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# Polarizing optics for the soft x-ray regime: Whispering-gallery mirrors and multilayer beamsplitters

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## Abstract

Two short-wavelength optical components are described. The first, the whispering-gallery mirror, uses many glancing-incidence reflections to deflect a beam through a large net angle. Because the Fresnel coefficient for each reflection depends upon the state of polarization, the whispering-gallery mirror can act both as a polarizer and as a birefringent element. The second, the multilayer polarizing beamsplitter, is a Brewster-angle reflector thin enough to allow partial partial transmission of the incident beam. Its behavior can be surprising; in some cases the same polarization mode is preferred on both reflection and transmission.

## Introduction

In spite of its potential usefulness, the phenomenon of polarization has yet to be widely exploited at wavelengths in the soft x-ray or extreme ultraviolet range. This situation is due partly to the scarcity of sources for polarized radiation, and partly to the general difficulty of doing optics at these wavelengths.

In the present paper we describe two optical components that have an effect on polarization: the whispering-gallery mirror (WGM) and the multilayer polarizing beamsplitter. Our original interest in them arose in the particular context of x-ray laser cavities[1]. The devices themselves, however, should have much broader applicability.

## Whispering-Gallery Mirrors

### *Introduction to WGM's*

A whispering-gallery mirror is an optical structure which, by means of a series of glancing angle reflections from a concave surface, can deflect light through a large total angle. The WGM has been proposed for various applications in the extreme ultraviolet and soft X-ray regimes, most notably for use in laser cavities and for steering synchrotron radiation[2-4]. As an alternative to multilayer technology, WGM's offer comparable ideal reflectivities. They also have some potential advantages, one example being their far greater bandwidth.

The surface a WGM would ideally be composed of a lossless dielectric material having a refractive index smaller than unity. Then, so long as the glancing-angle reflections all occurred at angles below the critical angle, the beam would be totally reflected at each bounce; this would give a WGM of perfect reflectivity. Although at the wavelengths of interest most materials do in fact have a refractive index smaller than unity, they are inevitably absorptive. As a result, the beam loses a small fraction of its power at each bounce.

The effects of a WGM upon polarization result from the fact that the Frensel reflection coefficients depend on the state of polarization. Although the reflection coefficients are both nearly equal to $-1$ at grazing incidence, it turns out that the small difference between the TE and TM cases leads to a substantial effect when accumulated over many bounces. In this respect, whispering-gallery optics is very different from conventional grazing-incidence optics, in which only a few reflections are typically involved and for which polarization issues can generally be ignored[5]. By contrast, WGM's are both slightly dichroic and significantly birefringent.

Letting $\varepsilon$ denote the complex dielectric constant of the surface (relative to vacuum), the Fresnel coefficients for reflection at a small grazing angle $\theta$ are approximately

$$R_1(\mathrm{TE}) = -\left[1 - 2\theta\frac{1}{\sqrt{\varepsilon - 1}}\right] \quad \text{and} \quad R_1(\mathrm{TM}) = -\left[1 - 2\theta\frac{\varepsilon}{\sqrt{\varepsilon - 1}}\right]. \tag{1}$$

The subscripts "1" are used simply to emphasize that these are reflection coefficients for a single bounce, rather than for the total trip through the WGM.





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*WGM's as polarizers*

The polarizing action of a WGM derives from the difference in the magnitudes of these Fresnel coefficients. The single-bounce reflectivities, which relate the reflected and incident intensities, are given by $r_1 = |R_1|^2$; for small grazing angles $\theta$ these become, in light of (1),

$$r_1(\mathrm{TE}) = 1 - 4\theta\,\mathrm{Re}\{1/\sqrt{\varepsilon - 1}\} \quad \text{and} \quad r_1(\mathrm{TM}) = 1 - 4\theta\,\mathrm{Re}\{\varepsilon/\sqrt{\varepsilon - 1}\}. \tag{2}$$

The total reflectivity for a path through the whispering-gallery mirror is given by the product of the individual reflectivities for each bounce. We assume that the beam follows a planar path, along which it is deflected through a sequence of small deflections at grazing angles $\theta_1, \theta_2, \ldots, \theta_n$ to yield a total deflection of $\psi = 2\theta_1 + 2\theta_2 + \cdots + 2\theta_n$. The net reflectivity is then given by

$$r(\mathrm{TE}) = \exp\left[-2\psi\,\mathrm{Re}\left\{1/\sqrt{\varepsilon - 1}\right\}\right] \quad \text{or} \quad r(\mathrm{TM}) = \exp\left[-2\psi\,\mathrm{Re}\left\{\varepsilon/\sqrt{\varepsilon - 1}\right\}\right]$$

Notice that this depends neither upon the mirror's radius, nor its shape, nor the number of bounces, but instead upon only the total deflection angle and the mirror dielectric constant. A simple argument to explain this perhaps counter-intuitive result is as follows: the loss experienced at each bounce — as expressed in decibels, for example — is proportional to the glancing angle, and hence the accumulated loss is in turn proportional to the total angle of deflection.

It follows from (2) that the TE mode generally experiences a smaller loss at each bounce than does the TM mode, for

$$r_1(\mathrm{TE}) - r_1(\mathrm{TM}) = 4\theta\,\mathrm{Re}\{\sqrt{\varepsilon - 1}\} \geq 0,$$

with equality holding only in the lossless case. After deflection through a total angle $\psi$, an initially unpolarized beam will be polarized by an extent

$$P = \frac{r(\mathrm{TE}) - r(\mathrm{TM})}{r(\mathrm{TE}) + r(\mathrm{TM})} = \tanh[\psi\,\mathrm{Re}\{\sqrt{\varepsilon - 1}\}]$$

Figure 1 shows the reflectivities and the polarization for a particular example, a WGM having a rhodium surface[6]. Unfortunately, good reflectivity and high polarization are not reached at the same wavelengths.

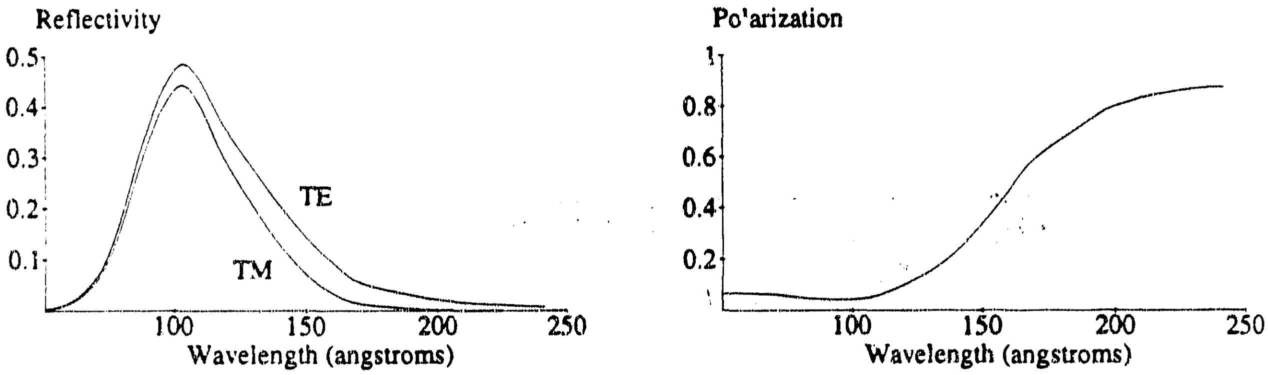


Figure 1. Polarizing effect of a rhodium whispering-gallery mirror. The net deflection angle $\psi$ is 180°.

*WGM's as birefringent elements*

The WGM is birefringent, for not only do the magnitudes of the Fresnel coefficients differ for the two polarizations, so do the phases. Both phases are nearly 180°, but again it is the differential that matters. In the limit of small grazing angles, the phases are given by

$$\arg[R_1(\mathrm{TE})] = 2\theta\,\mathrm{Im}\{1/\sqrt{\varepsilon - 1}\} \quad \text{and} \quad \arg[R_1(\mathrm{TE})] = 2\theta\,\mathrm{Im}\{\varepsilon/\sqrt{\varepsilon - 1}\}.$$

The net birefringence $\Delta\phi$, *i.e.* the phase difference accumulated as the WGM deflects the beam through a net angle $\psi$, is therefore

$$\Delta\phi = \psi\,\mathrm{Im}\{\sqrt{\varepsilon - 1}\}.$$

Returning to our rhodium example, at the reflectivity peak near 111 angstroms, the factor $\mathrm{Im}\{\sqrt{\varepsilon - 1}\}$ turns out to be roughly 0.26. This means that a deflection of just under 360° would be required in order to yield a quarter-wave of birefringence.

## Multilayer Polarizing Beamsplitters

Reflective polarizers based upon multilayer technology have been suggested by Lee[7,8] and demonstrated by Khandar, Dhez, *et. al.*[9-12]. The principle behind their operation is to exploit reflection at Brewster's angle in order to suppress the TM mode, while using an appropriately designed multilayer structure to provide good reflectivity for the TE mode. Recall that the Brewster angle may be characterized as that angle of incidence for which the reflected and transmitted beams are orthogonal; because materials have little refractive effect at the wavelengths of interest here, the Brewster angle is close to 45 degrees.

Although conventional multilayer mirrors are completely opaque, Hawryluk *et. al.*[13,14] have constructed normal-incidence beamsplitters for use as laser cavity output couplers. These devices are multilayer mirrors thin enough to allow partial transmission of an incident beam. This same idea could be applied to the 45°-incidence reflector to produce a polarizing beamsplitter.

The behavior of such a such a polarizing beamsplitter can be surprising. Experience with visible-light optics would lead one to expect this device to preferentially reflect the TE mode while preferentially passing the TM mode. In some cases, however, the behavior is different: the TE mode is preferred in both reflection and transmission.

As an explicit example, we considered a Mo/Si polarizing beamsplitter optimized for use at 194 angstroms. The design consisted of 6 Mo layers 113 angstroms thick alternating with 5 Si layers 31 angstroms thick. The dielectric constant of Mo at the design wavelength was assumed to be $\varepsilon(\mathrm{Mo}) = 0.8115 + 0.1732\,i$ and that of Si to be $\varepsilon(\mathrm{Si}) = 0.9611 + 0.007112\,i$. The resulting reflectivities and transmissivities are shown in Figure 2 as functions of the angle at which the incident beam strikes the mirror. Also shown are the extent to which the reflected and transmitted beams become polarized. Ignored here were the effects of overcoat layers, *e.g.* carbon, and any substrate, *e.g.* the silicon nitride used by Hawryluk *et. al.*[13,14].

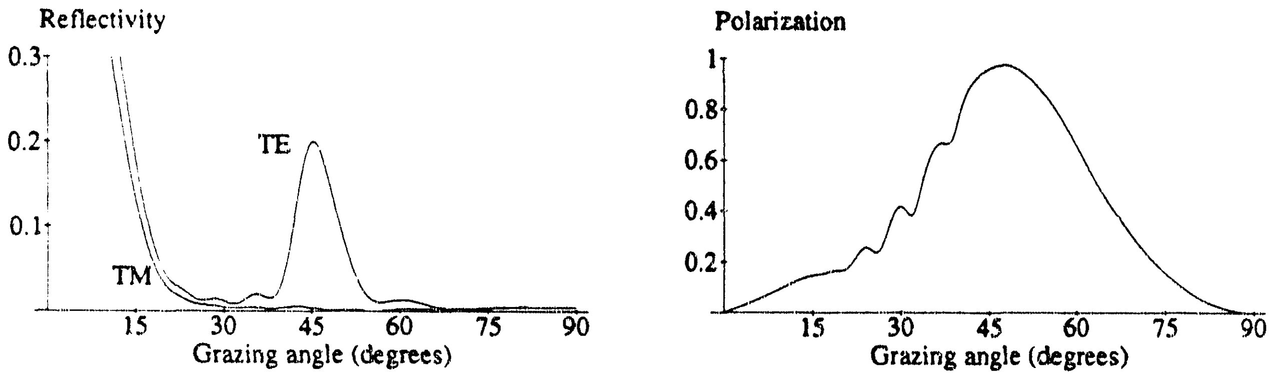


**Figure 2a.** Multilayer beamsplitter as a reflective polarizer

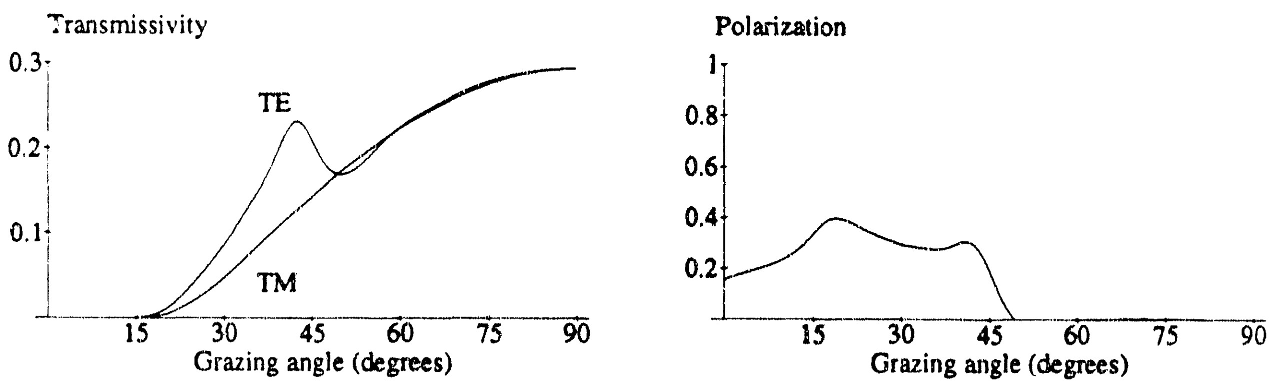


**Figure 2b.** Multilayer beamsplitter as a transmissive polarizer

At the intended grazing angle of 45°, the resulting TE reflectivity is 20.9% and the TE transmissivity 19.2%, while the TM reflectivity is 0.457% and the TM transmissivity 12.7%. For an unpolarized incident beam, the reflected beam would be TE polarized by 96% and the transmitted beam TE polarized by a more modest 19%. Another way of way of saying this is that the TM mode is suppressed by 16.6 dB on reflection and 1.8 dB on transmission. Presumably this anomalous behavior is a general feature of multilayer polarizing beamsplitters made of any sufficiently lossy materials, but the author is unable to offer a physical explanation. With the wavelengths and materials originally considered by Lee[7,8], where the refractive indices are closer to unity and the absorptions smaller than those here, the phenomenon does not occur; there the TE mode is preferred on reflection and the TM on transmission.

## Conclusion

In summary, we have described two short-wavelength optical components suitable for manipulating polarization. The whispering-gallery mirror was seen to act both as a weak polarizer and, more effectiviely, as a birefringent element. The multilayer polarizing beamsplitter was found in certain cases to behave anomalously, with the same polarization being preferred on both reflection and transmission.


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## References


1. John Paul Braud, "Laser cavities and polarization optics for soft x-rays and the extreme ultraviolet," *Appl. Phys. B*, vol. 50, pp. 205--212, 1990.

2. J. Bremer and L. Kaihola, "An x-ray resonator based on successive reflections of a surface wave," *Appl. Phys. Lett.*, vol. 37, no. 4, pp. 360--362, 15 August 1980.

3. A. V. Vinogradov, N. A. Konoplev, and A. V. Popov, "Broad-band mirrors for vacuum ultraviolet and soft x-ray radiation," *Sov. Phys. Dokl.*, vol. 27, no. 9, pp. 741,742, September 1982.

4. John Paul Braud and Peter L. Hagelstein, "Whispering-gallery laser resonators --- Part I: Diffraction of whispering-gallery modes," *IEEE J. Quantum Electron.*, April 1991.

5. Alan G. Michette, *Optical Systems for Soft X-rays*, pp. 37--44, Plenum, New York, 1986.

6. Peter L Hagelstein and T.-Y. Hung, private communication.

7. Ping Lee, "Multilayer mirrors and beamsplitters for soft x-rays," *Opt. Comm.*, vol. 43, no. 4, pp. 237--241, 15 October 1982.

8. Ping Lee, Roger Bartlett, and Don R. Kania, "Soft x-ray optics using multilayer mirrors," *Opt. Eng.*, vol. 24, no. 1, pp. 197--201, January/February 1985.

9. A. Khandar and P. Dhez, "Multilayers x-ray polarizers," *Applications of Thin-film Multilayered Structures to Figured X-ray Optics*, Gerald F. Marshall, editor, Proc. SPIE 563, pp. 158--163, 1985.

10. A. Khandar, P. Dhez, and M. Berland "Study of multilayered x-ray polarizers...," *Multilayer Structures and Laboratory X-ray Laser Research*, Natale M. Ceglio, Pierre Dhez, editors, Proc. SPIE 688, pp. 176--183, 1986.

11. P. Dhez, "Polarizers and polarimeters in the x-uv range," *Nuclear Instruments and Methods in Physics Research*, vol. A261, nos. 1,2, pp. 66--71, 1 November 1987.

12. E. S. Gluskin *et. al.*, "A polarimeter for soft x-ray and vuv radiation," *Nucl. Instr. and Meth. in Phys. Res.*, vol. A246, pp. 394--396, 1986.

13. Andrew M. Hawryluk *et. al.*, "Soft x-ray beamsplitters and highly dispersive multilayer mirrors...," *Multilayer Structures and Laboratory X-ray Laser Research*, Natale M. Ceglio, Pierre Dhez, editors, Proc. SPIE 688, pp. 81--90, 1986.

14. Andrew M. Hawryluk, Natale M. Ceglio, and Daniel G. Stearns, "Applications of microfabrication technology to x-ray laser cavities," *J. Vac. Sci. Technol. B*, vol. 6, no. 6, pp. 2153--2157, November/December 1988.

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