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WHISPER GALLERY MIRRORS REFLECTIVITIES FROM 100 Å TO 500 Å

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ABSTRACT

We have examined optical constants and predicted reflectivities of candidate surface coatings for whisper gallery mirrors in the extreme ultraviolet (100 Å to 500 Å). Previous work of Vinogradov and coworkers have identified the spectral regime near 100-150 Å as particularly promising due to the high whisper gallery mirror reflectivities of the noble metals in the vicinity of their Cooper minima in this regime. We confirm this basic result using newer optical data, and we have sought surface materials which would extend the range over which the whisper gallery mirrors may be used: between 100 to 500 Å. We find that substantial whisper gallery mirror reflectivities (near or greater than 50%) are predicted for a varity of elements, and that the TE peak reflection is larger than TM peak reflection by on the order of 10%. However, most of the elements which do reflect well have surfaces that are vulnerable to oxygen contamination, which seroiusly degrades mirror performance. A cryogenic mirror design using a dynamic solid rare gas surface which has the potential to defeat such surface contominations is described; it has peak reflectivity of more than 50% centered near 280 Å.

Introduction

We report here the whisper gallery mirror reflectivities for wavelengths range from 100 Å to 500 Å. Whisper gallery mirrors are concave mirrors which reflect beam through a large turning angle (Figure 1). The term, whisper gallery, was first used by Lord Rayleigh([1]-[3]) to describe how high frequency acoustic fields,such as a birdcall, travel around the dome St. Paul's cathedral.

A soft x-ray whisper gallery mirror was first proposed by Bremer and Kaihola([4]), and has been developed to some extent by Vinogradov and coworkers([5]-[6]). They pointed out that noble metals work well near 100 Å.

We are interested in developing soft x-ray cavities in 200-300 Å regime because of our efforts to develop a tablatop EUV laser (Figure 2). Therefore, we would like to explore how whisper gallery mirrors work above 100 Å.

We have surveyed essentially all elements (92) as possible candidates for the whisper gallery mirrors. We found that low photoabsorption alone does not give a high reflective WGM surface; the element usually has to have a moderately high atomic density. In addition, high reflectivity occurs near the Cooper minima. Essentially, no reasonable (nonoxidizing) solid surface at room temperature gives good WGM reflectivity above 150 Å.

Theory

The reflection coefficients of the whisper gallery mirrors, assuming that there is an infinite number of bounces and that the beam approaches the mirror surface at shallow angle, depend on the complex dielectric constant through

$$R^{TE} = \exp(-2\psi \,\mathrm{Re}\frac{1}{\sqrt{\epsilon-1}}) \qquad (II.1)$$

$$R^{TM} = \exp(-2\psi \,\mathrm{Re}\frac{\epsilon}{\sqrt{\epsilon-1}}) \qquad (II.2)$$

as is well known.

These formulas are derived for spherical or cylindrical whisper gallery mirror geometries.

Noble Metals

Between 100 Å and 130 Å, the noble metals: Mo, Ru, Rh, Pd, and Ag gives the largest predicted WGM reflectivities. This was pointed out by Vinogradov([7]). Here we recalculated the reflectivities using the updated data of Henke([10]). We also based our experimental data on Windt's measurements([11],[12]).

The highest predicted reflectivity for WGM's with these coatings in the present work is for molybdenum, as is shown in Figure 3.

We shall not discuss the accuracy of the optical constants of Henke's data here. We did use the Kramers-Kronig relations to estimate ϵ_r's (and hence f1's) and they are in excellent agreement with the results plotted in the Berkeley report, but not included in the data base.

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Rare Gases

There are a lot of elements with low photoabsorption between 200 Å and 400 Å. However, most of them tend to oxidize easily and give low WGM reflectivities in practice.

Rare gases, such as argon and krypton, are predicted to give high WGM reflectivity. Argon is predicted to reflect strongly near 290 Å (Figure 4). The data are based on the experimental photoabsorptin cross section measured by Schreiher and Keitel([13]) and also by Samson([14]). Krypton, on the other hand, is predicted to have a peak reflectivity of about 40% at 194 Å at the position which we believe the principal gain in nickel-like Mo should occur. Other rare gases (He, Ne, Xe, and Rn) give very low reflectivity in this region.

It is difficult to prepare solid rare gas surface and we propose an approach below.

Other Elements

Other elements which are predicted to give high WGM reflectivities are plotted in Figure 5-7. We note here that the LANL experimental effort focussed on a mirror composed of a discrete number of flat aluminum glancing angle mirrors([15]-[17]), which is closely related to the WGM work of interest here.

Cryogenic Whisper Gallery Mirrors

We propose here to work with a dynamic surface for the rare gases. If the surface temperature is raised, then sublimation will occur at a higher rate until an equilibrium is established wherein sublimation is balanced by condensation. This condition is characterized by a vapor pressure, which for argon is given very approximately by ([18])

$$P_{sub} = P_0 e^{-\Delta E/kT} \qquad (VI.1)$$

where the parameters P0 and ΔE are given by 4.17X10^7 torr and 0.0815eV, respectively.

As an example, if the ambient argon density were designed to be 5X10^{13} atoms/cm^3, then the corresponding photoabsorptin loss would be less than 1% at 290 Å for a 1 meter path length. In this case the pressure would be about 2x10^{-4} torr at 36K, which is the temperature corresponding to this value as a sublimation pressure. Under these conditions, the exchange between the surface and atmospher would be considernble, and as long as the atmospher were dominated by argon, the surface contamination should follow the atmospheric level and be small. For experimental purposed, it is advisable to work at the high end of the desirable temperatures.

Summary and Conclusions

We reported here the high reflective candidates for WGM's (Figure 8). Noble metals, as predicted by Vinogradov before give high reflectivities near 100 Å. Other nearby elements, due to the characteristic of the Cooper minima, also give moderately high reflectivities. Argon and krypton are predicted to reflect strongly between 200 Å and 300 Å. We proposed here a dynamical surface scheme to avoid the problem with oxidations. It might be possible to extend this scheme for solid surface working at high temperatures.

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Figure 1 Schematic of a ray path in a whisper gallery mirror.

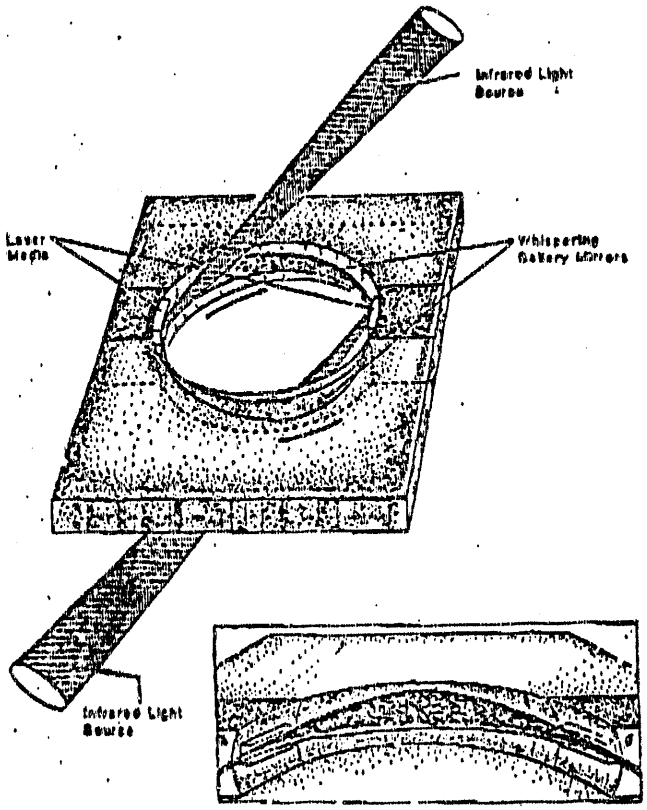

Figure 2 Simple whisper gallery EUV laser cavity. Two pieces of whisper gallery mirrors are joined by molybdenum gain media. The concave surface of the mirror is shown in the inset, where plasma is shown to focus at the two end points of the whisper gallery mirror.

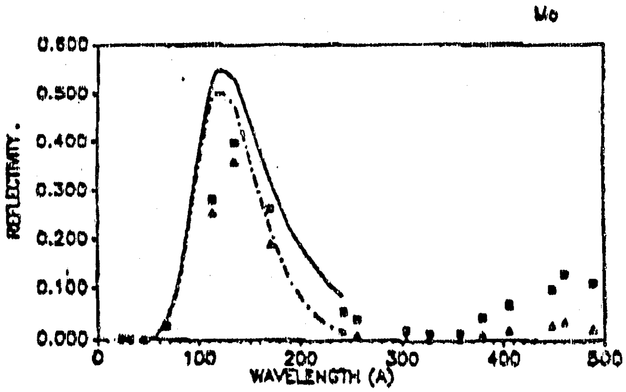

Figure 3 Whisper gallery mirror reflectivity of Mo for 180° turn: (—) TE reflectivity based on Henke's data, (-·-) TM reflectivity based on Henke's data, (⊓) TE reflectivity based on Windt's experimental data, (△) TM reflectivity based on Windt's data.

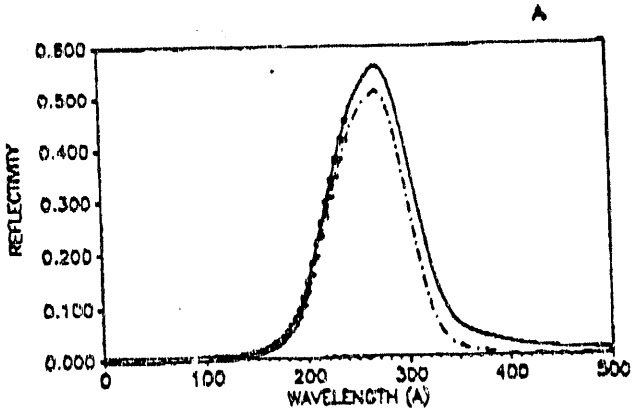

Figure 4 Whisper gallery mirror reflectivity of A for 180° tun: (—) TE reflectivity based on our manipulation of Henke's data using Kramers-Krönig, (···) TM reflectivity based on our manipulation of Henke's data, (◯) TE reflectivity based on Henke's data, (o) TM reflectivity based on Henke's data.

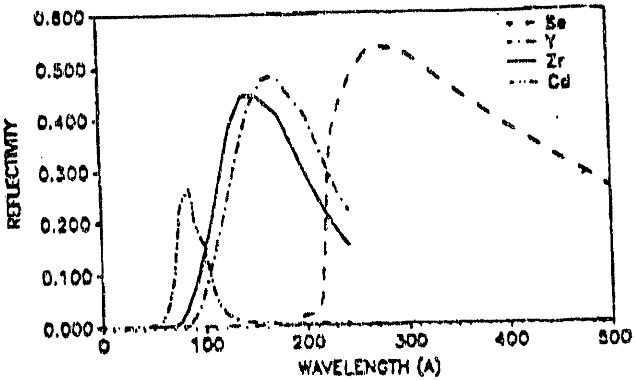

Figure 5 Whisper gallery mirror TE reflectivities of Se, Y, Zr, and Cd.

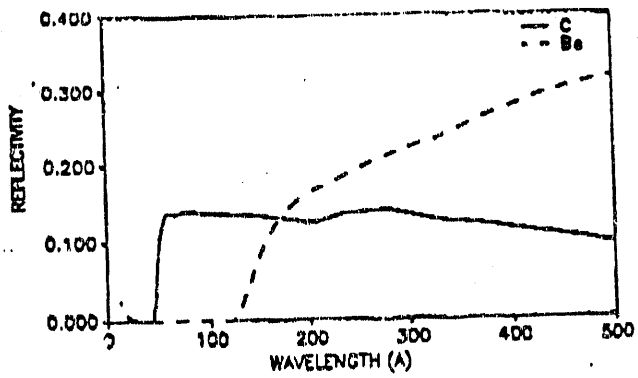

Figure 6 Whisper gallery mirror TE reflectivities of C and Be.

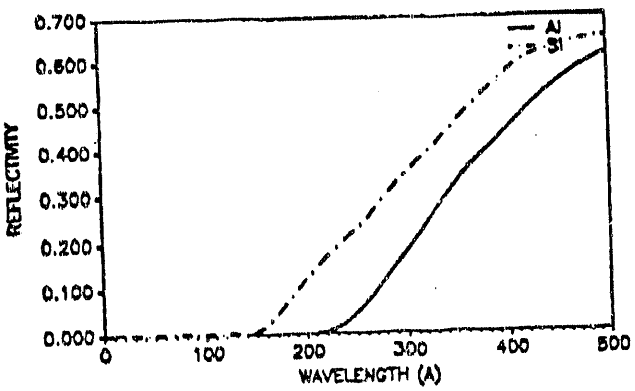

Figure 7 Whisper gallery mirror TE reflectivities of Al and Si.

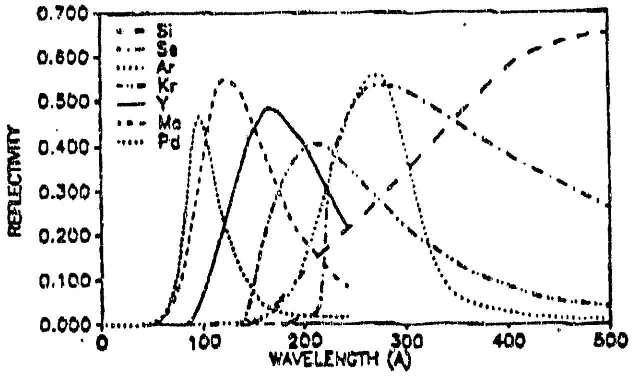

Figure 8 Whisper gallery mirror TE reflectivities of highly reflective coatings.

Investigations of Whisper Gallery Mirrors for Extreme Ultraviolet (EUV) and Soft X-Rays

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Abstract - We have examined optical constants and predicted reflectivities of candidate surface coatings for whisper gallery mirrors in the extreme ultraviolet. Previous work of Vinogradov and coworkers have identified the spectral regime near 100-150 Å as particularly promising due to the high WGM reflectivities of the noble metals in the vicinity of their Cooper minima in this regime. We confirm this basic result using newer EUV optical data, and we have sought candidate surface materials which would extend the range over which WGMs may be used to longer wavelengths.

We find that substantial WGM reflectivities are predicted for a variety of elements in the EUV, and that TE peak reflection is larger than TM peak reflection by on the order of 10%; however, most of the elements which do reflect well have surfaces which are vulnerable to oxygen contamination. Such contamination seriously degrades mirror performance. A cryogenic mirror design using a dynamic solid rare gas surface which has the potential to defeat such surface contamination is described.

I. Introduction

Whisper gallery mirrors are mirrors with concave surfaces which reflect acoustic or optical beams through a large total turning angle through a large number of successive glancing angle reflections; the concept is illustrated in Figure 1. Although the basic effect has been known since antiquity, a quantitative understanding of the effect was first achieved by Rayleigh [1]-[3].

An optical whisper gallery mirror would ideally be made from a lossless material having a refractive index smaller than unity. Light incident from a glancing angle will be reflected completely (total internal reflection, where internal in this case refers to the region inside of the mirror surface), and many such ideal reflections leads to a net deflection of the beam which is large angle and loss free. In practice, no surface is ever free from loss; losses accumulate on each successive reflection.

The use of whisper gallery mirrors for soft x-ray optics has been proposed recently [4]; and discussions of mirror surface materials [5]-[9], and surface figures [10]-[13] have been discussed. Our interest in whisper gallery mirrors is motivated by an interest in developing laser cavities (for example, see Figure 2) for use in the 200-300 Å regime, consistent with our experimental tabletop EUV laser effort at MIT [14]. The purpose of this paper, therefore, is to explore the possibilities of using whisper gallery mirrors for the spectral regime above 100 Å.

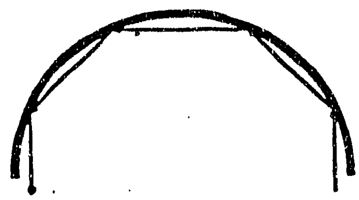

Figure 1: Schematic of a ray path in a whisper gallery mirror.

Vinogradov found that very high WGM reflectivities are expected in the vicinity of the Cooper minima of the noble metals which occur between 100-150 Å. The Cooper minimum itself is a minimum in the photoionization cross section due to a zero crossing of an outer shell dipole matrix element as it changes sign going from low energy to high energy [15]. Relatively high total reflectivity is obtained in this regime because the surface provides nearly total internal reflection with low loss at each glancing angle bounce. Based on this result, we expected that a survey of optical data at longer wavelengths would reveal high reflectivity essentially whenever low photoabsorption occured, and that we would be able to select highly reflec-

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