

# Dichroic beam splitter for extreme-ultraviolet and visible radiation

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A simple dichroic beam splitter capable of separating extreme-ultraviolet (XUV) radiation from high-powered visible and UV laser beams is demonstrated. The device has high XUV reflection efficiency ( $R \approx 44\%$ ) and high damage resistance to intense laser radiation and is therefore applicable to laser-generated XUV radiation sources, including harmonic generation, sum-frequency mixing, and anti-Stokes Raman scattering.

Laser techniques for generating extreme-ultraviolet (XUV) radiation<sup>1</sup> have made intense sources of coherent and incoherent radiation available below 1000 Å. For example, nonlinear processes have been used to generate high-order harmonics of Nd:YAG lasers<sup>2</sup> (from 887 to 380 Å), excimer lasers<sup>3</sup> (from 1027 to 570 Å), and tunable dye lasers<sup>4</sup> (near 930 Å). One difficulty in using such radiation is that the residual high-powered laser radiation at the fundamental wavelength is usually collinear with and typically 6 orders of magnitude more intense than the generated harmonic in the XUV. This intense fundamental beam can destroy a sample or saturate detectors. In this Letter we describe a simple reflector capable of separating high-powered, long-wavelength radiation from XUV radiation.

Since all bulk materials strongly absorb radiation below  $\sim 1040$  Å, the only filters available for XUV radiation are thin films.<sup>5</sup> These films, typically  $\sim 1000$ -Å thick metal foils, transmit XUV radiation ( $T \sim 50\%$ ) and attenuate visible radiation (attenuation  $\sim 10^7$ ). However, they are incapable of absorbing large energy fluxes from pulsed lasers used to generate the XUV radiation. A typical damage limit for 1500-Å-thick aluminum foils is 40 mJ/cm<sup>2</sup> for 5-nsec-long dye-laser pulses. The beam separator described in this Letter makes use of the reflecting properties of absorbing materials at high angles of incidence in the XUV. This property of materials at wavelengths  $< 1000$  Å is well known and has been exploited in device applications such as mirrors, gratings, and polarizers.<sup>5,6</sup> The key point here is that high-energy beam separators can be fabricated that transmit ( $T > 99\%$ ) at wavelengths  $> 1000$  Å, where materials are nonabsorbing, while reflecting ( $R \sim 50\%$ ) at XUV wavelengths.

The simplest example of such a device is illustrated in Fig. 1. A quartz slide is placed in the output beams from a nonlinear medium at an angle  $\theta$  with respect to the surface normal. If the fundamental (visible) laser beam is polarized in the plane of incidence ( $p$ -polar-

ized), and the slide is at the Brewster angle for this radiation (e.g.,  $\theta = 56^\circ$  for index of refraction  $n = 1.5$ ), then the reflection coefficient  $R_F$  goes to zero (see Fig. 2). However, in the XUV the index of refraction of quartz is complex,<sup>7</sup> given by a real part  $n$  and an imaginary part  $k$ . In this case, there is no angle for which the reflectivity goes to zero, and some fraction of an XUV harmonic beam will be reflected with the rest absorbed. In Fig. 3 we plot reflection from quartz as a function of wavelength for  $s$ - and  $p$ -polarized XUV radiation for various angles of incidence. For  $\theta = 56^\circ$ ,  $p$ -polarized radiation at 500 Å will have a reflection coefficient  $R_{XUV} = 8\%$ . If the angle of incidence is increased, the reflectivity at both the fundamental and XUV wavelengths increases, as shown in Figs. 2 and 3, respectively. For example, at  $\theta = 65^\circ$  we have  $R_F = 1\%$  and  $R_{XUV} = 19\%$ . For this simple configuration one could decide on an appropriate angle  $\theta$  by examining the ratio of  $R_F$  to  $R_{XUV}$ . In practice, one may choose to limit the fundamental reflection to an energy that does not destroy a detector or other experimental components in the beam path. These may include, for example, a diffraction grating or metal foil, which may be used as a more selective filter of XUV radiation.

Beam separators with more optimum properties can be designed by using commercial multilayer dielectric optical coatings. To demonstrate this, we designed a reflector that would separate a 2800-Å laser beam

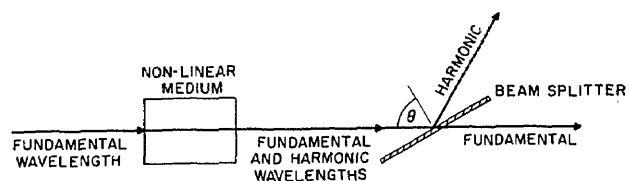


Fig. 1. Configuration of dichroic beam splitter to separate visible wavelength fundamental from XUV wavelength harmonic generated in a nonlinear medium.

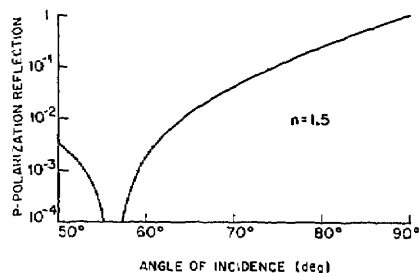


Fig. 2. Reflection of  $p$ -polarized radiation from nonabsorbing media with index of refraction  $n = 1.5$  as a function of angle.

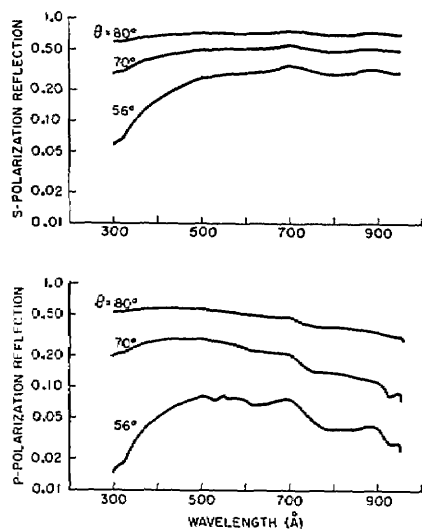


Fig. 3. Reflectivity of quartz in the XUV for  $s$ - and  $p$ -polarized radiation as a function of angle and wavelength.<sup>7</sup>

(fundamental wavelength) from its third harmonic at 933 Å generated in a Hg-vapor cell.<sup>4</sup> In order to keep the reflectivity high at 933 Å, the reflector was designed for a high angle of incidence with  $s$ -polarized radiation. (Note that polarization at the third harmonic is the same as the polarization of the fundamental for an isotropic nonlinear medium.) To maintain low reflectivity at the fundamental wavelength, the quartz substrate was antireflection (AR) coated<sup>9</sup> for  $s$ -polarized radiation at 2800 Å. The reflectivity was measured to be  $\sim 1\%$  at  $\theta = 70^\circ$  for 2800 Å. The topmost layer of the multilayer coating was intentionally made to be a full wave of  $\text{MgF}_2$ . In bulk,  $\text{MgF}_2$  has a calculated<sup>7,10</sup> reflection of 41% for  $s$ -polarized radiation at 933 Å for  $\theta = 70^\circ$ . Formulas for calculating reflectance of absorbing materials can be found in various optics texts.<sup>5,11</sup> Since the absorption depth ( $\lambda/4\pi k$ ) for radiation at  $\lambda = 933$  Å in  $\text{MgF}_2$  is 170 Å, we need only consider this top layer in computing the XUV reflectivity of the coating.

Experiments were performed using 2800-Å laser radiation produced by a frequency-doubled pulsed dye laser with a peak power of several megawatts. This radiation was focused using a 25-cm focal-length lens into a Hg-vapor cell at a pressure of  $\sim 1$  Torr of Hg vapor plus several Torr of the buffer gas. Several watts of peak power at 933 Å were generated. The XUV re-

flectivity of the coated substrate was measured, using the laser-generated harmonic, to be  $44 \pm 10\%$ , in good agreement with the calculation. (This was expected since the index-of-refraction data were obtained from reflectance measurements.) This measurement was made by first separating the 933-Å radiation from the fundamental laser wavelength by using a vacuum monochromator; the relative intensity of the 933-Å radiation was measured before and after reflection from the coated substrate at the exit slit of the monochromator.

We then used only the coated substrate to separate the fundamental and third harmonic, as shown in Fig. 4. Signal levels at the detector in this configuration were about six times larger than those obtained previously using the monochromator, indicating that the grating reflectivity was about 7% at 933 Å. The XUV detector in both experiments consisted of an indium thin-film filter, a sodium salicylate-coated window, and a photomultiplier tube. In addition to increased signal levels, a notable advantage of using the beam splitter described here in place of the grating monochromator is that it is nondispersive in the sense that the output XUV beam is not angularly deviated as the wavelength is changed.

We note that several factors must be considered in designing such a beam splitter. First, one must consider the polarization and reflectivity at all pertinent wavelengths. By examining various materials using reflectivity calculations such as those displayed in Figs. 2 and 3, one can decide if simple, bulk materials can be used (quartz or salt windows, for example) or if multilayer AR coatings are required. We note that resonance-absorption features in solids can lead to enhanced reflectivity at specific XUV wavelengths. For example, lithium halides<sup>12</sup> exhibit enhanced reflectivity near 200 Å corresponding to an absorption feature of the  $\text{Li}^+$  ion. As was demonstrated here, commercial technology is available to fabricate AR coatings at high angles of incidence even at UV wavelengths. It appears to be sufficient to consider only the final layer in calculating the XUV reflectance if that layer is thick enough. Additionally, second surface reflectance at visible wavelengths must also be considered; in our experiment we used a wedged substrate to eliminate the need for AR coating both surfaces. We also note that the optical

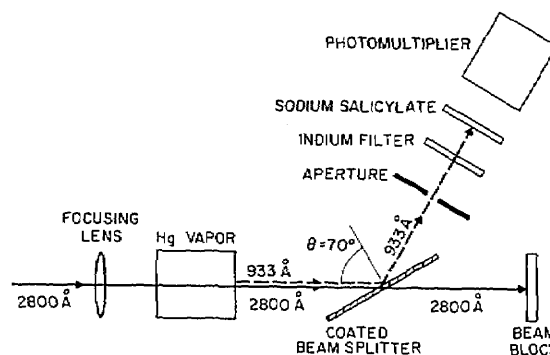


Fig. 4. Experimental configuration used to separate 2800-Å laser from 933-Å harmonic generated in Hg-vapor cell; 933-Å beam path was in He buffer gas.

power damage limits must be considered. Current coating technology typically permits power densities  $>1$  GW/cm<sup>2</sup> for nanosecond pulse widths. By comparison, replica diffraction-grating damage limits are in the range of a few megawatts per square centimeter. In our experiments, a darkening of the optical coating was observed after several hours of operation at peak power densities of  $\sim 20$  MW/cm<sup>2</sup> at 2800 Å (average power density  $\sim 1$  W/cm<sup>2</sup>). This was attributed to absorption by condensed Hg vapor on the coating, which could be eliminated by better cell design. Last, we note that rapidly diverging beams from tightly focused geometries of nonlinear experiments may be recollimated or refocused by using concave reflecting surfaces. Consideration must be given to the highly astigmatic focusing properties of curved surfaces at high angles of incidence.<sup>13</sup> In this regard, toroidal mirror surfaces could be of use.

In conclusion, we have demonstrated a simple dichroic capable of separating XUV radiation from high-powered laser beams at UV and longer wavelengths. We have discussed several design considerations for such devices. The advantages of these devices over diffraction gratings include high efficiency, high damage threshold, and lack of angular dispersion. This technology should be immediately applicable to laser-generated XUV sources including harmonic generation, sum-frequency mixing, and anti-Stokes Raman scattering.<sup>13</sup>

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