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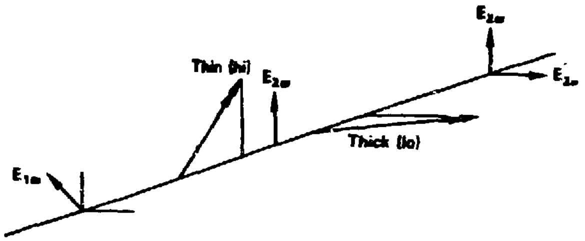
The quadrature conversion scheme[1,2] is a method of generating the second harmonic. The scheme, which uses two crystals in series, has several advantages over single-crystal or other two crystal schemes. The most important is that it is capable of high conversion efficiency over a large dynamic range of drive intensity and detuning angle.[3]



$\eta = \eta_1 + (1 - \eta_1)\eta_2$

Figure 1

Consider a pair of KDP crystals cut for type-II phase matching (Fig. 1). In the quadrature scheme, the optic axes of the crystals are arranged so that the planes containing the direction of the laser beam and their optic axes (the kz planes) are mutually perpendicular. This arrangement has two important properties. First, in type-II phase matching, the incident wave is polarized at 45 deg to the kz plane of the crystal. This, in the quadrature scheme, if the incident wave is correctly polarized for efficient conversion in the first crystal, it is also correctly polarized for efficient conversion in the second crystal. Both crystals can therefore convert efficiently.

Second, the second harmonic waves generated in the two crystals are orthogonally polarized (hence the term quadrature). The output from the first crystal thus has the wrong polarization to experience gain in the second crystal. If the conversion efficiency is η_1 in the first crystal and η_2 in the second, the output from the first crystal is $\eta_1 I$ (where I is the incident intensity of the fundamental wave) and the input intensity to the second crystal is $(1 - \eta_1)I$. Because the second crystal does not change the output of the first, the overall output is simply the sum of the output from each crystal. The overall conversion efficiency is then

$$\eta = \eta_1 + \eta_2(1 - \eta_1).$$

The advantage of quadrature conversion is that it enables us to arrange for the second crystal to convert whatever light is left unconverted from the first crystal. Because of the unavoidable slight aberrations present in any laser beam, the intensity and local direction of the beam (angular detuning) will vary over its face. As the crystal acts locally in converting the laser light to the second harmonic, the conversion efficiency varies from point to point over the face of the beam. The relevant conversion efficiencies are defined, therefore, by the range of intensities and angular detuning present in the beam. Clearly, any energy in the laser beam that meets the crystal with an intensity and detuning for which the conversion efficiency is low will remain unconverted. For efficient operation, the crystals must convert efficiently over a sufficiently large range of intensity and angular detuning. With crystals of different thicknesses, the thick one converts the low intensity portion of the pulse and the thin one, the high intensity portion. The quadrature scheme is therefore capable of very high dynamic ranges in intensity, and is less sensitive to angular detuning, polarization misadjustment, and frequency bandwidth, than single crystal schemes. Details of its design and properties are published in Refs. 1 and 2.

The concept was tested using the Cyclops laser at LLNL to verify the high dynamic range. The experiment confirmed that quadrature schemes are capable of very high system or external conversion efficiencies (> 95%) over a wide range of drive intensities; and that this efficiency can be obtained using pulses which are Gaussian in space and time.

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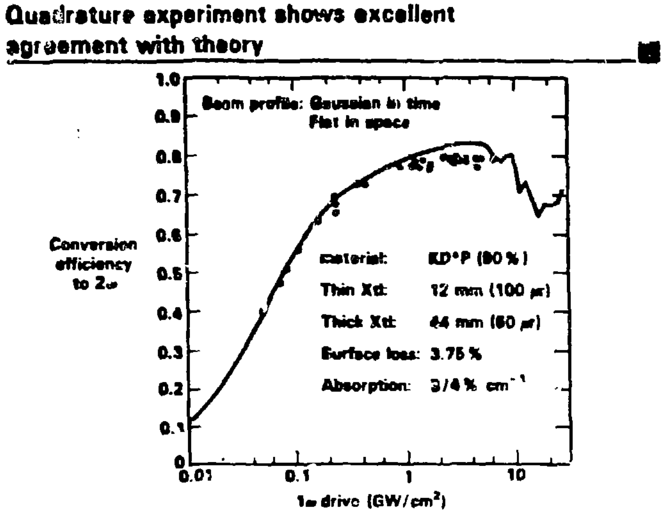


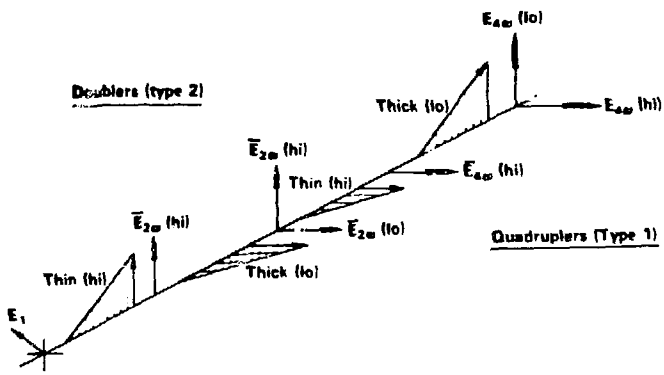
Figure 2

The experiment used two crystals of KD*P, with thickness 12 mm and 44 mm. The deuteration level was measured using NMR to be 90.6%, and the optical absorption at 1.053μm was measured to be 0.6 %/cm for light appropriately polarized for Type II operation. The optical absorption at 0.532μm is essentially zero. The Fresnel loss from the surfaces is 3.75%. Thus, the losses lie between 15 and 18.4%, depending on the conversion efficiency, with the higher loss corresponding to lower efficiency. The 1.053μm drive had a Gaussian profile in space and time with a pulsewidth (FWHM) of 1.2 ns, and a diameter of 3 cm. It was close to diffraction-limited. Figure 2 shows the measured conversion efficiency, including all the losses, as a function of the average drive intensity. The efficiency rises above 70% at around 200 MW/cm^2. In the region 1-3 GW/cm^2 the efficiency was close to 80%, which is very close to the maximum achievable in a system with 15-18% passive loss. This experiment demonstrates the high dynamic range (∼ 45) and the high efficiency of quadrature schemes. With AR coatings developed recently at LLNL, there is every reason to expect that efficiencies approaching 95% are possible with this approach, even for Gaussian pulses.

Quadrature schemes are robust in that their sensitivity to beam profile, polarization errors, laser bandwidth, and angular and thermal misadjustments is lower than that of single crystal schemes. A four-crystal quadrature scheme has been developed to give high dynamic range at 4ω. This is shown in Figure 3. As yet, high dynamic range at 3ω appears to be impossible, although some four-crystal 3ω schemes do show a slight increase over the two crystal doubler/mixer approach. However, their dynamic range is still less than 10.

4ω Polarization-Switched Quadrature Arrangement

Figure 3



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