High-Efficiency, Large-Aperture Fifth-Harmonic Generation of 211-nm Pulses in Ammonium Dihydrogen Phosphate Crystals for Fusion Diagnostics

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High-energy ultraviolet (UV) sources are required to probe hot dense plasmas from fusion experiments by using Thomson scattering resulting from the lower self-generated background from the plasma in the 180- to 230-nm spectral region.[1] The fifth-harmonic generation (5HG) of a neodymium laser with a 211-nm wavelength fits that window. Recently[2] we demonstrated 30%-efficient, joule-class fifth-harmonic conversion of 1053-nm pulses using a cesium lithium borate (CLBO) crystal, but larger crystals are necessary for increased UV energy. Also, the extremely hygroscopic property of CLBO crystals requires that they be kept under high (~120°C) temperature. Ammonium dihydrogen phosphate (ADP) crystals, which can be grown to much larger sizes, should be considered as an alternative way of generating a high-energy beam at 211 nm.

For cascade 5HG, however, ADP has a significant limitation: phase-matching conditions for sum–frequency generation are not met at room temperature. Noncritical phase-matching conditions could be reached by cooling ADP crystals to –70°C. This is not trivial, especially for large-aperture crystals, because a definite temperature must be strictly stabilized and maintained across the entire crystal. Any holder that keeps a crystal in the vacuum chamber and maintains a crystal temperature through thermal conductive contact provides some gradient of temperature through a crystal.

The most-effective way to stabilize an entire crystal under low temperature is a two-chamber cryostat, where the internal chamber keeps a crystal almost isolated from a holder but surrounded by 1 atm of helium gas. The internal chamber is held in the high-vacuum external chamber to minimize heating. The cross section of the designed and fabricated two-chamber cryostat is shown in Fig. 1. "Cold flow" travels down from the liquid nitrogen tank through two hollow cylinders to the internal chamber; it then reaches the 65 × 65 × 10-mm ADP crystal through the helium. As soon as the temperature of the crystal (or the internal chamber wall, depending on which temperature sensor is chosen as the control) approaches a chosen set point temperature, the heaters on the wall of the lower cylinder begin working to maintain that temperature through a temperature stabilization loop. A high-performance cryogenic temperature controller is used to monitor and control temperature within the internal chamber to better than 0.01°C resolution. Each of the two heaters mounted on the cryostat is controlled by a proportional-integral-derivative feedback loop. The feedback continually adjusts the output power to the heaters in order to keep the chosen temperature constant. The system has high thermal mass and reaches a target temperature of 200 K in about 36 h.

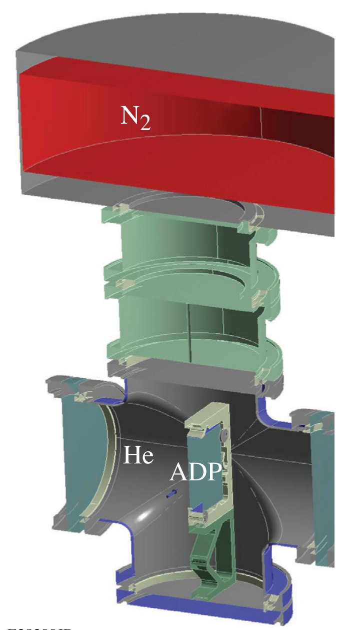

Figure 1
The cross section of the internal chamber, filled with helium (He), with the crystal (ADP) and liquid nitrogen tank (N_2).

This experiment is shown in Fig. 2. Some portion of the energy must be saved at the fundamental frequency (20% in an ideal-case plane wave without any type of absorption and Fresnel reflections), untouched through the first two crystals to mix with the 4ω beam. We have chosen the cascade $o_1e_1 \longrightarrow e_2{:}o_2o_2 \longrightarrow e_4{:}o_1o_4 \longrightarrow e_5$, which allows the energy distribution between o and e waves to be changed by polarization rotation with a half-wave plate (HWP). The first frequency doubler was a Type-II deuterated potassium dihydrogen phosphate (DKDP) crystal (30 × 30 × 27 mm). A second frequency doubler, a Type-I KDP crystal (30 × 30 × 15.5 mm), was used to convert $2\omega \longrightarrow 4\omega$.

An Nd:YLF laser was optimized to produce square pulses with a flattop, square beam profile (1053 nm, 1 to 2.8 ns, 12 × 12 mm, ≤1.5 J, ≤5 Hz). The fused-silica prism separates the harmonic beams in space. The input and output beam energies were measured using identical cross-calibrated pyroelectric energy meters. All beam profiles were recorded.

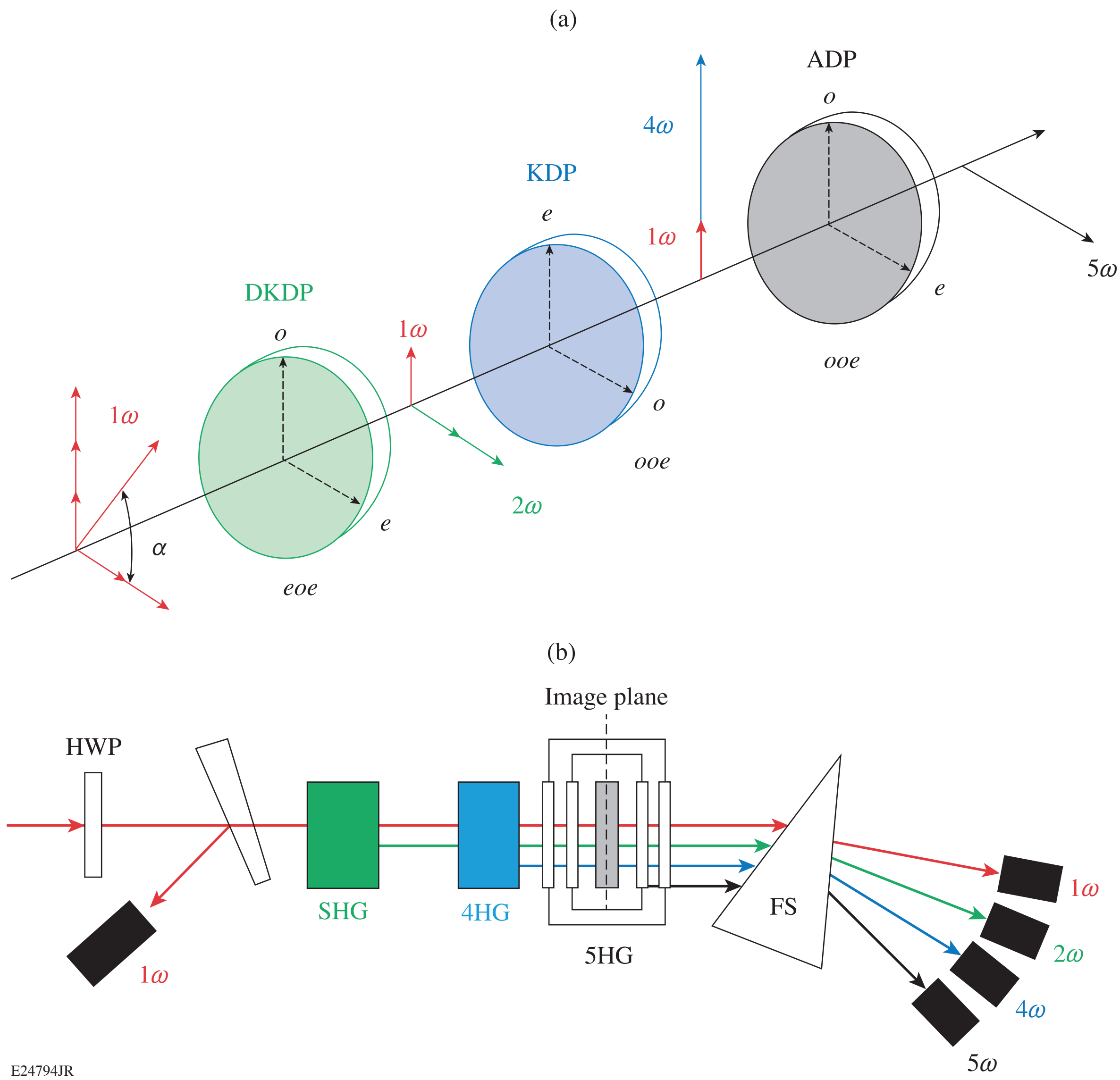

Figure 2
Experiment: (a) The orientation of the crystal axes and polarizations. The angle (α) of the 1ω polarization was set using a half-wave plate for optimal conversion, e: extraordinary, o: ordinary. (b) Setup. HWP: half-wave plate; SHG: second-harmonic generator; 4HG: fourth-harmonic generator; 5HG: fifth-harmonic generator; FS: fused-silica wedge.

Accurate tuning of the experimental parameters allowed for total conversion efficiency from the fundamental to the fifth harmonic, including surface losses and absorption, of 26% (Fig. 3). Temperature acceptance of 5HG is extremely narrow and less than 0.4 K (FWHM). Angular acceptance was measured at 200 K and is 8 mrad external (FWHM).

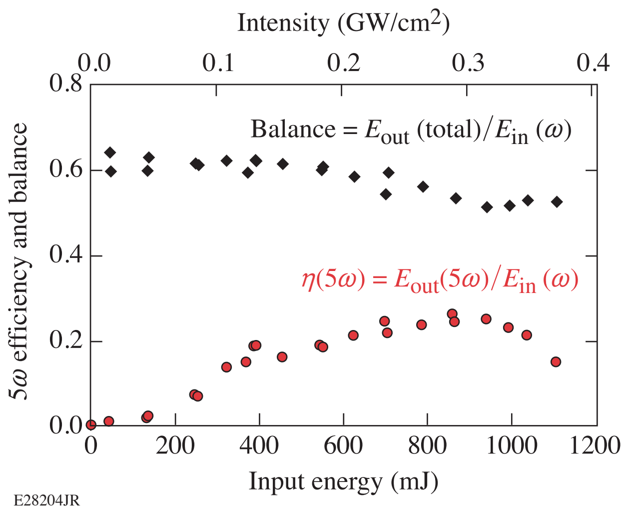

Figure 3
Fifth-harmonic efficiency and energy balance measured as a function of input-pulse energy and intensity.

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1. J. S. Ross *et al*., Rev. Sci. Instrum. **81**, 10D523 (2010).

2. I. A. Begishev *et al*., Opt. Lett. **43**, 2462 (2018).