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Technical Progress Report

LASER PARTICLE ACCELERATOR PROGRAM

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Table of Contents

Section	Page
1 Overview	1-1
2 Summary of FY85 Results	2-1
2.1 Basic Laser System Requirements	2-1
2.2 Glancing Incidence Measurements	2-4
2.3 Demo Experiments Using IPFL Mechanism	2-13
Appendix A	A-1
1985 Boulder Damage Symposium Paper - "Glancing Incidence Absorption Measurements of Metal Mirrors"	

Section 1

OVERVIEW

1.1 INTRODUCTION/STATEMENT OF WORK

This document provides a summary progress report on the Laser Particle Accelerator Program at Spectra Technology, Inc. This year's efforts have been broken into two phases. The first is an experimental measurement task to determine the scaling of glancing incidence mirror damage thresholds with angle of incidence. The second is an analysis effort directed at determining laser requirements for laser particle accelerators.

In the first task, an experimental facility has been designed, fabricated, assembled and tested for the measurement of glancing incidence absorption using a sensitive photoacoustic technique. Further, this facility has successfully determined angle of incidence scaling for a number of base metal mirror materials such as aluminum, copper, gold and silver. In the second task, laser systems and a 100 MeV demonstration IPFL experiment have been evaluated; also, information exchange interfaces have been maintained in the form of meetings (January UCLA and HEPAP subpanel) and personal communications within the laser accelerator community.

Section 2, of this progress report, is a summary of these FY85 results. This section also formed a part of our FY86 proposal for continued laser/optics studies. In addition, we have included, in Appendix A, a paper presented by Wayne Kimura at the 1985 Boulder Damage Symposium entitled "Glancing Incidence Absorption Measurements of Metal Mirrors." This paper was very favorably received by workers in the field and will be expanded into a full journal article during this contract period.

Section 2

FY85 RESULTS

2.1 BASIC LASER SYSTEM REQUIREMENTS

The systems analysis carried out during this past year has shown that laser particle accelerators (LPAs) can be grouped according to fundamental physical characteristics associated with the accelerator mechanisms. These features can be consolidated in a figure of merit called the coupling coefficient, which is the ratio of the accelerating field to the electric field of the laser beam. The assumption of desired properties in the accelerator can be reflected immediately as laser requirements. Specifically, the laser energy per pulse can be fixed by the increment in electron energy desired in each stage of the accelerator and by the number of electrons per bunch to be accelerated. The laser repetition rate is specified by such test parameters as the luminosity of the colliding electron bunches issuing from the accelerator and by the physical dimensions of each bunch. Finally, the pulse length of the laser is determined by the acceleration gradient (which connects the laser energy per pulse to the laser intensity), the diameter of the laser beam in the interaction region, and the strength of the coupling coefficient. These parameters are summarized in Figure 2-1 for the case of a 5 TeV electron bunch, 2.5×10^9 particles per bunch, with a luminosity of $10^{34} \text{ cm}^{-2} \times \text{sec}^{-1}$ and an acceleration gradient of 1 GeV/m.

These laser requirements can be translated directly into the number of lasers required once laser pulse length and the coupling coefficient are known. The basic relation between number of lasers and the coupling coefficient stems from the acceleration gradient desired and the energy per pulse. Once these parameters have been fixed, for example from technology considerations, then the number of stages can be derived by knowing the coupling coefficient. Figure 2-2 shows sample calculations for weak and strong coupling coefficients. This data has been used to justify the

Figure 2-1. Laser Requirements Fixed By Accelerator Parameters

CONDITIONS

$\frac{dP}{dz} = 1 \text{ GeV/m}$
 $L_{acc} = \frac{5 \text{ TeV}}{1 \text{ GeV/m}} = 5 \text{ km}$

$E_L(\text{TOTAL}) = 2000 \text{ J}$
 $A = 10^{-2} \text{ cm}^2$

	$E_L(\text{J})$	$\tau_p(\text{ps})$	N_L
$q_c = 10^{-3}$ Weak Coupling*	2000	1	1
$q_c = 10^{-1}$ Strong Coupling†	200 20 2	10^3 10^2 10	10 100 1000

* Weak Coupling Requires Full Laser Energy Transport

† Strong Coupling Utilizes Multiple Stages

Figure 2-2. Required Number of Lasers vs. Pulse Length

classification of LPA concepts into monolithic and staged types of accelerators.

Because the average optical power resulting from such requirements is generally high (i.e., 20 MW for the 5 TeV case of Figure 2-1), the efficiency of the laser component is highlighted as a critical issue and with it the cost of the laser facility. Modern lasers suitable for an LPA are 10 to 15% efficient; that is, approximately 200 MW of raw electric power will have to be supplied under these circumstances. Therefore, the costs of that type of facility can be on the order of \$100 million, just from the viewpoint of installed electric power, while the laser component itself may cost as much as \$1000/Watt. The technical issues for laser drivers can be summarized as:

- o wall plug efficiency
- o pulse extraction format
- o achievable rep rate
- o picosecond pulse lengths
- o interface between lasers and accelerator structure
- o phase matching between stages
- o laser system cost

2.2 GLANCING INCIDENCE MEASUREMENTS

As can be seen from the previous discussion, lasers for use in laser particle accelerator (LPA) applications will need to have high average power in order to provide high particle luminosity. The laser beam also will need to be focused to a small diameter to enable optimum coupling with the small diameter electron beam and, in monolithic laser particle accelerators, the laser beam must be transported over long distances (of order 1 km). These requirements point strongly to the need to use glancing incidence mirrors in the laser system. In addition, some accelerator schemes, such as the inverse Cerenkov method, inherently need to cross the electron and laser beams at very small angles; in these geometries, the need for glancing incidence mirrors is quite clear.

There is a surprising lack of experimental verification of glancing incidence mirror performance. Some work has been done at 10.6 μm and 1.06 μm ,^(1,2) but none at angles of incidence $>80^\circ$ (measured from the normal). Work has also primarily dealt with actual physical damage of the optics and, therefore, does not provide quantitative information on the absorption of the laser energy at the mirror surface. This information is important because deformation of the mirror surface caused by laser heating will tend to occur before the mirror is actually damaged. Absorptivity must be in the range of 0.1 percent or better for high power systems.

The aim of the existing glancing incidence measurement program at STI is essentially two-fold. The first objective is to measure the thermal absorption coefficients of selected mirrors at angles of incidence from 0° to as close to 90° as possible. These measurements are for light polarized either perpendicular or parallel to the plane of incidence (s or p-polarization, respectively), and for laser wavelengths at 0.5 μm and 10.6 μm . As will be described in more detail later, optics tested are primarily bare metal mirrors; a few have protective dielectric overcoats. The second objective is to compare the absorption data with the theoretical absorption as predicted by the Fresnel equations. To do this, values of the index of refraction for the mirror type, as measured by other sources, are substituted into the Fresnel equations.

To summarize our accomplishments thus far in the program, the absorption characteristics from 0° to $>89^\circ$ have been measured at 0.5145 μm for bare Cu, Mo, Au, Ag, Al, and overcoated Ag and Al mirrors. Work is currently in progress to repeat these measurements at 10.6 μm .

The results indicate that new, "clean" bare metal mirrors appear to follow the Fresnel equations very well at all angles. We have demonstrated the 0.1 percent absorption appropriate for high power systems. Used, less "pristine" bare metal mirrors tend to have higher absorptance, which becomes worse at glancing angles of incidence. Finally, metal mirrors that have a thin protective dielectric overcoat on their reflective surface can deviate

greatly in their absorption characteristics from that predicted by the Fresnel equations. This implies that bare metal theory is not always applicable to overcoated metal mirrors. It also should be noted that these overcoats are not the same as multi-layer dielectric coatings.

Description of Experimental Apparatus

Photoacoustic calorimetry is used to measure the very small absorptance expected at glancing incidence. The basic technique is well established,⁽³⁾ a modified version, first pioneered by Nordvik and Schlossberg in 1977,^(4,5) is being used in this experiment. Essentially, the modified version consists of attaching the acoustic transducer directly onto the mirror rather than on a test chamber wall. The transducer then senses directly the acoustic waves generated by the mirror rather than indirectly through the gas in the chamber. This modification greatly enhances the sensitivity of the technique; absorption coefficients (absorbed light/incident light) of 10^{-4} to 10^{-5} are detectable.

Figure 2-3 is a schematic of the glancing incidence measurement system. To investigate two different wavelengths, two different cw lasers are used: an argon ion laser ($0.5145 \mu\text{m}$) and a CO_2 laser ($10.6 \mu\text{m}$). Both lasers are vertically polarized. The output from the lasers is sent through a chopper, a collimating telescope, a half-wave plate to rotate the polarization, and a "clean-up" polarizer that rejects all light not rotated by the half-wave plate. The laser light then reflects off the test mirror mounted on a rotation stage. Attached to the back of the mirror is a piezoelectric transducer. A phase sensitive lock-in amplifier measures the piezoelectric transducer output, which may be as low as 10-100 nV at glancing angles.

Experimental Results to Date

The glancing incidence measurements at $0.5145 \mu\text{m}$ are completed. Data analysis of the measurements is still in progress; a brief review of the

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Figure 2-3. Schematic of Glancing Incidence Measuring System

results accumulated thus far is presented in this section. All results shown are for $0.5145 \mu\text{m}$.

Figure 2-4 shows the absorptance dependence for a bare copper mirror; at $0.5 \mu\text{m}$, the absorptance is expected to be high for both polarizations. Error bars on the data points represent the reproducibility of the measurement process. The highest angle of incidence measured is 89° . The absolute value of the absorptance is uncertain by approximately $\pm 1-2$ percent. We see that for the parallel polarization, there is the expected slightly higher absorptance at an angle corresponding to Brewster's angle. Also plotted as the solid curves in Figure 2-4 are the theoretical absorptance curves derived from Fresnel's equations in which the values of n and k given by Robusto⁽⁶⁾ are used. We see there is some disagreement in absolute magnitude and fair agreement in regards to the overall shape of the theoretical curves and the data. Even better agreement has been obtained for bare molybdenum mirrors and bare gold mirrors.

Up to this point, the results presented have been for metal mirrors in which the absorption is fairly high at $0.5 \mu\text{m}$ for normal incidence. Of more interest is the glancing incidence characteristic of mirrors that have high reflectivity at normal incidence and very high reflectivity at glancing incidence. For example, bare silver should have one of the highest reflectivities at $0.5 \mu\text{m}$. The problem with unprotected silver is that Ag_2S quickly forms on its surface once exposed to room air, which drastically reduces its reflectance. In order to test bare untarnished silver, the freshly coated silver mirror (and aluminum mirror) were sealed at the coating vendor's facilities in a specially made, leak-tight container. When the mirrors (both the silver and the aluminum) were tested, they were enclosed in a glove bag that was purged with dry nitrogen so that very little, if any, tarnishing to the mirror occurred during the measurement process.

The results for the bare silver case are shown in Figure 2-5 along with the theoretical curve using Weaver's⁽⁷⁾ data. This time the data indicates a lower absorptance than that predicted by Weaver. This is not unreasonable;

Figure 2-4. Absorbance Dependence for Bare Copper Mirror

Figure 2-5. Absorptance Dependence for Bare Silver Mirror

recall that the absolute magnitude of the absorptance curve can change dramatically depending on which source one uses for the values of n and k . Schulz's^(8,9) values of n and k produce curves which, at normal incidence, indicate an absorptance of approximately 2%. This is a factor of 4 different from that given by Weaver.

Although there may be disagreement on which values of n and k to use in Fresnel's equations, the bottom line in regards to the data is the absorption of the mirror tested. We see that at 89° absorptance for the s-polarization is less than 0.1%, a value appropriate for high power laser systems. In regard to the overall curve shapes, the agreement with theory and data is excellent.

To prevent tarnishing of both silver and aluminum mirrors, a thin protective overcoat is typically applied over the mirror surface. This overcoat should not be confused with a multi-layer dielectric coating. Multi-layer dielectric coatings are typically many layers thick and are designed to have a high reflectivity at a certain angle of incidence. Protective overcoats are usually very thin (a fraction of visible wavelength) and applied with no concern for angle dependence in mind.

Figure 2-6 shows the absorptance results for a protected silver mirror. The mirror is overcoated with a layer of Th_4F approximately 1000 angstroms thick. We see there is still fair agreement with theory. Comparing the protected silver case, Figure 2-6, with the bare silver case, Figure 2-5, more subtle differences become more evident. The curve for the s-polarization in the protected silver case tends to have higher absorptance at glancing incidence than the bare silver mirror. The p-polarization for the protected silver case has higher absorption at Brewster's angle than both the theory and the bare silver data. This may be due to a "channeling" effect occurring between the overcoat and the metal surface, which tends to trap some of the laser light at the higher angles of incidence, causing higher absorption. This is only a hypothesis and has not been proven.

OVERCOATED WITH 1000 Å THICK LAYER OF ThF₄

$\lambda = 0.5145 \mu\text{m}$

Figure 2-6. Absorption Dependence for Protected Silver Mirror

The analysis of this disagreement is not complete yet. Bare metal theory may still be useful if the Fresnel equations are changed slightly. For example, instead of assuming an index of refraction of unity for the dielectric next to the metal surface, the index of refraction of the overcoated material can be used. This is still an approximation because the derivation of Fresnel's equations assumes the dielectric extends out to infinity which, of course, for the thin overcoats is not true. Work is continuing on analyzing this question further and on performing more analysis of the other data.

2.3 DEMO EXPERIMENTS USING IFEL MECHANISM

During the early phases of this year's program, an evaluation of demonstration experiments using the inverse free-electron laser (IFEL) concept was completed. Our goal was to determine what could be done with STI's existing FEL hardware that includes a 1 GW CO_2 laser and 2 meter wiggler. At the 1 GW level, the FEL mechanism requires an electron beam limited to the few MeV range in order to achieve acceptable gradients and energy gain; also, the wiggler must be gas loaded to do the phase matching properly at this low electron beam energy. Unfortunately, the gas loading introduces scattering that is quite severe, at these electron beam energies, and quickly destroys the resonance condition. The only alternative for a significant demonstration using the IFEL mechanism requires increasing the laser power available and using a conventional wiggler without gas loading.

This possibility has been considered in some detail and is keyed to the existing STI CO_2 laser used in our FEL program. This laser delivers ≈ 20 Joules in 20^5 nseconds, or about 1 GW. By increasing this power to the 10 GW level, we can add 10 MeV to a 20 MeV electron beam within a 1-meter interaction length. Existing wiggler magnets can be used in a new support frame to provide the correct wiggler wavelength as a function of position, and an amplifier unit could be added to the existing CO_2 laser train to achieve the 10 GW power levels.

An experiment of this kind is a demonstration using modest upgrades of existing hardware and a relatively well understood (low risk) acceleration mechanism as compared to the beat wave and grating LINAC schemes. Nevertheless, the cost of such an experiment is significant. For example, the large CO₂ laser amplifier (20-cm aperture) needed to reach 10 GW would cost ~\$300 K, and a remake of the wiggler might cost ~\$200 K, even with the surplus magnets. Then there is the cost of assembling the apparatus, interfacing with the accelerator, and carrying out the experiments. Our estimate for the cost of such a demonstration experiment is at least \$1.5 M, based on our previous FEL work at the Boeing 20-MeV accelerator.

In the following subsections, we review the technical factors that have led to these conclusions. We start with the concept of a gas-loaded FEL and then move on to the conventional wiggler concept.

The Gas-Loaded IFEL Demonstration

Gas loading of the wiggler is attractive because it lowers the laser power required to add a significant increment of energy to an electron beam. This can be seen from the gradient and resonance conditions for a conventional FEL.

$$\frac{d\gamma}{dz} \text{ (MeV/M)} = \frac{40 B_w(T) \lambda_w \text{ (cm)} I^{1/2} \text{ (GW/cm}^2\text{)}}{\gamma}$$

$$\gamma^2 = \frac{\lambda_w}{2 \lambda_L} \left[1 + .43 B_w^2(T) \lambda_w^2 \text{ (cm)} \right]$$

Here, a high gradient is achieved at relatively low laser power levels if γ is made small (~1 MeV). However, the resonance condition then demands the wiggler wavelength to be unacceptably small (~10⁻² cm). To avoid this problem, gas loading is added to the wiggler, which decouples γ and λ_w . The result is:

$$\eta - 1 = \frac{1 + [1 - 4 \beta_{\parallel} \lambda_L / \lambda_w]^{1/2}}{2 \beta_{\parallel}} - 1$$

where

$$\gamma_{\parallel}^2 = \frac{1}{1 - \beta_{\parallel}^2} = \frac{\gamma^2}{1 + .43 B_w^2 (T) \lambda_w^2 (cm)}$$

Unfortunately, for typical values ($B_w = 1$ T, $\lambda_w = 1$ cm, and $\lambda_L = 10$ microns) the gas pressure required for phase matching is large and causes severe scattering problems. Very low pressure schemes involving atomic resonance line phase shifts also were examined but found to be unsuitable. Consequently, an IPEL demonstration using existing low power lasers and gas loading to achieve high gradients is not feasible. As an alternative, we have considered a modest upgrade to the existing laser system at STI and taken a conventional wiggler (no gas loading) to determine what level of demonstration could be achieved.

Conventional IPEL Demo Experiment

Here we assume a 10 GW CO_2 laser is available and that a "tapered" wiggler will be constructed from existing permanent magnets. The first-cut design parameters were determined starting with the following given parameters:

Laser Power, P_L	10 GW
Laser Wavelength, λ_L	10.6 microns
Magnet Width, h	2.25 cm
Wiggler Length, L	100 cm
Rayleigh Range, Z_R	$L/2$

The wiggler gap size, g , was chosen to avoid unwanted optical beam truncation at the magnet ends.

$$g = 1.25 (\sqrt{2} \lambda \omega_0)$$

The magnetic field strength from these permanent magnets is related to their spacing in the wiggler and the wiggler gap.

$$B_w (T) = \frac{1.6}{\sqrt{2}} \sin\left[\frac{\pi}{4} \epsilon\right] \exp[-3.32 g/\lambda_w]$$

where ϵ is the ratio of magnet width, h , to wiggler wavelength. The optical beam intensity is specified within the magnet by assuming Gaussian beam propagation; the beam area is then a function of position

$$\pi\omega^2 = \pi\omega_0^2 \left[1 + \left(\frac{z}{z_R} \right)^2 \right]$$

where $-\frac{L}{2} < z < \frac{L}{2}$

These expressions, along with the gradient and resonance equation, were integrated numerically to obtain the increase in energy of a 20 MeV beam traversing the one-meter-length wiggler. The results show a 10 MeV increase in the electron beam energy.

A more detailed computer model has been run for this case to determine the output energy spectrum of the accelerated electrons. The results are quite encouraging, as over 40 percent of the initial electrons are accelerated to 30 MeV. This code-calculated spectrum is presented in Figure 2-7. With conversion efficiencies of 40 percent and energy gains of 50 percent, the detection of these electrons would not be difficult.

Although this demonstration technique uses existing hardware and is low-risk, it does not demonstrate any other new properties required of laser particle accelerators, such as very high gradients, lower electron energy beam spread, or improved beam emittance. If one could combine this demonstration with some of these other desirable characteristics, its implementation would become compelling.

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Figure 2-7. Electron Energy Spectrum Before and After Acceleration

APPENDIX A

Glancing Incidence Absorption Measurements of Metal Mirrors

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Glancing incidence absorption measurements are performed on bare Cu, Mo, Au, Al, and Ag mirrors, and on Al and Ag mirrors with a protective dielectric overcoat. Data is obtained for angles of incidence from 0° to 89°. Wavelengths studied are 0.5 μm and 10.6 μm at both s and p polarizations. The absorption is measured using a photoacoustic calorimetry technique in which the transducer is attached directly to the back of the test mirror. Absolute calibration of the absorption data is obtained by using a radiometer to independently measure the absorption at near normal incidence.

The results are compared with the absorption predicted by Fresnel's equations for bare metals using values of n and k of the complex index of refraction measured by other sources. The absorption of a mirror at glancing incidence appears to be a sensitive function of its surface condition. New mirrors tend to agree with Fresnel's equations; while "old" mirrors have much higher absorption probably due to a layer of tarnish. The overcoated Al data deviates greatly from Fresnel's equations indicating that bare metal theory cannot be used and a thin film theory should be used instead. Representative results are given.

Key words: absorption; Fresnel equations; glancing incidence; metal mirrors; overcoats; photoacoustic calorimetry; polarization; 0.5 and 10.6 μm .

1. Introduction

Various concepts for laser particle accelerators (LPA) [1] require lasers with high average power (to provide high particle luminosity) and small beam diameters (for optimum mode matching). Thermal distortion and damage of the reflective optics used in such systems can become a critical issue. Glancing incidence mirrors can be used to overcome this problem; however, data on their performance is sparse. Previous experiments have primarily measured optical damage and were limited to $\leq 80^\circ$ angle of incidence [2,3].

In the work described in this paper, the thermal absorption characteristics of various mirrors are measured from 0° to 89° angle of incidence for both s and p polarized laser light (perpendicular and parallel to the plane of incidence, respectively). Measurements are taken at two laser wavelengths: 0.5 and 10.6 μm . Tested are commercially available bare metal mirrors (Cu, Mo, Au, Al, and Ag) and protected Al and Ag mirrors with thin overcoats on their surfaces.

In the next section, Fresnel's equations for the reflectivity of a metal surface is briefly reviewed. The experimental setup is described in Section 3 and sample results are given in Section 4. Section 5 concludes with a discussion of the results obtained thus far in this program.

2. Theory

The complex index of refraction, n , of a material is given by.

$$n(\lambda) = n(\lambda) + ik(\lambda)$$

[1]

where n is the index of refraction and k is the extinction coefficient. The values of n and k are in general a function of the wavelength of the light.

Beginning with Maxwell's equations and assuming a plane electromagnetic wave impinging from a dielectric medium (such as air) onto a conducting metal surface at an angle, θ , measured from the normal, one can solve for the amplitude, $\rho_{\perp}$ and $\rho_{\parallel}$, of the reflected wave whose polarization is perpendicular and parallel to the plane of incidence, respectively. These are referred to as the Fresnel equations [4]. Assuming unity for the dielectric refractive index, Fresnel's equations are,

$$\rho_{\perp}^2 = \frac{(\cos\theta - u)^2 + v^2}{(\cos\theta + u)^2 + v^2} \quad (2)$$

$$\rho_{\parallel}^2 = \frac{[(n^2 - k^2)\cos\theta - u]^2 + [2nk\cos\theta - v]^2}{[(n^2 - k^2)\cos\theta + u]^2 + [2nk\cos\theta + v]^2} \quad (3)$$

where

$$2u^2 = [n^2 - k^2] - \sin^2\theta + \left\{ \left[[n^2 - k^2] - \sin^2\theta \right]^2 + 4n^2k^2 \right\}^{1/2}$$

$$2v^2 = -[n^2 - k^2] + \sin^2\theta + \left\{ \left[[n^2 - k^2] - \sin^2\theta \right]^2 + 4n^2k^2 \right\}^{1/2}$$

During this program, a computer code solves for the absorption at the mirror surface, i.e. $1 - \rho_{\perp}^2$ and $1 - \rho_{\parallel}^2$, using Equations 2 and 3.

When comparing our data to theory, values of n and k at the wavelength of interest must be chosen to substitute into Equations 2 and 3. A number of different sources [5]–[8] are used for values of n and k . It is important to realize that often these sources do not agree with one another on the values of n and k for the same material. This is not totally surprising when one considers that different forms of the same material may have been tested (e.g., films versus bulk), the condition of the surfaces may vary from author to author, and the various measurement techniques are susceptible to different systematic errors.

Fortunately, the overall shape of the absorption curves as a function of the angle of incidence for a material do not change significantly for small changes in n and k . The magnitude of the absorption at normal incidence, however, does change significantly for small changes in n and k . Hence, when comparing our data with theory, it is important to compare both the overall shape of the curves and their absolute magnitudes. As will be shown, there are times when the overall shape agreement between the data and theory is excellent, but there may be a disagreement with the absolute magnitude of the absorption.

As will be explained in the next section, during the experiment the absolute magnitude of the absorption at near normal incidence is measured independently with a radiometer energy meter. Therefore, any disagreement between the data and theory in regards to the absolute magnitude of the absorption is probably due to differences in the mirror surface condition rather than disagreement with the theory itself. Viewed with this perspective, it is more important that the overall shapes agree rather than the absolute magnitudes.

Finally, in regards to the practical usage of these mirrors at glancing incidence, it is the magnitude of their absorption at glancing incidence that is important. Since our data, once it is calibrated with the radiometer measurements, provides the absolute magnitude of the absorption for all angles, our experimental results are still valid despite any disagreements with theory.

3. Description of Experiment

Photoacoustic calorimetry is used to measure the very small absorptance expected at glancing incidence. The basic technique is well established [9]; a modified version [10] is being used in this experiment where the acoustic transducer is attached directly to the back of the mirror rather than on the test chamber wall. This modification greatly enhances the sensitivity of the technique; absorption coefficients (absorbed light/incident light) of 10^{-4} to 10^{-5} are detectable.

Briefly, in photoacoustic calorimetry, energy from a laser beam incident upon a mirror is absorbed at the mirror surface. This absorbed energy generates an elastic strain wave (acoustic wave) which propagates through the mirror substrate. This strain wave passes through the piezoelectric transducer rigidly attached to the back of the mirror substrate. The strain induced in the piezoelectric causes a voltage to be generated across the transducer electrodes which is directly proportional to the magnitude of the strain wave. Thus, the voltage gives a direct indication of the amount of energy absorbed at the mirror surface.

Figure 1 is a schematic of the glancing incidence measurement system. Two different cw, vertically polarized lasers are used: an argon ion laser ($0.5145 \mu\text{m}$) and a CO_2 laser ($10.6 \mu\text{m}$). The output from the lasers is sent through a chopper, a collimating telescope, a half-wave plate to rotate the polarization, and a "clean-up" polarizer which rejects all light not rotated by the half-wave plate. The laser light then reflects off the test mirror mounted on a rotation stage. A phase sensitive lock-in amplifier measures the piezoelectric transducer output which may be as low as 10-100 nV at glancing angles.

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Figure 1. Schematic of glancing incidence measurement apparatus.

There is a small dependence of the transducer output on the shape of the laser footprint on the mirror surface. At glancing incidence, the laser footprint on the mirror becomes very elongated and much longer than the diameter of the transducer. This footprint dependence can be easily determined by directing the laser beam at normal incidence to the test mirror surface and using a cylindrical lens to create an elongated beam spot on the mirror. The absorption at the mirror surface is relatively constant as the footprint size is varied because the angle of incidence of the laser beam never exceeds 10° as the beam expands from the cylindrical lens. Knowing the length of the footprint and the diameter of the laser beam, the equivalent angle that corresponds to the footprint can be calculated.

The correction for footprint dependence is found to be negligible for angles less than about 80° . Even at 89° the correction is typically only a factor of two which is small when compared with the orders of magnitude changes in reflectivity that occur at glancing incidence. The footprint calibration curve is obtained for every mirror tested and at the two wavelengths investigated.

Absolute calibration of the photoacoustic calorimeter is obtained by using a dual-head laser energy radiometer. Using the same laser as used for the angle dependence measurements, the calibration is performed by measuring the amount of energy absorbed on the mirror surface at near normal incidence. A beamsplitter reflects a portion of the incident laser light into one of the radiometer sensing heads which is used as a reference source in order to eliminate fluctuations in the

laser output energy. The other radiometer head is positioned alternately before and after the mirror to measure the incident and reflected light, respectively. The radiometer automatically averages over hundreds of light pulses.

4. Experimental Results

Figure 2 shows the absorptance characteristics of bare silver at $0.5145 \mu\text{m}$. To minimize tarnishing of the bare silver mirror, the mirror was shipped to Spectra Technology from the coating vendor in a leak-tight container filled with an inert gas and was tested in a nitrogen purged environment. Error bars on the data indicate the reproducibility of the data. The calibration at normal incidence is uncertain by approximately $\pm 1\text{--}2\%$ absolute absorptance. The solid curve is Fresnel's equations (eq. 2 and 3) using the values of n and k given in reference 5. There is a slight disagreement between the data and theory in regards to the absolute value of the absorptance; however, there is excellent agreement in overall curve shapes.

Figure 2. Absorptance curves for bare silver at $0.5145 \mu\text{m}$ for both s and p polarizations. The solid curve is Fresnel's equations using the values of n and k given in reference 5.

The effects of a protective overcoat (≈ 1000 angstrom thick layer of ThF_4) on the silver surface is shown in figure 3. The protected silver mirror appears to have slightly higher absorptance at glancing angles than the bare silver mirror. This is true for both polarizations and may be related to a "trapping" of the laser radiation between the dielectric layer and the metal surface at high angles of incidence.

In general, for the metals and wavelengths tested, either $(\sin\theta/n)^2 \ll 1$ and/or $(\sin\theta/k)^2 \ll 1$. Then, for the perpendicular polarization case, eq. (2) simplifies to first order to a simple $\cos\theta$ dependence [2]. Hence, a simple comparison of the experimental absorptance curve shape can be made with the theoretical one by calculating the deviation of the data from the $\cos\theta$ dependence.

Figure 4 is a plot of the percentage deviation from this $\cos\theta$ dependence of the data for the bare and protected Ag mirrors. If the data followed exactly the $\cos\theta$ dependence, the points would lie on a straight line at zero deviation. The bare silver (fig. 4a) does exhibit a low deviation until approximately 85° , at that point the data actually indicates lower absorption than theory predicts.

However, since the error bars are also relatively large for these points, it is more likely that the absorption is very close to that predicted by theory.

Figure 3. Absorbance curves for protected silver at $0.5145 \mu\text{m}$ for both s and p polarizations. The overcoat is an ≈ 1000 angstrom thick layer of ThF_4 . The solid curve is Fresnel's equations using the values of n and k given in reference 5 for bare silver.

The protected silver mirror (fig. 4b) displays clear deviations away from the $\cos\theta$ dependence. At approximately 40° it has lower absorbance than predicted, and for angles greater than 70° it has significantly higher absorbance.

Absorbance results for bare gold and copper mirrors at $10.6 \mu\text{m}$ are given in figures 5 and 6. Values of n and k for the theoretical curve are from references 5 and 6 for the bare gold and copper cases, respectively. The bare copper mirror is an example of the results when testing a "old" mirror; that is, a mirror which, although undamaged, has a tarnished surface as a natural result of aging. The copper data displays a curious increase in absorption at around 82° - 86° ; this may be related to the effects of the tarnish layer.

Figure 7 shows the deviation of the bare gold and copper data from the $\cos\theta$ dependence. The bare gold follows the dependence quite well until approximately 80° ; at higher angles the absorbance tends to be higher than that predicted by theory. At glancing angles, the absorbance of the tarnished copper mirror is significantly higher than theory predicts. The tarnish layer is probably largely responsible for this higher absorbance.

Finally, figure 8 gives an example of how an overcoat can dramatically alter the absorption characteristics of a mirror. The results are for a protected aluminum mirror with a MgF_2 overcoat measured at $0.5145 \mu\text{m}$. It is clear the data does not follow theory (7,8); however, this simply implies a theory which incorporates the effects of a thin dielectric film needs to be used.

$\lambda = 0.5145 \mu\text{m}$
PERPENDICULAR POLARIZATION

Figure 4. Deviation of data shown in figures 2 and 3 from the first order $\cos\theta$ dependence as predicted from Fresnel's equations.

Figure 5. Absorbance curves for bare gold at $10.6 \mu\text{m}$ for both s and p polarizations. The solid curve is Fresnel's equations using the values of n and k given in reference 5.

Figure 6. Absorptance curves for a bare but tarnished copper mirror at $10.6 \mu\text{m}$ for both s and p polarizations. The solid curve is Fresnel's equations using the values of n and k given in reference 6.

$$\lambda = 10.6 \mu\text{m}$$

Figure 7. Deviation of data shown in figures 5 and 6 from the first order $\cos\theta$ dependence as predicted from Fresnel's equations.

Figure 8. Absorptance curves for protected aluminum at $0.5145 \mu\text{m}$ for both s and p polarizations. The overcoat is a thin layer of MgF_2 . The solid curve is Fresnel's equations using the values of n and k given in references 7 and 8 for bare aluminum.

5. Conclusion

Glancing incidence absorption measurements have been performed at angles $>89^\circ$ on a number of different bare metal and overcoated metal mirrors. Absorptions as low as 0.04% have been measured at 89° . While agreement between the data and Fresnel's equations for a bare metal surface is generally good for new bare metal mirrors, there is occasionally great disagreement when the mirror is either tarnished or has a protective overcoat.

Codes are available which predict the absorptance of mirrors with thin films [11]. Efforts are under way to compare the data obtained during this program with some of those code predictions. Work is also continuing on further measurements and reduction of the data.

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