Multiple-Tripler Broad-Bandwidth Frequency Conversion for Laser Fusion

Phoebe Rounds

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Irondequoit High School
Rochester, NY

Advisor: Dr. R. S. Craxton,
Senior Scientist

Laboratory for Laser Energetics
University of Rochester
Rochester, NY

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Summary:

Many researchers worldwide are using high-power lasers to obtain the conditions necessary for nuclear fusion. Such laser systems include crystals, known as doublers and triplers, which convert infrared beams to the higher-frequency ultraviolet beams necessary for fusion. I developed a systematic method for generating new designs which use additional crystals to significantly increase the bandwidth and thus the smoothness of the laser beams.

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Multiple-Tripler Broad-Bandwidth Frequency Conversion for Laser Fusion

1. Background

Many researchers worldwide are investigating laser-induced inertial confinement fusion (ICF) as a possible energy source [1,2]. Laser-fusion researchers garner from intensely focused laser beams enough power to induce deuterium and tritium fusion in small, spherical pellets with plastic shells and deuterium and tritium cores. The high-intensity power directed on a pellet ionizes the atoms of the pellet's shell into a plasma; this plasma, as it is heated, separates from the pellet and ablates outward. Complementing the force of the plasma accelerating outward, in accordance with Newton's Third Law, is an opposite force which drives the pellet inward upon itself, so much so that its radius is decreased by as many as fifty times [1]. The dramatic implosion of the pellet generates the high-density, high-temperature environment necessary for the fusion of the pellet's deuterium and tritium and the accompanying release of an energetic neutron. Researchers hope that eventually laser-induced ICF will reach an ignition state, a state at which more energy is released by the fusion process than that used to produce the high-temperature, high-density conditions necessary for ICF.

One site of ICF research is the Laboratory for Laser Energetics (LLE) at the University of Rochester. The OMEGA laser system at LLE employs 60 ultraviolet beams directed on a pellet from all sides [3]. While these 60 beams overlap as they hit the pellet, their incidence on the pellet remains somewhat nonuniform. Many researchers are working to minimize this nonuniformity and thus maximize the effectiveness of target implosions. My work involved amending one portion of the OMEGA laser system—the frequency conversion portion—to increase uniformity. My work is applicable to other laser systems in need of increased uniformity, among them the National Ignition Facility (NIF) laser, which is currently under construction in Livermore, California [2].

1.1. Frequency conversion

The neodymium-doped glass lasers used on OMEGA and included in the NIF design emit beams in the infrared range. Infrared beams, however, are ineffective in ICF because only a small fraction of their energy is actually absorbed by fuel pellets and, furthermore, much of the absorbed energy is diverted to "suprathermal" electrons which move through the plasma and heat the fuel before it is compressed [1, 2]. Thus, all neodymium-doped glass ICF laser systems employ some method of frequency conversion to generate from IR frequencies the UV frequencies better suited for target implosions. The problem of infrared beams' ineffectiveness is conveniently solved on the OMEGA laser system with potassium dihydrogen phosphate (KDP) crystals, which, when correctly oriented to an incoming beam, triple its frequency. KDP crystals are appropriate for OMEGA's frequency conversion process because they convert relatively broad bandwidths of IR frequencies to the UV. Generation of the third harmonic frequency (see Fig. 1), which is used for the OMEGA system, involves at least two KDP crystals, a "doubler" and at least one "tripler." The doubler crystal splits the incoming laser beam into components polarized along each of the crystals' two axes, the ordinary

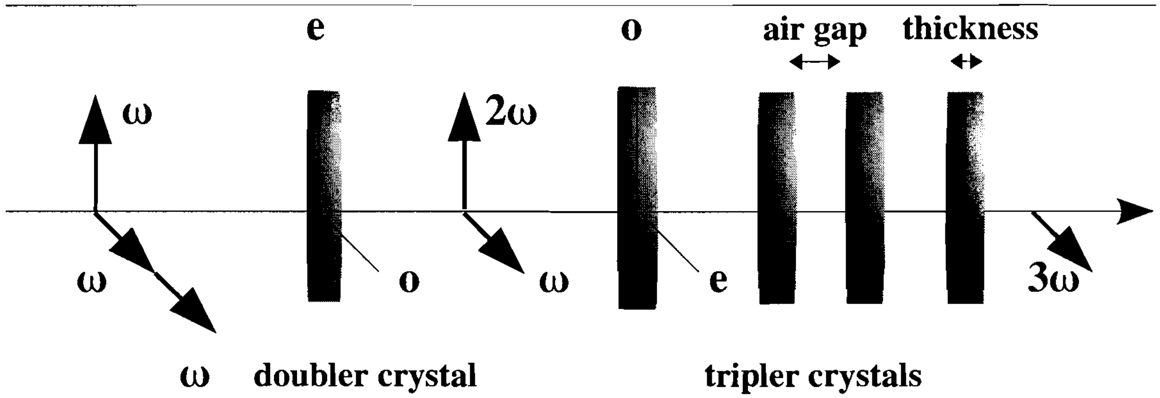


Figure 1. Third-harmonic frequency generation with doubler and tripler crystals. Three IR photons (ω) polarized in two directions enter the doubler, and two combine to form a green photon (2ω) with twice an IR photon's frequency. The green photon and the remaining IR photon enter the tripler and combine to form a UV photon (3ω) with three times an IR photon's frequency. The air gaps between the triplers, the thicknesses of the triplers, and the tilts of the triplers affect the efficiency of this conversion at various incoming frequencies.

(*o*) axis and the extraordinary (*e*) axis [4]. When the beam is polarized at 35° to the doubler's *o* axis, there are two *o*-polarized photons for each *e*-polarized photon at the original frequency. One *o*-polarized photon and the *e*-polarized photon combine into one green second-harmonic photon polarized in the *e* direction. The tripler crystal(s) combine the green photon and the remaining IR *o*-polarized photon into one *e*-polarized ultraviolet photon with three times the frequency and energy of one of the three IR photons [4].

1.2. Broadband frequency conversion on OMEGA

The original frequency-conversion-crystal design for OMEGA involved only one tripler crystal. The design converted efficiently (near 80%), but it only converted for a small range of wavelengths—about 5 Å—surrounding the wavelength to which it was tuned (see dotted line on Fig. 2). Wavelengths too far from the tuning wavelength of the tripler did not convert to the UV efficiently because they were not phase-matched: that is, the driving force for the UV wave did not move in phase with the UV wave [5]. Broader conversion bandwidth than afforded by the one tripler was required for Smoothing by Spectral Dispersion (SSD) [6], a technique used for the creation of smoothly focused laser beams. Eimerl et al. [7] suggested that a second tripler could increase the bandwidth of wavelengths efficiently converted, since two triplers could be tuned to wavelengths on either side of the central wavelengths and thus convert, together, a wider range of wavelengths than that converted by one tripler. Oskoui [5] wrote a program which calculated dual-tripler conversion and with his

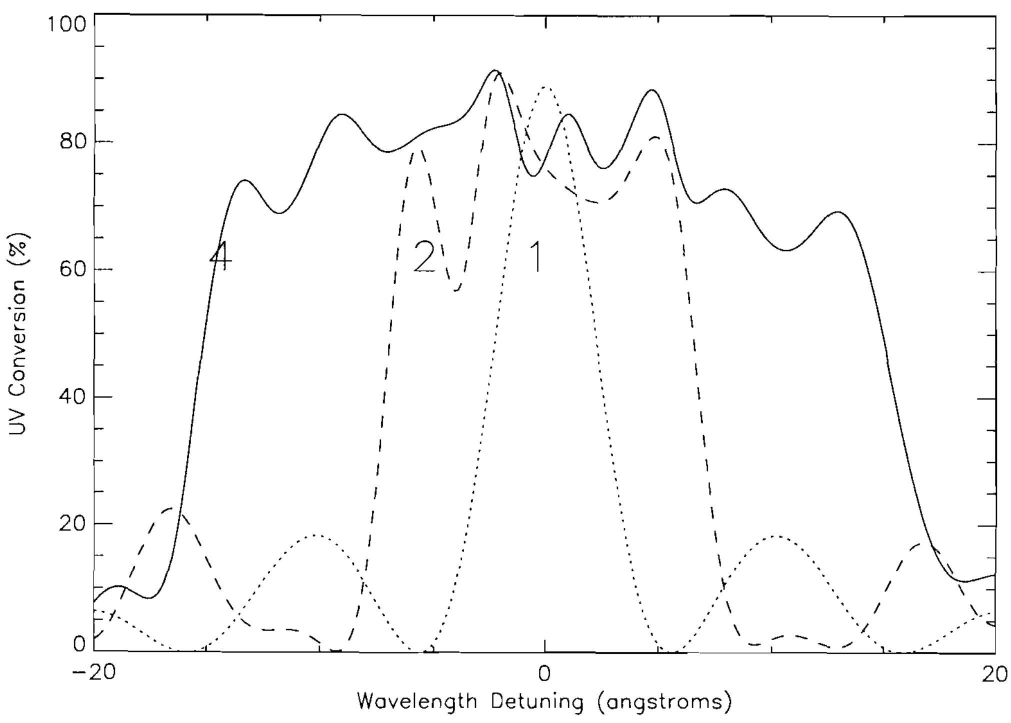


Figure 2. UV conversion as a function of IR laser wavelength at laser beam intensity of 1.5 GW/cm² for three frequency-conversion-tripler designs: OMEGA's original one-tripler design (dotted line), the two-tripler design as implemented on OMEGA (dashed line), and my four-tripler design (solid line). Bandwidth of the 1-tripler design is 5 Å; that of the 2-tripler design, 14 Å; that of the 4-tripler design, 30 Å.

program developed an optimized solution to the two-tripler problem. His design, subsequently implemented on OMEGA with slight modifications, converted about 14 Å of IR bandwidth with efficiency almost equivalent to that of the single tripler and sustained over a broad range of wavelengths (see dashed line on Fig. 2) [5]. Experimental results matched his program's conversion predictions very closely [8]. A similar broadband two-tripler design was developed for the NIF laser [9].

1.3. Project goal

Because broader bandwidth on OMEGA is still desired, it was wondered if additional triplers could broaden OMEGA's bandwidth yet again. Designs with more than two triplers had not been explored prior to this project. I modified Oskoui's code to accommodate multiple-tripler designs and then developed a systematic method for creating broadband designs for any number of triplers. This method involves the optimization of tripler thicknesses, tilts, and spacings. I used this method to generate designs for three, four, and five triplers, designs which significantly broaden the conversion bandwidth on OMEGA. Whereas the original one-tripler design and OMEGA's current two-tripler design convert 5 and 14 Å, respectively, my four-tripler design converts 30 Å with no loss in conversion efficiency (see solid line on Fig. 2).

2. Methodology

The program in the PV-Wave language which simulates multiple-tripler designs is based upon the frequency-conversion equations. These differential equations

$$\frac{dE_1}{dz} = -\tfrac{1}{2}\gamma_1 E_1 - iK_1 E_3 E_2^* \exp(-i\Delta k \,.\, z) \qquad (1)$$

$$\frac{dE_2}{dz} = -\tfrac{1}{2}\gamma_2 E_2 - iK_2 E_3 E_1^* \exp(-i\Delta k \,.\, z) \qquad (2)$$

$$\frac{dE_3}{dz} = -\tfrac{1}{2}\gamma_3 E_3 - iK_3 E_1 E_2 \exp(i\Delta k \,.\, z) \qquad (3)$$

Frequency-conversion equations.

track the growth of the electric fields ($E_1 - E_3$) of the three different frequencies as the waves travel in the z direction through the crystals [4, 10]. Each equation's main term (e.g., $-iK_3E_1E_2$) describes the growth of the corresponding electric field; each K term is the growth coefficient for the corresponding electric field. The presence of the electric fields or the complex conjugates of the electric fields (e.g. E_2^*) of other waves in each wave's equation demonstrates the interdependence of the three waves. The intensity of an electric field is proportional to the square of the amplitude of the electric field. The air gap between each tripler and the preceding tripler determines the initial direction of electric field growth in the complex plane. The phase term ($-i\Delta kz$) describes the relative phase of the three waves. The Δk term is determined from the angle detuning and wavelength detuning of a tripler. Δk is linearly proportional to both angle detuning and wavelength detuning, so tuning a crystal to a certain wavelength involves tilting it to a corresponding angle. The conversion factor is 166 μrad of tilt per 1.0 Å of IR wavelength. Each equation also includes an absorption term (γ), though this term is of little import in the approximately 1 cm-thick crystals I used. The program uses the

Halfstep-Wholestep approximation method (calculation of the slope at a point, calculation of a "halfstep" point between the original point and the intended second point, calculation of the slope at the halfstep point, then calculation of the second point) to trace the electric fields' growth through the crystals. Three categories of variables—crystals' tilts, thicknesses, and separations—are involved in the optimization process. Because many variables are involved with even a modest number of crystals (eleven variables for four triplers, for instance), it was necessary to experiment with many setups to arrive at the multiple-tripler designs.

3. Results

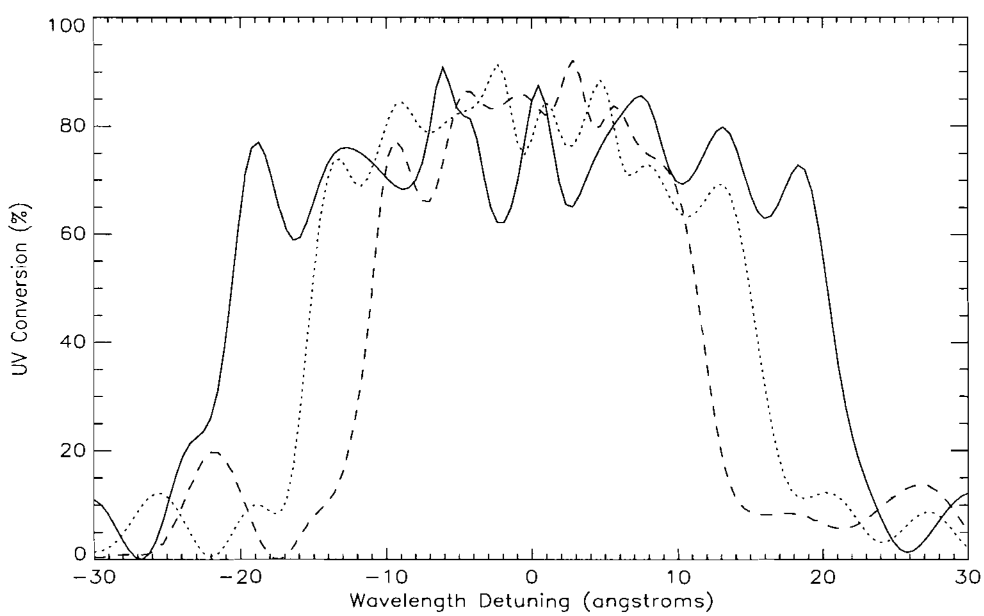


Figure 3. Baseline 3- (dashed line), 4- (dotted line), and 5-tripler (solid line) designs at an input intensity of 1.5 GW/cm². Bandwidth increases with each additional tripler.

I developed designs with broad bandwidth and consistently high conversion efficiency for three, four, and five triplers (see Fig. 3 and Table 1). The four-tripler design more than doubles the bandwidth of OMEGA's current two-tripler design, and the five-tripler design more than triples it. Both the three- and four-tripler designs have conversion efficiency across the bandwidth more consistent than that of the two-tripler design (see Fig. 2 and Fig. 3).

Table 1. Characteristics of baseline designs for 1-5 triplers at 1.5 GW/cm² input intensity. The 1-tripler design was originally used on OMEGA. The 2-tripler design is the current OMEGA design. Detuning refers to tilt in μrad from the angle at which a crystal is phase-matched. Separation refers to the air gap between a given tripler and the previous tripler. Mean conversion refers to the mean conversion above half-maximum. In all designs the doubler crystal has a thickness of 12.2 mm and a detuning of 0 μrad.

	1-tripler design	**2-tripler design**	**3-tripler design**	**4-tripler design**	**5-tripler design**
1st tripler thickness detuning	 12.2 mm 0 μrad	 12.2 mm 620 μrad	 10.0 mm 1350 μrad	 10.0 mm 2250 μrad	 10.0 mm 3000 μrad
2nd tripler thickness detuning separation	-----	 8.0 mm -380 μrad 1.00 cm	 8.0 mm 0 μrad 0.90 cm	 9.0 mm 900 μrad 0.75 cm	 9.0 mm 1450 μrad 0.9 cm
3rd tripler thickness detuning separation	-----	-------	 9.0 mm -1350 μrad 1.00 cm	 9.0 mm -450 μrad 0.90 cm	 9.0 mm 0 μrad 0.8 cm
4th tripler thickness detuning separation	-----	-------	-------	 9.0 mm -1800 μrad 0.90 cm	 9.0 mm -1250 μrad 0.8 cm
5th tripler thickness detuning separation	-----	-------	-------	-------	 9.0 mm -2650 μrad 0.9 cm
Bandwidth at half-maximum	4.9 Å	13.7 Å	22.6 Å	30.3 Å	41.4 Å
Mean conversion	67.8 %	71.3 %	77.0 %	75.3 %	72.3 %

To create an efficient design, it is necessary to understand how the multiple-tripler conversion process functions; this process will be explained in terms of the three-tripler design but applies to designs for any number of triplers.

3.1. Three-tripler design

Any multiple-tripler frequency-conversion curve arises from the individual frequency-conversion curves of the triplers involved. Each tripler in a given design has its own frequency-conversion pattern similar to that of the tripler in OMEGA's original one-tripler design (see the dotted lines on Fig. 4). Such a single-tripler curve is symmetrical and centered at the wavelength to which it is tuned. The curve's height and

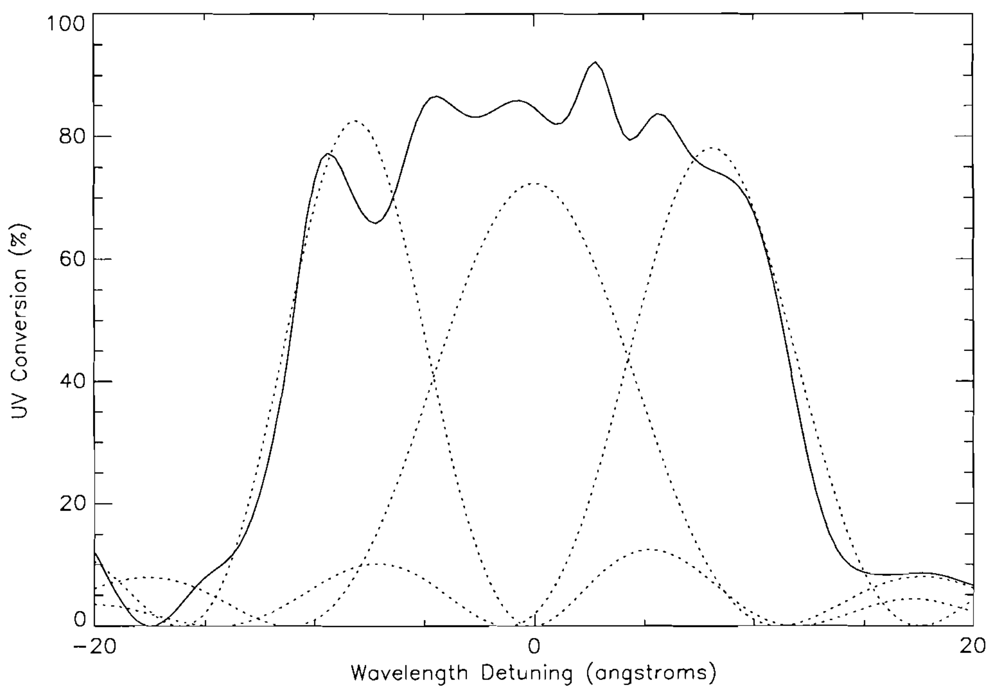


Figure 4. Three single-tripler curves (dotted lines) which combine constructively and destructively, as determined by phase, to create the baseline 3-tripler conversion curve (solid line; see Table 1). Input intensity is the usual 1.5 GW/cm².

length are determined for a given incoming-laser-beam intensity by the tripler's thickness: thicker triplers yield taller, narrower conversion curves. Each tripler in a design converts to varying degrees the wavelengths in the neighborhood of the wavelength to which it is tuned. Tripler parameters determine whether the conversion achieved by a given tripler at a specific wavelength is increased or decreased by the next triplers in a design. A tripler-by-tripler plot such as Figure 5 demonstrates that each tripler is primarily responsible only for the conversion of the wavelengths near that to which it is tuned. However, such a plot demonstrates that later triplers can significantly influence conversion at wavelengths nearer to the tuning wavelengths of earlier triplers.

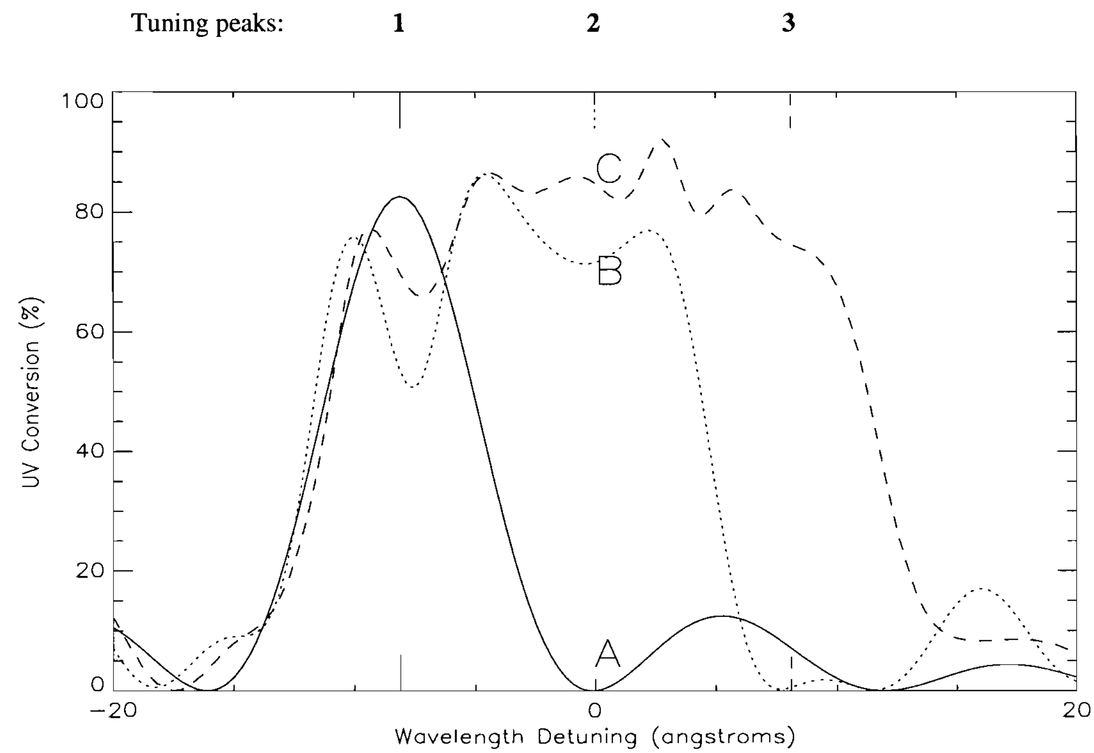


Figure 5. Tripler-by-tripler buildup of baseline 3-tripler curve. The solid line represents conversion after the beam has traveled through the 1st tripler; the dotted line, after it has traveled through the 2nd tripler; and the dashed line, after it has traveled through the 3rd tripler. Small notches represent tuning peak locations for the 1st, 2nd, and 3rd triplers. Electric field growth from point A to point C is shown in Fig. 6.

Figure 5 reveals that the second tripler is tuned almost exactly to the zero of the first tripler's curve and that the third tripler is tuned near the zero of the combined curve of the first and second triplers. The technique of tuning a tripler to the zero of the previous combined conversion curve is often successful. The final conversion at this zero wavelength is attained solely by the additional triplers. It is important to note that the optimum tuning for additional triplers is not necessarily exactly at the zeroes of previous curves. Because of the complicated phase interactions of the triplers at all wavelengths, the tuning which provides optimum conversion at a certain wavelength may not serve well wavelengths on one or the other side of this wavelength.

A plot of the UV electric field in the complex plane provides an enlightening view of conversion curve generation (see Fig. 6). Figure 6 shows the growth through three tripler crystals of the UV electric field generated from the IR

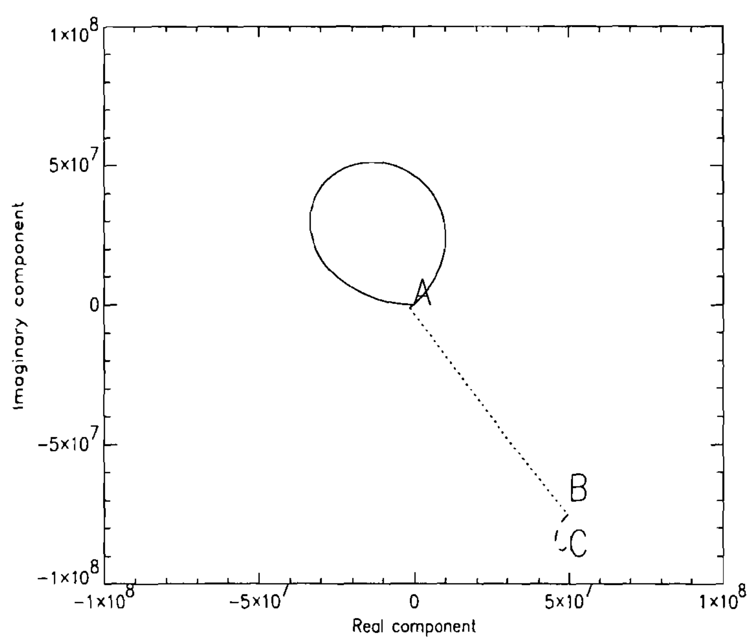


Figure 6. Growth of the UV electric field (plotted in the complex plane) generated from the central IR wavelength as waves travel through the baseline three-tripler design at an input intensity of 1.5 GW/cm². The solid line represents the path through the 1st tripler (to A); the dotted line, the path through the 2nd tripler (A to B), and the dashed line, the path through the 3rd tripler (B to C). At this wavelength most growth occurs in the 2nd tripler, which is tuned to this wavelength, a wavelength very near a zero in the 1st tripler's conversion curve.

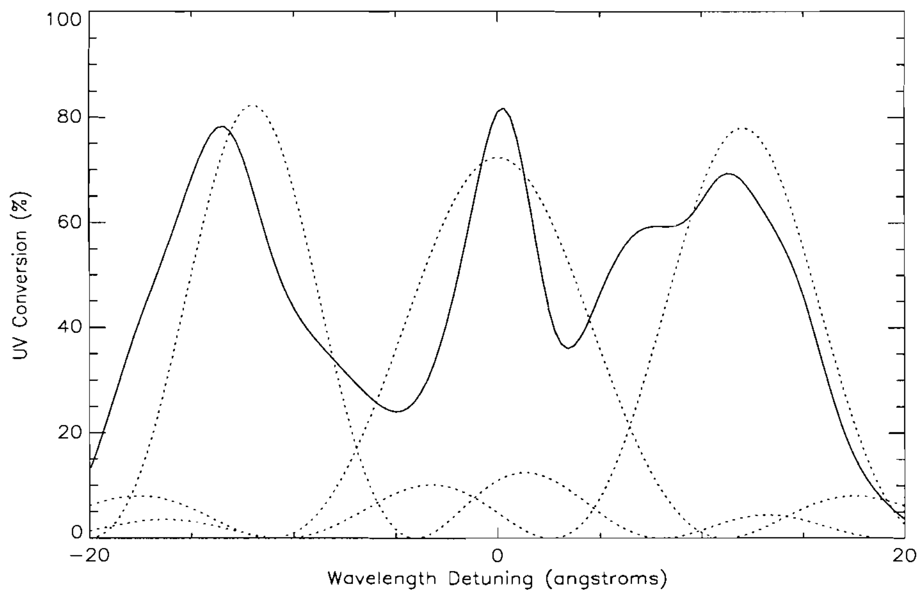
central wavelength. The electric field's curve as the waves travel through the first tripler returns nearly to zero (point A). Because the second tripler is tuned to the selected wavelength, its waves are in phase and thus the UV electric field grows in a straight line (see A to B on Fig. 5 and Fig. 6). It can be seen that the third tripler influences conversion at this wavelength little, since its tuning wavelength is far from the wavelength in question (see B to C on Fig. 5 and Fig. 6).

The air gap between any two triplers in a multiple-tripler design determines the relative phase of the waves entering the second of the two triplers and must be adjusted so that conversion increases at as many wavelengths as possible with the addition of the second tripler.

3.2. Tripler detuning

Optimum detunings of the triplers are essential to the success of a multiple-tripler design. Triplers tuned too far from one another (see Fig. 7) do not achieve high enough conversion at intermediate wavelengths to create an acceptable conversion curve. If triplers are tuned too closely to one another, the resulting conversion curve is also poor, in this case because there is so much interference that adjusting the tripler spacings cannot satisfactorily minimize the pronounced modulations (see Fig. 8).

Figure 7. As Fig. 4 but with 3 triplers widely detuned (detuning of the 1st tripler is 2000 μrad; that of the 2nd tripler is 0 μrad ; and that of the 3rd tripler is -2000 μrad). The separation between the 2nd and 3rd triplers has been adjusted to 2.0 cm to optimize conversion with these detunings. The conversion is low in regions between triplers.



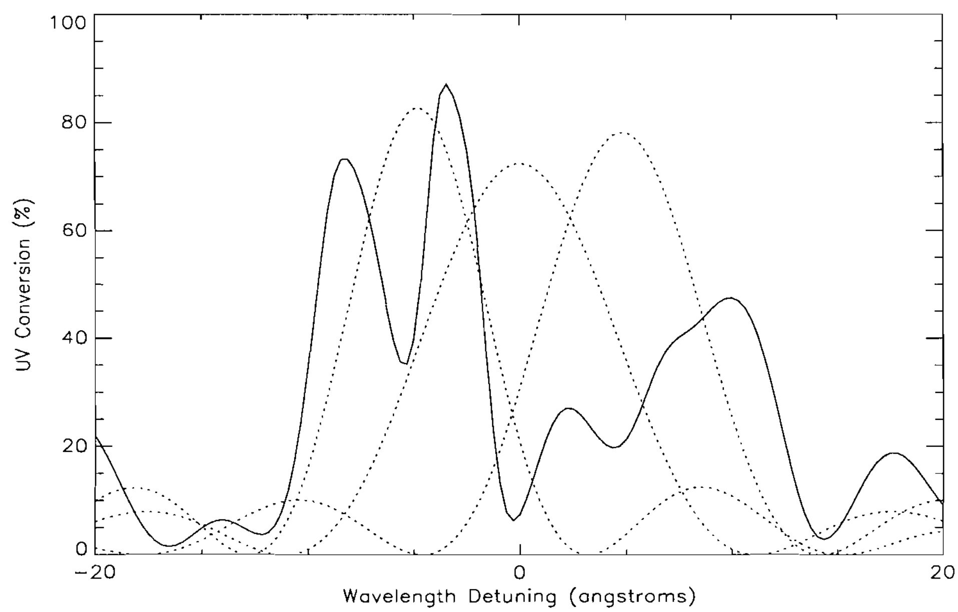


Figure 8. As Fig. 4 but with 3 triplers narrowly detuned (detuning of the 1st tripler is 800 μrad; that of the 2nd, 0 μrad ; that of the 3rd, -800 μrad). Extreme modulations persist due to unavoidable destructive interference.

3.3. Tripler thickness

The thickness of the triplers in a design must be set appropriately. Figure 9 shows the dependence on the third-tripler thickness for the otherwise-optimized three-tripler-design conditions. The 11-mm length effects better conversion at wavelengths near the tuning wavelengths of the third tripler but decreases conversion in the central part of the bandwidth. The 7-mm length produces an unwanted dip on the left side of the curve and also converts weakly on the right side. Thus, the 9-mm thickness produces the best overall performance. Triplers thicker than 11 mm induce profound modulations and isolated peaks rather than uninterrupted regions of high efficiency.

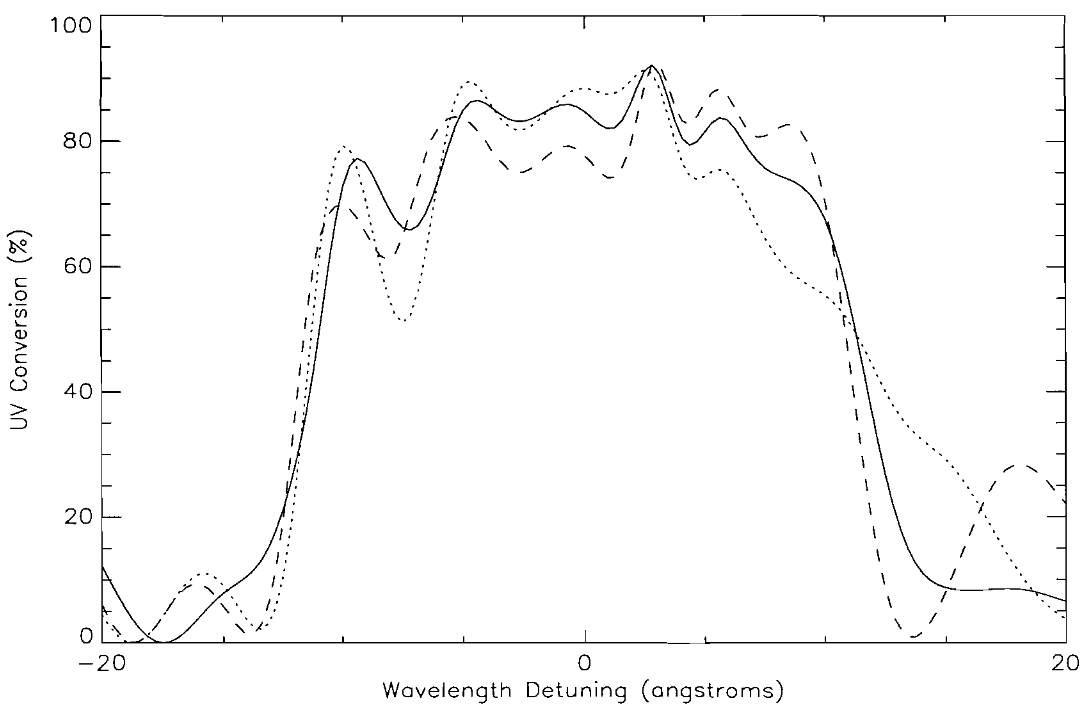


Figure 9. Baseline 3-tripler design (solid line; see Fig. 4) compared with 3-tripler designs with different thicknesses of the 3rd tripler. For the dashed line, the thickness of the 3rd tripler is 11 mm; for the dotted line, it is 7 mm.

All designs have been optimized at an input intensity of 1.5 GW/cm^2; however, it can be shown from Equations 1-3 that any design can be scaled for any intensity by multiplication of the tripler lengths by the square root of the reciprocal of the ratio of intensities and the detuning angles by the square root of the ratio of intensities. Thus, my designs could be applied to any high-intensity laser.

3.4. Performance at lower intensities

I initially optimized my conversion curves exclusively for an input intensity of 1.5 GW/cm^2. However, intensities vary throughout OMEGA laser pulses; 1.5 GW/cm^2 is OMEGA's peak operating intensity but not the only operating intensity of interest. Early in the implosion broad bandwidth is required in the small-signal input intensity regime, which includes intensities as low as 0.1 GW/cm^2. Therefore, I investigated the viability of my designs at a range of lower intensities. The four-tripler design performs particularly well over a wide range of intensities, maintaining an impressive bandwidth of 29 Å at small-signal intensity (0.1 GW/cm^2) and symmetry at all intensities of interest. The three- and five-tripler designs also retain broad bandwidth at small-signal intensity.

3.5. Designs which include OMEGA's current triplers

One question of particular interest to OMEGA researchers is whether multiple-tripler designs exist which incorporate the existing tripler crystals. Investigation showed that broad-bandwidth three- and four-tripler designs including OMEGA's current triplers are possible. Though both designs contain more modulation than their optimized counterparts, they achieve bandwidths—18.6 and 26.3 Å, respectively—significantly broader than OMEGA's current bandwidth of 14 Å. Their mean conversions are, in fact, slightly higher than that of OMEGA's current design.

4. Conclusions

In investigating multiple-tripler designs, I developed a systematic method for creating a design for any number of triplers. The method involves choosing triplers thick enough that individual conversion is strong but not so thick that the combined curve degrades. It also involves tuning each successive tripler near the zero of the curve produced by the preceding triplers and adjusting tripler separations so that constructive interference is emphasized. My research led to the creation of three-, four- and five-tripler designs which facilitate broad-bandwidth, high-efficiency frequency conversion. These designs broaden the current conversion bandwidth, achieved with two triplers, by a factor of two or three. The multiple-tripler designs I created could be implemented on the OMEGA laser system or on any other high-power laser system which requires smooth laser beams.

5. Acknowledgments

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