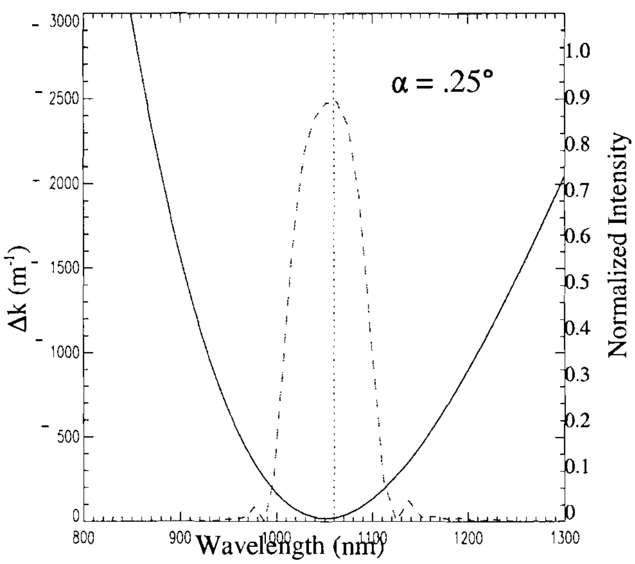


Figure 3c. When the crystal tilt is increased slightly, while maintaining the angle of noncollinearity constant (compare to Fig. 3b), the Δk plot is pulled upward, forcing the two intensity peaks back together. Phase-matching to achieve the nearly-degenerate condition can be achieved by tilting the crystal (~.215 radians). The noncollinear phase-matching angle was calculated by finding a crystal tilt value which brings about a Δk of zero for a specific angle of noncollinearity and a given central wavelength.

4c. Crystal tilt

The spectrum of the output signal pulse can also be changed by tilting the crystal. Increasing the crystal tilt increases the angle between the pump and the optic axis. Because the pump pulse is an extraordinary wave, its index of refraction will change as the crystal tilt is altered. In an LBO crystal, as the crystal tilt increases, the pump index of refraction decreases. Since the index of refraction is proportional to k, when the pump index of refraction decreases, k_{pump} decreases as well. According to Eq. 2, when k_{pump} decreases, all values of Δk decrease; therefore, increasing the crystal tilt will pull the entire plot of Δk upwards. The spectrum of the signal pulse is important to consider when choosing the tilt of the crystal, because it influences the compressibility of the amplified signal seed pulse.

Another important characteristic of the pulse is its total intensity. It is desired to maximize the total intensity of the signal seed pulse. The total energy corresponds to the sum of all the energies attained from each wavelength in the chirped signal pulse. The total energy corresponds to the total area beneath each of the intensity curves seen in Figure 3, and can by calculated by analytically integrating the intensity over a range of wavelengths. By calculating the total intensity integrated over wavelength for a range of crystal tilts, one can calculate the crystal tilt that will maximize the total energy of the signal pulse. I discovered that the angle needed to achieve maximum total intensity is slightly less than the angle needed to achieve the degenerate phase-matching condition (illustrated by dotted lines in Fig. 4). As the crystal tilt decreases, the Δk plot is pulled downward and the two intensity peaks of maximum amplification in the pulse spectrum are pulled apart. This is important because it allows scientists to calculate the angle needed to maximize signal amplification.

Since maximum total intensity is achieved for a slightly nondegenerate phase-matching angle, there exist two wavelengths for which maximum amplification occurs. This development gives rise to two intensity peaks in the pulse spectrum. To some extent, the separation of the two intensity peaks results in a relatively wide bandwidth but a low contrast ratio in the compressed pulse.

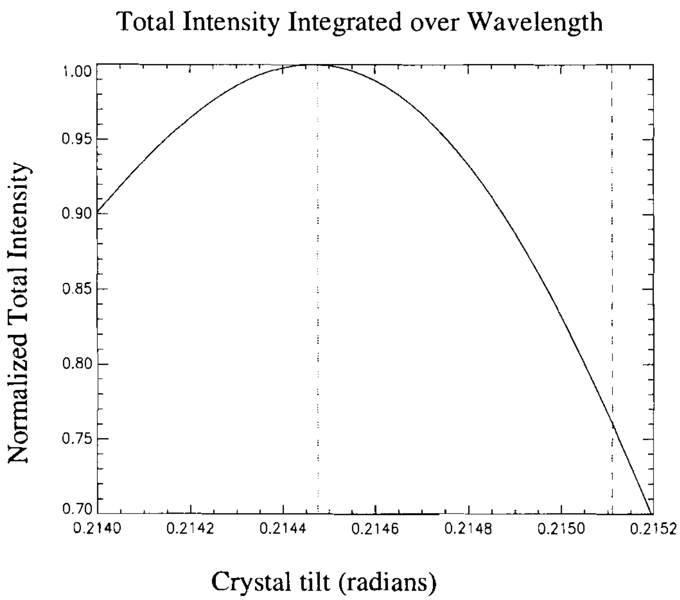


Figure 4. This graph shows the relationship of total intensity integrated over wavelength as a function of crystal tilt. It is clear that the angle needed to achieve maximum total intensity (left dotted line) is slightly less than the angle needed to achieve the degenerate phase-matching condition (right dotted line). When the crystal tilt decreases the two intensity peaks of maximum amplification are pulled apart; consequently, when the crystal tilt is slightly detuned from the degenerate phase-matching angle, the two intensity peaks separate, and maximum total intensity is achieved because the spectral bandwidth is enhanced.

5. Fluorescence

When the pump passes through the crystal, signal and idler pulses are generated spontaneously at a wide range of wavelengths and at numerous angles. The intensity distribution of parametric fluorescence depends on the phase-matching conditions, analyzed before, within the crystal. Fluorescence development is similar to that involving the amplification of the seed by the pump. A notable difference between the two processes is that while the signal seed has a limited bandwidth and a single chosen angle of noncollinearity, fluorescence is generated at all wavelengths and at numerous angles of noncollinearity. Many aspects of the fluorescence intensity distribution, such as the number of fluorescence intensity peaks, are determined by the tilt of the crystal[3].

Each point (Fig. 5) corresponds to a value of maximum intensity; therefore, the total intensity for a specific angle of noncollinearity can be calculated by summing up all the intensities across a horizontal region. When the slope approaches zero, more intensities are being summed together; consequently, maximum total intensity occurs where horizontal tangents take place. With regards to the wavelengths left of the dotted line, for some values of crystal tilt (e.g. 13.5°), there exist two locations where the slope approaches zero, or two total intensity peaks (Fig. 5b). Whereas for other values of crystal tilt (e.g. 11.5°) there exists only one location where the slope approaches zero, or one total intensity peak(Fig. 5c).

Many patterns can be drawn from the plot in Figure 5a. For the wavelengths used for the signal seed pulse, there are specific wavelengths and angles of noncollinearity for which Δk equals zero and the intensity is peaked. Intensity peaks for a specific arrangement of wavelength and angle of noncollinearity can be achieved by changing the tilt of the crystal. The total intensity for a specific angle of noncollinearity can be calculated by summing up all the

Curves for which Δk =0

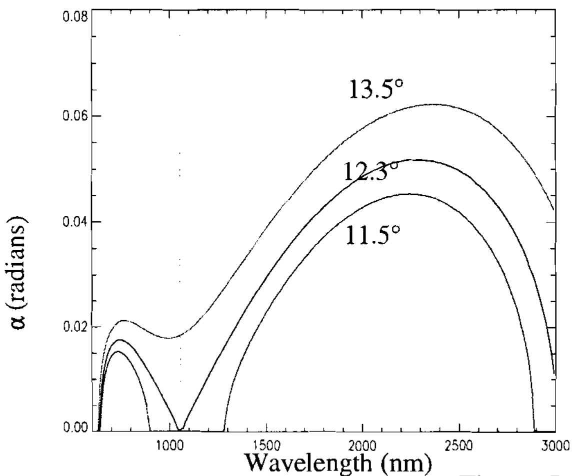
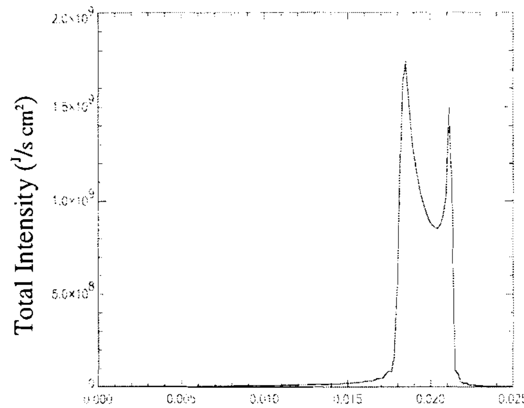


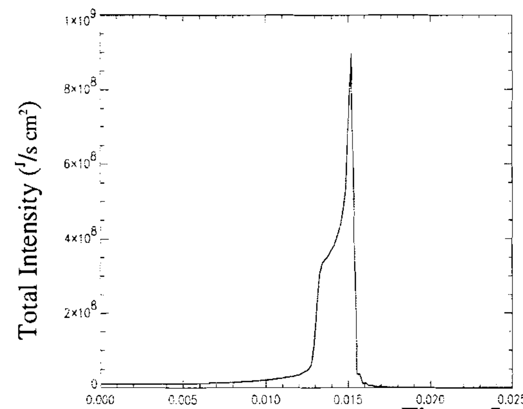
Figure 5a.

Total Intensity (Crystal tilt = 13.5°)



α (radians) **Figure 5b.**

Total Intensity (Crystal tilt = 11.5°)



α (radians) **Figure 5c.**

Figure 5. These are curves for which Δk equals zero or the intensity is maximized for various values of crystal tilt (Fig. 5a). Each point in Fig. 5a corresponds to a value of maximum intensity. The central plot represents the Δk curves for the collinear degenerate phase-matching angle (12.3°). The other two plots depict arbitrary crystal tilts (11.5° and 13.5°). Each point in Fig. 5a holds a value of maximum intensity. If the intensities of each crystal tilt plot were calculated and summed as a function of the angle of noncollinearity (α), the graphs on the right would result. Notice that for some values of crystal tilt, there exists two peaks of maximum total intensity (Fig. 5b); whereas, other angles only have one (Fig. 5c)

intensities along a specific angle of noncollinearity, or α. Maximum total intensities occur at turning points, in the curves of Fig. 5a, where more intensities are being summed together. The number of fluorescence intensity peaks, as well as the angle of noncollinearity at which they occur, are determined by the tilt of the crystal (Figure 5b and 5c).

Fluorescence is generated in all directions from the pump pulse. Since the signal and idler are ordinary waves, Δk depends on the angle of noncollinearity. Assuming that the fluorescence patterns seen before apply to all directions within the crystal, the fluorescence image as captured by a camera at the end of the crystal would appear to be a series of concentric circles (Fig. 6). The radius of each circle corresponds to the angle of noncollinearity, and the number of maximum total intensity rings and the angle(s) of noncollinearity at which they occur, are determined by the tilt of the crystal. Fig. 6 illustrate the images of the the signal and idler if taken by a camera at the end of the crystal. The two white rings, best seen in the signal represent the two intensity peaks seen before (Fig. 5b).

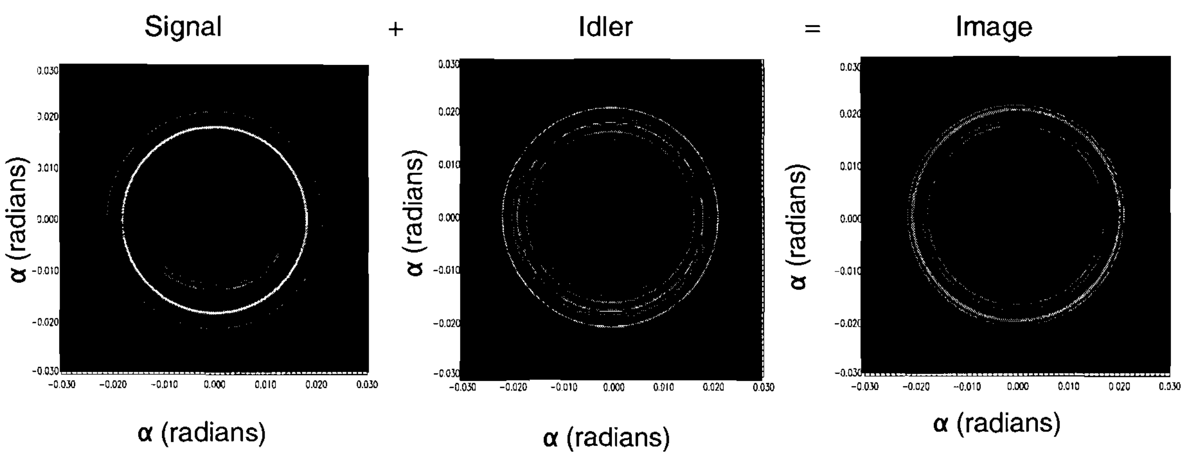


Figure 6. These are the images of the signal and idler if taken by a camera at the end of the crystal. Notice the two rings of maximum total intensity which correspond to the two total intensity peaks seen before for this particular crystal tilt (13.5°). The actual image seen at the end of the crystal is a combination of the signal and idler and has characteristics of both.

Fluorescence plays a significant role in the formation of an amplified signal seed pulse. When the angle of noncollinearity between the signal and the pump of the generated fluorescence is the same as the chosen angle between the signal seed and the pump, energy from the fluorescence amplifies the energy of the signal seed. The amplified signal pulse is raised upon a pedestal of energy obtained from the fluorescence. The spectrum of the amplified signal pulse is such that the contrast ratio of the compressed amplified signal is decreased and any prepulses are exacerbated. Scientists hope to manipulate the tilt of the crystal and the angle of noncollinearity, such that the contrast ratio is maximized. When the laser beam hits the target, the prepulses preheat the fuel pellet and change the initial conditions for when the actual pulse hits the target. If the prepulses are too high and the contrast ratio is too low, the effectiveness of the hit can be compromised. It is hoped to get experimental results to confirm my predictions in Fig. 6 as this will help improve our understanding of fluorescence.

6. Future Work

Future work in this field entails writing a numerical model to show how fluorescence affects the amplified signal seed pulse. Studies can be performed to investigate the effect of fluorescence on signal pulse bandwidth, and to find the conditions needed to minimize the pre-pulse level in the compressed OPCPA pulse. Increased accuracy can be achieved by not assuming a small signal regime. Since the pump energy decreases as it transfers energy to the signal and idler, the amount of energy transferred will also decline. It would be interesting to see how these patterns might change if the energy of the pump was limited. Specifically, it would be interesting to see how the optimum tilt predicted in Section 4c will compare to the optimum tilt in a large signal regime.

7. Conclusion

My research concentrates on the Δk term, a heretofore unappreciated but essential factor, involved in laser amplification, which will in turn allow us to model and better understand and predict the conditions needed for fusion to occur. Likewise, my research concerning OPCPA will give insight to the University of Rochester Laboratory for Laser Energetics as it plans on building a more powerful and efficient laser system. I calculated the influence of noncollinearity and crystal tilt on the spectrum and intensity of a signal seed pulse. The program indicated how these factors influenced Δk. These investigations showed that maximum signal was achieved when the crystal was slightly detuned. The crystal tilt needed to achieve optimum amplication was calculated for the small signal regime. The program also predicted the parametric fluorescence patterns that would be generated. By comparing my results with experiments to be carried out on fluorescence, my research will help to improve our understanding of OPCPA. These findings allow us to further investigate the conditions necessary for creating a short pulse with high energy and low prepulses, necessary for laser fusion to occur.

Acknowledgments

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