EUV Spectral Purity Filter for Full IR-to-VUV Out-of-Band Rejection, with IR Power Recycling

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Abstract

A plasma light source for EUV lithography can be spectrally filtered by a phase-Fresnel collector mirror to reject all out-of-band radiation in the IR-to-VUV spectral range, leaving only pure EUV in the filtered output. EUV collection efficiency is not significantly compromised, and EUV conversion efficiency can be enhanced by recycling rejected or uncollected IR back to the plasma via retroreflection.

Introduction

A phase-Fresnel optic is a grating-type surface (reflecting or transmitting) with a sawtooth profile similar to a Fresnel lens, which preserves optical phase coherence between Fresnel facets at a particular "blaze" wavelength. [Ref. 1] This paper discusses the application of phase-Fresnel spectral filters for extreme ultraviolet (EUV) lithography using a laser-produced plasma (LLP) source, which requires elimination or separation of the infrared (IR) drive-laser radiation from the EUV. Ideally, the full out-of-band spectrum from the deep IR to the vacuum ultraviolet (VUV) should be eliminated in the EUV collection optics. [Ref's. 2, 3]

One type of filter that has been developed for lithography is an LPP collection mirror with a lamellar (rectangular-section) diffraction grating on its surface, which is designed to extinguish the zero-order IR radiation at the 10.6- μm laser wavelength. [Ref's. 4-8] The IR radiation is scattered into first and higher diffraction orders, and an aperture at the collector's intermediate focus (IF) blocks the scattered IR while transmitting the focused EUV radiation beam. The EUV beam is substantially unaffected by the grating because its wavelength (13.5 nm) is much smaller than the grating period (which is of order 1 mm). In a variation of this process, one of the grating's first diffraction orders in the IR is directed back ("recycled") to the plasma source to improve conversion efficiency. [Ref. 9]

A limitation of spectral filtering via diffractive IR scattering is that it only eliminates out-of-band radiation at one or very few design wavelengths. Also, power recycling is limited by the grating diffraction efficiency.

An alternative LPP filtering mechanism discussed in this paper similarly rejects IR by diverting it into a ring or halo around the IF aperture, but not via diffractive scattering. Instead, the collection mirror shape is configured to reflect the specularly reflected IR away from the focus, and a blazed phase-Fresnel grating on the mirror surface diffracts the 13.5-nm EUV toward the focus. The grating dimensions are too small to significantly affect the IR, and complete rejection of unwanted radiation can be achieved over the full IR-to-VUV spectral range. Moreover, efficient power recycling can be achieved by retroreflecting the rejected IR (and also uncollected IR) back to the plasma.

EUV Spectral Filtering Mechanisms

Kierey et al. [Ref. 10] demonstrated a grazing-incidence, phase-Fresnel mirror that spatially separates EUV and IR radiation, as illustrated in Figure 1. The grating is located in the convergent beam of an EUV collector, near the intermediate focus (IF). The first diffracted order in the EUV is focused onto the IF, while the zero-order IR radiation is directed outside of the IF aperture. (The EUV reflection efficiency is 59%.) The mirror comprises sawtooth-profile grating lines in ruthenium (shown schematically in cross-section in Figure 1), which are illustrated perpendicular to the incidence plane although the lines could alternatively be oriented parallel to the incidence plane. The grating design could be considerably improved by employing modern fabrication technology (e.g., to allow a nonuniform distribution of grating blaze angles).

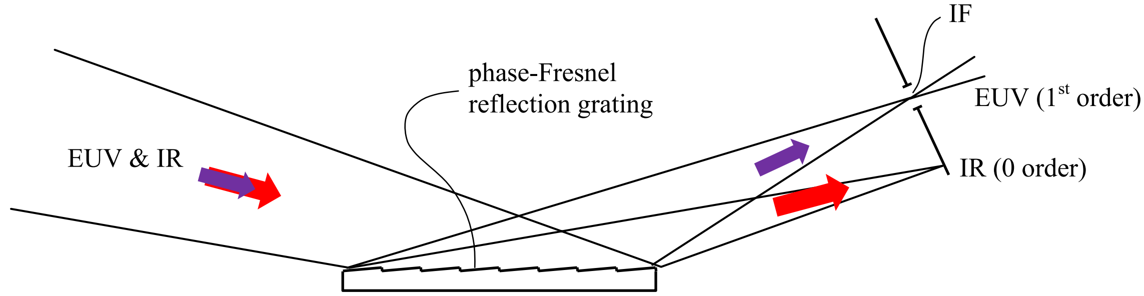

Figure 1. A phase-Fresnel, grazing-incidence reflection grating in ruthenium separates the 1st-order EUV (13.5 nm) from the 0-order IR (10.6 µm).

Phase-Fresnel EUV reflection gratings operating at near-normal incidence have been researched by Liddle et al. [Ref. 11] and by Boogaard et al. (2009) [Ref. 12], although it is unclear from these publications how such gratings might be incorporated into an LPP collector for spectral filtering.

EUV/IR separation could alternatively be achieved by a free-standing transmission phase-Fresnel grating, similar to transmission filters described by Chkhalo et al. [Ref. 13] and Suzuki et al. [Ref. 14]. These filters employ IR-reflecting/EUV-transmitting films, but similar structures could employ phase-Fresnel transmission gratings to separate the EUV and IR as illustrated in Figure 2. (The grating can be formed in a molybdenum layer.) The transmission grating is functionally similar to the reflection grating of Figure 1.

A preferred method of spectral filtering is to incorporate the filtering function in the EUV collector's main condenser mirror, rather than in a separate optical element. [Ref's. 4-8] As illustrated in Figure 3, the filtering mechanism is a lamellar (rectangular-profile) diffraction grating with annular grating zones formed on the mirror surface. (A cross section of the grating is shown in the enlarged detail view.) In contrast to the grating structures illustrated in Figures 1 and 2, the Figure 3 structure operates to diffract IR radiation while having minimal impact on the EUV beam. The grating scatters the IR into a halo around the IF aperture through which the EUV transmits.

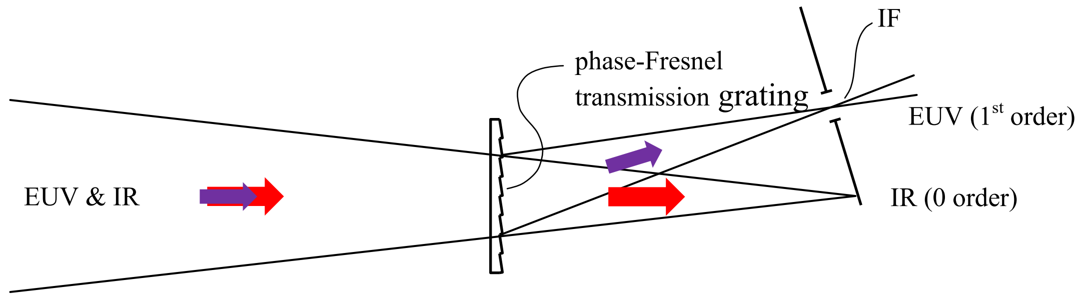

Figure 2. A phase-Fresnel, transmission grating (e.g. in molybdenum) separates the 1st-order EUV (13.5 nm) from the 0-order IR (10.6 µm).

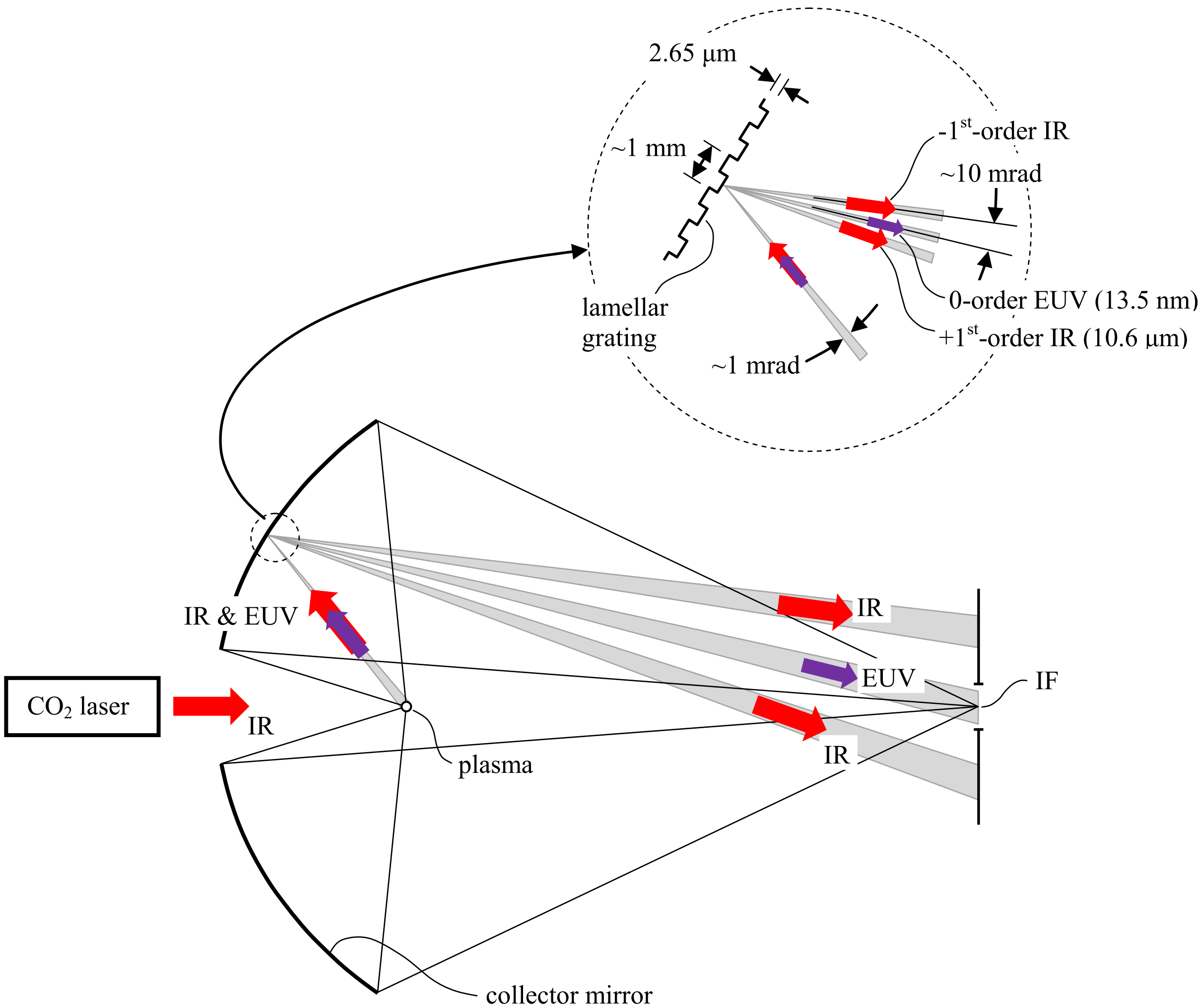

Figure 3. Lamellar-grating spectral filter.

As illustrated in the detail view, the grating depth is approximately 2.65 μm (one-quarter of the CO_2 drive laser's IR wavelength of 10.6 μm), resulting in extinction of the zero diffraction order and redirection of IR radiation into first and higher orders. The grating period is of order 1 mm, resulting in a first-order scattering angle of approximately (10.6 μm)/(1 mm), or roughly 10 mrad. By comparison, the plasma source's subtend angle at the grating is typically of order 1 mrad (e.g., for a 200-μm plasma diameter and 200-mm condenser focal length). All of the light cones illustrated in Figure 3 have approximately 1 mrad extent, so the 10 mrad IR scatter angle is more than sufficient to separate the first-order IR and zero-order EUV light cones. The grating also induces some diffractive scatter in the EUV, but the scatter angle is only of order (13.5 nm)/(1 mm), i.e. 13.5 μrad, which is insignificant in relation to the plasma's 1 mrad angular extent.

In a variation of this approach, the grating is designed to direct one of the first diffraction orders in the IR back onto the plasma to improve the EUV conversion efficiency. [Ref. 9] About 37% of the collected IR power can be recycled by this method, but it would require a much smaller grating period to retroreflect the IR. For example, to retroreflect the first diffraction order with a 30° incidence angle, the grating period would be equal to the 10.6-μm IR wavelength. Deposition of a multilayer EUV reflection coating over the 2.65-μm steps of such a high-pitch grating might result in non-negligible loss of EUV optical efficiency. (The multilayer stack would typically be around 400-nm thick.)

Spectral Filtering with a Phase-Fresnel Collector Mirror

An alternative spectral filtering mechanism illustrated in Figure 4 similarly directs IR radiation onto a circle or halo surrounding the IF aperture, but not via diffractive scattering. Instead, the collector mirror shape is designed to direct specularly-reflected light out of the aperture, and a phase-Fresnel grating directs the EUV radiation into the aperture. (The grating dimensions are too small to significantly affect the IR.) This method achieves virtually complete elimination of out-of-band radiation from the far IR to the deep VUV with minimal impact on EUV collection efficiency.

The enlarged detail view in Figure 4 illustrates the phase-Fresnel grating profile in cross section. The 1-mrad light cone from the plasma source is reflected into a 1-mrad, zero-order reflected light cone in the IR (10.6 μm), and a 1-mrad, 1^{st}-order diffracted light cone in the EUV (13.5 nm). The angular separation between the IR and EUV cone axes must be greater than 1 mrad to achieve spatial separation of the two wavelengths. The grating blaze angle is half the diffractive deviation angle at the 13.5 nm blaze wavelength; hence the blaze angle is at least 0.5 mrad. For near-normal incidence, phase matching between Fresnel facets is achieved when the grating depth is half the blaze wavelength, 6.75 nm. (This is comparable to the thickness of a single bilayer in a Mo/Si EUV multilayer mirror stack.) For off-normal incidence the depth is greater by a factor of the reciprocal cosine of the incidence angle, but is less than 10 nm over the full mirror aperture. Thus, the maximum grating period is approximately (10 nm)/0.0005 = 20 μm. A significantly smaller period (larger diffraction angle) may be required to accommodate tolerance factors or other design constraints. (This assumes that the grating is blazed for the first diffraction order. As discussed below, the period can be much larger if a higher order is used.)

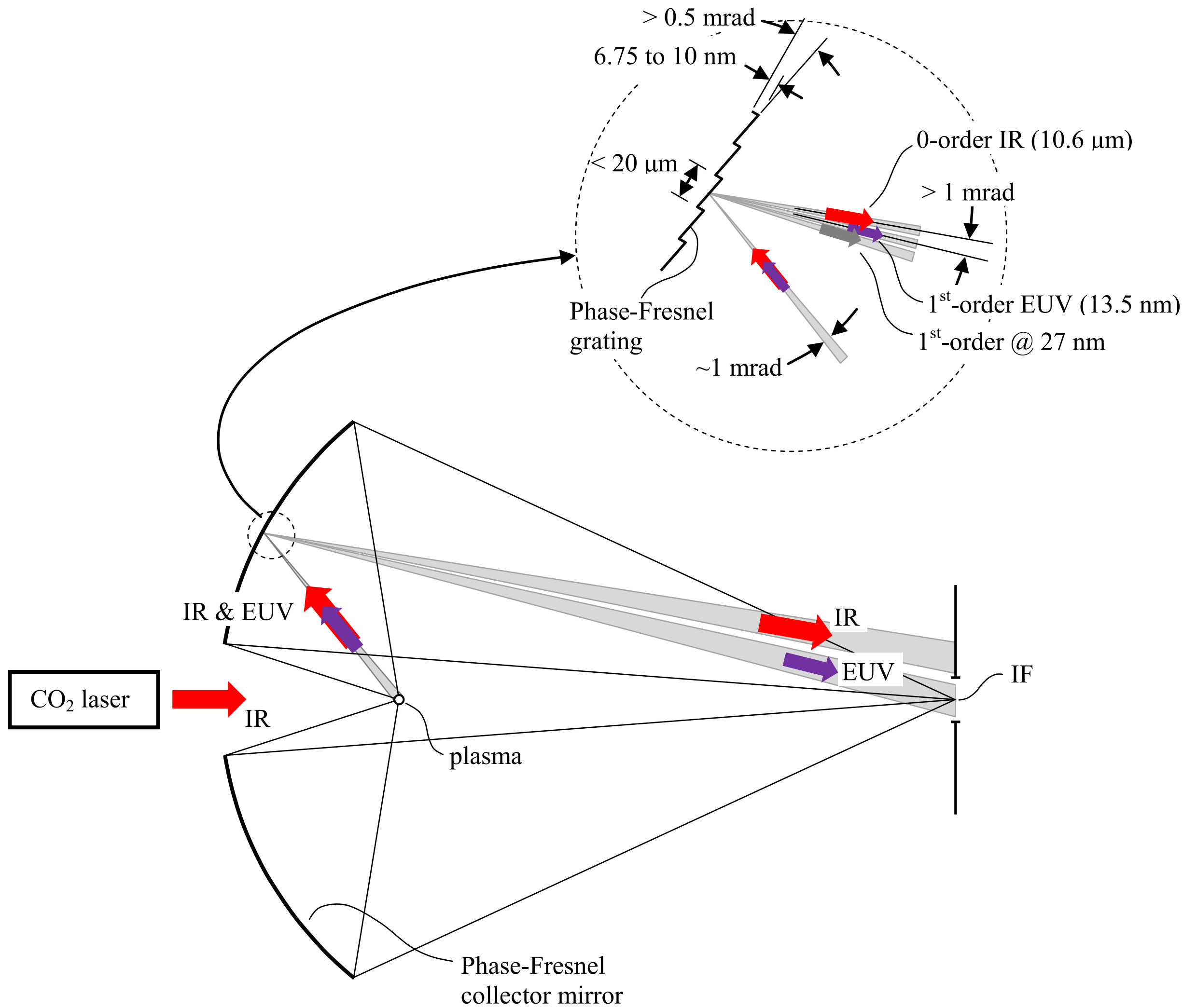

Figure 4. Phase-Fresnel-grating spectral filter.

The detail view in Figure 4 also illustrates a 1st-order diffraction cone for wavelength 27 nm (twice the 13.5-nm blaze wavelength), for which the diffraction angle is larger by a factor of 2. This wavelength is angularly separated from the 13.5-nm EUV by at least 1 mrad and will hence be eliminated at the IF aperture. The diffraction angle is approximately proportional to wavelength; hence all wavelengths greater than twice the blaze wavelength will be eliminated.

The 1st-order diffraction efficiency η of the phase-Fresnel grating at wavelength λ is approximately

$$\eta = \mathrm{sinc}^2[\pi(\lambda_B / \lambda - 1)]$$

where λ_B is the first-order blaze wavelength (13.5 nm) and $\mathrm{sinc}[x] = \dfrac{\sin x}{x}$. ($\mathrm{sinc}[0] = 1$.) This is the "relative efficiency", normalized to the reflectance of an unpatterned mirror. (The formula is based on Fourier-optics approximations.) Within the 2% EUV wavelength band of an LPP source and collection mirror, λ is very close to λ_B and the above formula can be approximated as

$$\eta \approx 1 - \tfrac{1}{3}\pi^2 (\lambda_B / \lambda - 1)^2 \quad (\text{for } \lambda \approx \lambda_B).$$

The factor $\lambda_B / \lambda - 1$ is in the range 0.99 to 1.01, and $\eta > 1 - 3.3 \times 10^{-4}$, over the collected EUV spectrum. This implies that the grating's optical efficiency loss is negligible, but in practice there may be some non-negligible loss due to distortion of the multilayer EUV mirror coating by the step in the blaze profile.

The efficiency loss could possibly be mitigated by designing the grating to operate in a higher blazer order. For example, if the grating illustrated in Figure 4 is designed to operate in the second order, then the grating profile dimensions would be doubled (i.e., a depth of 13.5 to 20 nm, period less than 40 μm) and the multilayer stack thickness would be a proportionately smaller fraction of the grating period. Also, a coarser grating structure might be more manufacturable. But there are two possible tradeoffs to using a higher blaze order: The rejection wavelength band is not as broad, and the grating's theoretical optical efficiency over the 2% EUV band will be somewhat reduced.

With 2nd-order blazing, the Figure 4 illustration remains applicable with the grating dimensions doubled and the two "1st-order" labels replaced by "2nd-order". The 2nd-order light cone at 27-nm wavelength is sufficiently separated from the 2nd-order blaze wavelength, 13.5 nm. But the 1st order at 27 nm will be directly superimposed on the 13.5-nm 2nd order; thus this wavelength will not be eliminated in the IF-filtered spectrum. However, the 1st-order light cone at 54 nm (4 times 13.5 nm) will coincide with the 27-nm 2nd-order light cone, and this wavelength along with all higher wavelengths will be eliminated. In general, for a phase-Fresnel grating operating in the m-th diffraction order, the system will exclude all wavelengths greater than $2m\lambda_B$, where λ_B is the order-m blaze wavelength (13.5 nm).

With order-m blazing, the above efficiency formulas are modified as follows:

$$\eta = \mathrm{sinc}^2[m\pi(\lambda_B / \lambda - 1)] \approx 1 - \tfrac{1}{3}m^2\pi^2(\lambda_B / \lambda - 1)^2$$

The optical loss is increased by approximately a factor of m^2 relative to 1st-order blazing. For example, the loss at the 2% EUV band limits increases from 3.3×10^{-4} for 1st-order blazing to 1.3×10^{-3} with 2nd-order blazing. This is still insignificant, and optical efficiency would not be a limitation in using a higher blaze order. Even with 10th-order blazing the efficiency loss would be less than 4%. (A 10th-order grating would exclude wavelengths greater than 270 nm.)

Power Recycling

The spectral filtering system can be adapted for power recycling by constructing the IF aperture as a small, annular retroreflecting mirror ("retro mirror"), which returns the rejected IR radiation to the plasma; see Figure 5. (The reflector could be a high-efficiency multilayer dielectric coating, which is optimized to reflect 10.6-μm radiation and can withstand high radiation flux levels.) Also, large spherical-shell retro mirrors can be arrayed around the plasma to salvage the uncollected IR radiation. (The flux levels on these elements would not be very high, so they could probably be comparatively simple metal-film reflectors.) The retro mirrors create a kind of optical "echo chamber", which has the effect of amplifying the IR drive laser.

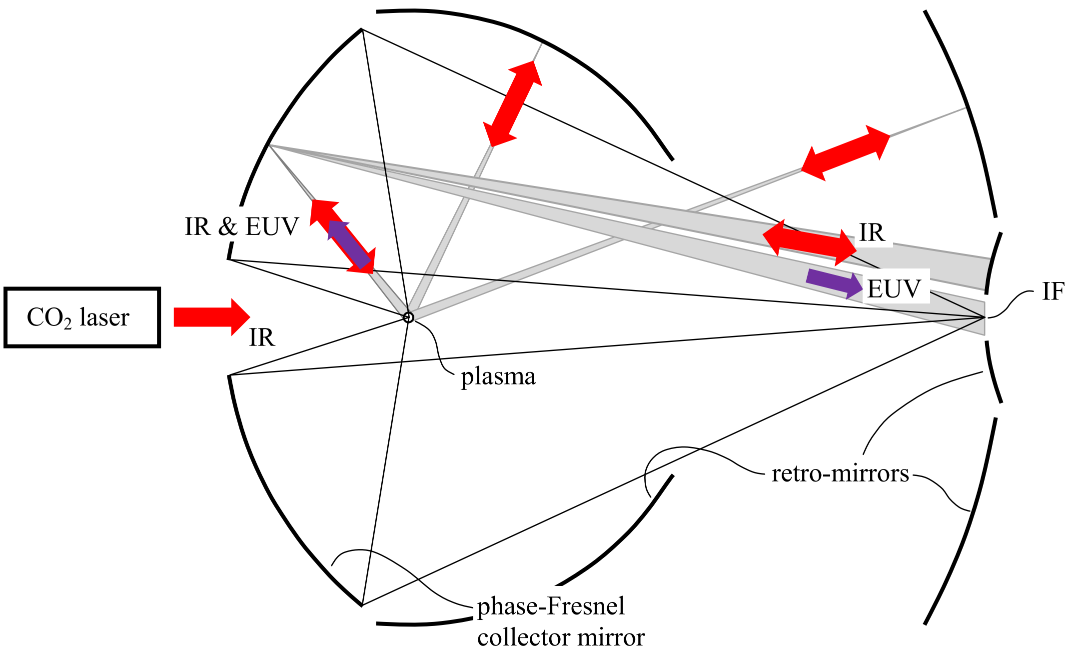

Figure 5. IR power recycling.

Power recycling would add some complication to the optical design because the collector's condenser mirror would need to operate in conjunction with the IF retro mirror as an IR imaging device, which images the plasma back onto itself. The optical construction geometry is illustrated in Figure 6.

The optics are designed to recycle IR radiation intercepting the collector mirror between minimum and maximum aperture radii $R_{\min}$ and $R_{\max}$, respectively. (These radii may or may not coincide with annular mirror aperture limits, but the mirror is only designed to recycle radiation within these limits.) The portion of the collector mirror within this radius range is ellipsoidal, and it images IR (10.6-μm) rays from the plasma center onto a conjugate axial point P on the line through the plasma center and the IF. (Point P can be on either side of the IF.) The retro mirror is a spherical surface centered at P, and it has an annular aperture. EUV (13.5-nm) rays are diffractively focused to the axial IF point at the center of the annular aperture.

The specularly reflected IR light cone and diffracted EUV light cone from an inner aperture point at radius $R_{\min}$ must have an angular separation of at least 1 mrad between the cone axes, as described above, to avoid any overlap between the cones (Figure 6; cf. Figure 4). For other aperture points the angular separation is larger in approximate proportion to the point's radial distance from the optical axis. Thus, for an outer aperture point at radius $R_{\max}$ the IR and EUV ray separation angle is approximately $(1\ \text{mrad}) \times R_{\max} / R_{\min}$ or greater. For example, with

$R_{max} / R_{min} = 5$ the separation angle would be at least 5 mrad; the grating blaze angle would be at least 2.5 mrad; and the grating period would be less than 4 μm (for 1st-order blazing, or $4m$ μm for order-m blazing). In general, with power recycling the grating blaze angle and line density at the mirror periphery may need to increase by approximately a factor of R_{max} / R_{min} relative to what would be required to just separate the IR and EUV.

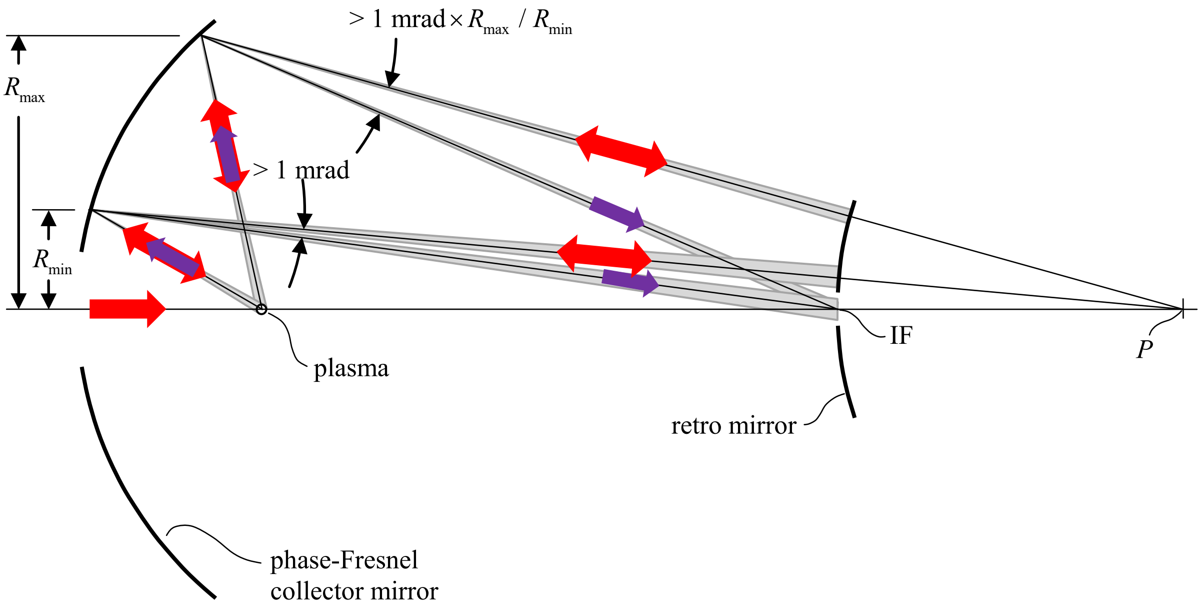

Figure 6. Collector geometry for IR power recycling.

<u>Grating Manufacture</u>

The phase-Fresnel grating can be fabricated by the method used by Kriese et al. [Ref. 7], i.e., single-point diamond turning on a nickel-plated substrate followed by application of a smoothing layer to remove the diamond machining marks. Feigl et al. [Ref. 8] formed complex grating structures by ion etching into a polished nickel mirror. Phase-Fresnel gratings could similarly be formed by an "ion turning" process analogous to diamond turning but using a focused ion beam in place of the diamond cutter.

The linear-profile, sawtooth form of phase Fresnel facets can be approximated by a multi-level, stepped profile, which can be fabricated by ion-beam (or e-beam) patterning of a multilayer film with embedded etch stops. [Ref 15] The last patterning step selectively etches the structure down to the etch-stop layers, so the grating profile can be controlled to atomic-scale dimensions if a deposition process such as magnetron sputtering or atomic layer deposition is used.

Conclusion

Phase-Fresnel grating structures formed on EUV collector mirrors can be used to efficiently eliminate out-of-band LPP radiation over the full IR-to-VUV spectrum without significantly compromising EUV collection efficiency. The rejected or uncollected IR power can potentially be recycled back to the plasma via retroreflection to improve EUV conversion efficiency.

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