Scattering and surface evaluation techniques for the optics of the future

By Jean M. Bennett

A key to improving the performance of high quality optics, and in particular the thin film coatings on the optics, is to reduce scattering and absorption losses, especially caused by roughness at interfaces. In this paper are discussed the origins of scattered light, scalar and vector theories to predict scattering from surface microirregularities, and methods for measuring hemispherical and angle-resolved scattering. In addition, ways of measuring surface microstructure and defects, and bulk and interface absorption in films and substrates are also described.

Introduction

As the requirements for optical systems become more stringent and new fabrication techniques are developed, it becomes necessary to have more sensitive methods for evaluating optical components while they are being made, after they are completed, and when they are made part of an optical system. Evaluation includes measures of (1) the ability of an optic or a system to focus light to a diffraction-limited spot so that the actual performance can be compared to calculated performance; and (2) deleterious effects—scattered light, surface defects, absorption, changes of properties with time (material creep) or temperature (nonuniform heating by high power laser beams). There are well-established ways of testing the focusing properties of spherical lenses or mirrors, but the testing of aspheric elements by using holographic techniques or null correctors still poses challenging problems.

The primary purpose of this paper, however, is to consider problems associated with surfaces and coatings, mainly scattered light and, additionally, surface microroughness, imperfections, and absorption. The first section on scattering contains a discussion of (1) the origins of scattered light, (2) scalar and vector scattering theories which predict scattering based on inputs of surface statistics and optical parameters, and (3) methods for measuring hemispherical scattering and angle-resolved scattering. Methods for observing and measuring surface microstructure and defects are discussed in the next section. Finally, in the last section on absorption, techniques for measuring absorption in films, interface absorption, and bulk absorption are described, along with some specialized methods for detecting thin surface films of water.

Scattering

Scattering is, perhaps, the most harmful effect in an optical system. It can reduce light transmission even before it degrades system resolution. The most common type of scattered light in optical systems is light that enters the system at oblique angles outside the field of view and is scattered by walls, mounting fixtures, etc. into the field of view. This type of scattering frequently can be eliminated by the use of appropriately placed baffles. However, out-of-field light that strikes lenses or mirrors and is redirected into the system by surface or bulk scattering in the optics is much more difficult to eliminate.

Bulk scattering in transmitting optics arises because of imperfections in the material: bubbles or striae in amorphous materials and randomly ordered crystallites, voids, foreign material, inclusions, slip planes, etc. in poly-crystalline materials. Purer, more homogeneous, and better annealed material is the remedy for this type of scattering. Bulk scattering can also be produced by microcracks or subsurface damage remaining from the polishing process. Under certain conditions, it is possible to identify and separate subsurface damage from surface imperfections and also to eliminate it by special polishing processes. Laser annealing or laser polishing can heal or seal over sur-
Scattering from optical surfaces and films is the most difficult type of scattering to eliminate and upon which the most effort has been spent. This type of scattering arises from three main effects which are discussed below.

1. **Scratches, pits, or other imperfections** which are large compared to the wavelength of light produce scattering in the geometrical optics regime. In order to understand and predict the magnitude and angular distribution of the scattering as well as its wavelength dependence, a detailed knowledge of the geometrical shapes of the surface defects is required, which is generally not known. However, scattering from some baffles, diffusers, etc. can be treated by considering the surfaces as ensemble averages of randomly oriented facets.\(^7\)

2. **Smaller isolated features** such as tiny pits, dust particles, microcracks, or other individual surface defects produce dipole scattering which, in principle, can be handled by Mie scattering theory.\(^8\) In practice, however, the sizes, shapes, and optical constants of the scattering sites must be input into the theory. These are generally unknown. Multiple scattering between defects is usually not considered. For these reasons, there have been only limited theoretical studies of Mie-type particulate scattering, and most of the work has dealt with specially prepared surfaces such as those covered with small silver particles.\(^9\)

3. **High-quality optical surfaces** are, fortunately, nearly defect-free, so that scattering comes only from the surface microirregularities produced by the polishing or other fabrication process. The microirregularities can be randomly distributed as on high quality optically polished glass or fused quartz surfaces, or occur as unidirectional grooves such as on diamond-turned metal surfaces like copper or electroless nickel. Ruled or replicated diffraction gratings are more ordered surfaces where all equally spaced grooves have identical shapes, but also there can be additional roughness produced by the ruling diamond. Some surfaces have combinations of all three types of defects—scratches, dust, and microirregularities—so that all types of scattering mechanisms should be considered. A general review of this subject is given in Refs. 7 and 10. Figure 1 shows a schematic diagram of various types of microirregularity scattering which can occur because of roughness on surfaces, in the bulk of thin transparent films, or at interfaces. Long-range surface irregularities also produce very near-angle scattering.

Scattering from correlated surface microirregularities has been treated by scalar and vector scattering theories. The scalar theory\(^1,12\) is valid for the cases of (1) light incident at a particular angle on a surface and scattered into all angles of a hemisphere, i.e., total integrated scattering (TIS); (2) the decrease in specular reflectance caused by scattering; and (3) very near-angle scattering, either as a function of angle or integrated into a cone about the specular direction. The only assumption in this theory is that the heights of the surface microirregularities must be small compared to the wavelength of light. There is no restriction on the analytical form of the autocorrelation function\(^13\) or on the magnitude of the correlation length, i.e., the approximate distance on the surface over which the surface irregularities are correlated.

Two simple forms of this theory are most useful: If light is normally incident on a slightly rough surface, the specular reflectance \(R\) is slightly less than \(R_0\), the total reflectance of the surface, because of light scattered out of the specular beam. If the rms surface roughness \(\delta\) is known, \(R\) can be calculated or, conversely, if \(R\) can be measured, \(\delta\) can be calculated, both from the simple expression\(^11\)

\[
\frac{R}{R_0} = \exp\left[-(4\pi\delta/\lambda)^2\right] \approx 1 - (4\pi\delta/\lambda)^2, \tag{1}
\]

where \(\lambda\) is the wavelength of the incident light. If, on the other hand, we consider TIS into a hemisphere, which is all the light except for the specularly reflected beam, we can write

\[
\text{TIS} = (R_0 - R)/R_0 = 1 - \exp\left[-(4\pi\delta/\lambda)^2\right] \approx (4\pi\delta/\lambda)^2. \tag{2}
\]

When microirregularity scattering is the dominant mechanism, the wavelength dependence of the TIS has been shown experimentally to be inversely proportional to the square of the wavelength\(^14\) in the visible spectral region where TIS is well above a base value \(\sim 10^{-4}\). Also, roughness values calculated from measured TIS values using Eq. (2) have been verified by direct surface profile measurements.\(^15\) Equation (2), in fact, forms the basis for a new ASTM standard on a method for measuring the effective roughness of an optical surface.\(^16\)

Vector scattering theories\(^7,10,17\) enable scattering to be predicted as a function of angle, provided that the surface spectral density function or autocovariance function is known. Additional inputs are the angles of
incidence, $\theta_0$, $\phi_0$, and scattering, $\theta$, $\phi$ (polar angle $\theta$ measured relative to the surface normal in the plane of incidence and azimuthal angle $\phi$ measured relative to the plane of incidence), the optical constants $n - ik$ of the (opaque) surface layer, and the state of polarization $\chi_{0\alpha}$ of the incident and scattered beams, respectively.

Vector scattering theories have the form\textsuperscript{7,17}

$$\frac{1}{P_0} \frac{dP}{d\Omega} = \frac{C}{\lambda^4} F(\theta_0, \phi_0, \theta, \phi, n - ik, \chi_{0\alpha})g(k), \quad (3)$$

where the scattering per unit solid angle $dP/d\Omega$ is divided by $P_0$, the incident beam intensity. The scattering is inversely proportional to the fourth power of the wavelength, as in Rayleigh and Mie scattering.\textsuperscript{8} where $C$ is a constant. The quantity $F$ in Eq. (3), the so-called “optical factor,”\textsuperscript{18} is a function only of parameters that are independent of the condition of the surface and are usually known. The “surface factor,” $g(k)$, usually called the spectral density function, depends only on the surface roughness; it is the Fourier transform of the surface autocovariance function which can be calculated from the surface profile. The bidirectional reflectance distribution function (BRDF)\textsuperscript{19} can be calculated by dividing both sides of Eq. (3) by $\cos \theta$, where $\theta$ is the scattering angle measured relative to the surface normal. An alternate approach is to use a geometrical construction that involves $\beta - \beta_0$, the difference between the direction cosines of the incident and scattering angles.\textsuperscript{20} This quantity is proportional to the surface spatial wavelengths, and in this representation the angular scattering should become scale invariant; interpretation of the data can be greatly simplified.

Although Eq. (3) in its complete form is exact and can be used for calculating angular scattering, it does not lend itself to visualizing the relation between the scattering angle and separation of (correlated) features on the surface. This relation can be obtained directly from the grating equation. A rough surface can be considered to be composed of a series of randomly oriented diffraction gratings having different amplitudes and spacings. The separations of the surface microirregularities correspond to the grating spacings and their heights to the amplitudes of the rulings.

Thus, the angles into which light is scattered depend on the angle of the incidence, wavelength, and surface spatial wavelength (grating spacing) according to the grating equation:

$$N\lambda = d(\sin \theta_0 \pm \sin \theta), \quad (4)$$

where $N$ is the order of interference, $d$ the surface spatial wavelength, and $\theta_0$ and $\theta$ the angles of incidence and scattering, respectively, measured from the surface normal. Since the heights of the microirregularities are small compared to the wavelength, only first-order scattering occurs, i.e., $N = 1$. In Fig. 2 is a nomograph giving the relation between scattering angle and surface spatial wavelength as a function of the illuminating wavelength for normal incidence illumination, i.e., $\sin \theta_0 = 0$ in Eq. (4).

The amplitude of the scattering, which depends on the heights of the surface microirregularities, is proportional to the quantity\textsuperscript{21}

$$[(2\pi h/\lambda)\cos \theta_0]^2, \quad (5)$$

where $h$ is the amplitude of the sinusoidal component. Expression (5) assumes that the amplitudes of the microirregularities are small compared to the wavelength so that multiple scattering does not occur.
Diamond-turned surfaces are exceptions to the first-order scattering assumption, \(N = 1\) in Eq. (4). Sometimes there can be many orders of diffracted light.\(^{22,23}\) Figure 3 shows the good agreement which has been obtained between measured and calculated angular scattering from two diamond-turned surfaces for which the intensities of the first 10 diffracted orders were easily measured.\(^{22}\)

Table I summarizes methods for measuring scattering and other surface-related quantities. Scattering into a hemisphere (TIS) can be measured using an aluminized collecting hemisphere in an experimental arrangement similar to that shown in Fig. 4.\(^{14,16}\) Light from a He-Ne laser is chopped, spatially filtered and attenuated if necessary, and then strikes the test surface (\(\sim 1\) mm diameter spot). The specular reflectance \(R\) of the sample can be measured if it is not already known, while the light scattered out of the specularly reflected beam strikes the aluminized surface of the collecting hemisphere and is focused onto the detector. The TIS is defined by Eq. (2), where \(R_0\), the total reflectance of the sample, is the specular reflectance plus scattered light, while \(R_0 - R\) is the scattered light. The quantity \(R_0 - R\) is ratioed to \(R_0\) to make TIS independent of the sample reflectance.

The instrument shown in Fig. 4 is a simplified version of other similar instruments, one of which has multiple laser sources and can measure forward scattering and specular reflectance at a variety of angles.\(^{14,24}\) TIS can also be measured using an integrat-

![Figure 4. Schematic diagram of an instrument for measuring total integrated scattering (TIS).](image)

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**Table I.** Methods for measuring scattering, surface structure, and absorption.
Excellent agreement was obtained between values of the TIS measured on a series of roughness standards using the two different types of instruments. Angle-resolved scattering is typically measured in the plane of incidence using a laser source and a detector on a movable arm which rotates about the sample. Some instruments can also map the intensity of the scattering as a function of position on the surface or as a function of the sample azimuth, i.e., when the sample rotates about an axis parallel to its surface normal. Figure 5 shows a map of the scattering as a function of position on the surface. What makes this map unusual is that the high scatter levels are not caused by surface defects but most probably are produced by subsurface damage in the silicon wafer generated during the polishing process.

Surface Microstructure and Defects

Surface microstructure and defects can be studied to learn about the process used to produce the surface or to obtain an rms roughness value which can then be used in scalar and vector scattering theories. Differential interference contrast or Nomarski microscopy is probably the most useful method for easily and nondestructively observing an optical surface. The microscope works on an interference principle: Two light beams spatially separated and polarized at right angles to each other strike the surface. Any surface defects or variation in the optical constants that change the state of polarization of the beams are made visible when the beams are reflected from the surface, recombined, and destructively interfere. The Nomarski micrographs in Fig. 6 show different kinds of optical surfaces and illustrate the versatility of this useful instrument. A new instrument based on the Nomarski principle is being developed to make quantitative measurements of surface heights.

Two main drawbacks of Nomarski microscopes are: (1) quantitative information cannot be obtained about surface heights, and (2) it is very difficult to see detail on transparent surfaces. Fortunately, total internal reflection microscopy (TIRM) works very well for transparent surfaces. As shown in Fig. 7, this technique uses polarized light incident inside a coupling prism at an angle just slightly greater than the critical angle. Any defects on the surface of the test piece, which has been oiled onto the coupling prism with an index matching fluid, scatter light out to be observed or photographed.

The TIRM technique is much more sensitive to surface defects because of a four-times enhancement of the electric field at the internal reflection as compared to an external reflection. Figures 8 and 9 give examples of the detail in a transparent evaporated film.
shown by TIRM and the improvement that can be obtained by laser annealing the surface of a piece of polished fused quartz. The technique is also a useful aid in cleaning transparent optics prior to coating by making visible particulate contamination on surfaces.

Quantitative measurements of the heights of surface microirregularities can be made by specialized optical interferometers or by mechanical probe-type instruments, some of which are listed in Table I. Optical interferometers use two-beam or multiple-beam interference between a test surface and a reference surface to create a surface profile. (In the case of the optical heterodyne interferometer, the reference surface is a single point on the test surface).

The optical interferometers are absolute and do not need external calibration standards, since the interference fringes are formed from light of a known wavelength. Some interferometers are completely noncontact or can be used to measure uncoated surfaces. Others, however, require highly reflecting coatings on the test and reference surfaces, and the two surfaces must be placed nearly in contact. (It has been shown by sensitive angular scattering measurements that the process of removing a silver coating from a very smooth fused quartz surface can cause a slight increase in scattering, although there is no roughness increase that can be measured with a diamond stylus profiling instrument.

A disadvantage of all interferometers is that the lateral resolution, i.e., the separation of surface features whose heights can be distinguished, is limited by (1) the resolving power of the lenses associated with the interferometer; (2) the finesse of the interferometer (i.e., the contrast of the interference fringes), or (3) the size of the illuminating spot on the surface.

The most versatile noncontact interferometer currently available is the Mireau interferometer, with which surface profiles can be quickly and easily measured on coated or uncoated surfaces with a lateral resolution of about 3 \( \mu \text{m} \). Other statistical data such as the height distribution function, autocovariance function, and spectral density function can also be easily and rapidly obtained. Although the basic noise level of the instrument is equivalent to a surface roughness of about 1 Å rms, it is much more difficult to measure surfaces smoother than about 10 Å rms because the roughness of the internal reference surface must be corrected for.

Mechanical probe-type instruments use a diamond stylus to measure a surface profile as the stylus or the surface is translated. The stylus loading should be very carefully controlled to avoid obtaining distorted surface profiles and damaging soft optical films such as gold, silver, or aluminum or soft substrate materials. Stylus loadings in the 0.5 - 2 mg range are appropriate.

The lateral resolution depends on the stylus radius and the slopes of the surface features; it is typically one- to two-tenths of the stylus radius for very smooth surfaces. If the surface profile is assumed to be in the form of a sine wave having a period \( d \) and amplitude \( h \), the lateral resolution can be calculated from the simple expression derived by Elson:

\[
d > 2\pi \sqrt{hr}
\]  

where \( r \) is the stylus radius. Examples of incompletely and completely resolved surface profiles are given in Ref. 38. Under ideal conditions, a stylus profiling instrument can have up to 30-times better lateral resolution than an interferometric profiling instrument. Of course, the stylus profiling instruments must be calibrated using an external reference (height) standard, preferably one which has been measured interferometrically.

Table I summarizes methods for obtaining surface profiles and other statistical properties of optical surfaces. In addition to the two types of instruments discussed above, there are specialized techniques for obtaining surface profiles on electron micrographs that have much higher lateral resolution. First-stage replicas are made by shadowing optical surfaces at oblique incidence with thin layers of platinum-carbon or tung-
sten-carbon,41 then depositing a heavy strengthening layer of carbon. The carbon replica is removed by dissolving the underlying surface and placed on a grid for observation in an electron microscope. If the original surface cannot be dissolved from the Pt-C replica, it is first copied using a press-on plastic tape. The tape is then stripped from the surface and shadowed as before.

To obtain heights of surface features or profiles using a stereo technique,42-45 pairs of electron micrographs are taken by rotating the replica by equal and opposite amounts about an axis perpendicular to the axis defined by the electron beam. Then the stereo pairs are measured using a stereo viewer and parallax bar42 or a special optical instrument designed for measuring aerial photographs.46 This technique has not been too successful because of curvature in the field of the electron microscope and difficulty in using an instrument designed for measuring aerial photographs.46 This technique has not been too successful because of curvature in the field of the electron microscope and difficulty in using an instrument designed for measuring aerial photographs to deduce information on electron micrographs. However, the principle has been verified and work is continuing.

An alternate method for obtaining surface profiles from electron micrographs of surface replicas has been developed by the Rasignis and co-workers.47 They have shown that microdensitometer scans of the micrographs are proportional to the slopes of the surface microirregularities. By using sophisticated data-processing techniques, they are able to take smoothed microdensitometer data and integrate it to obtain surface profiles, autocovariance functions, and other statistical data. Examples of their profile and autocovariance function data are shown in Fig. 10. The lateral and height resolution obtainable with the Rasignis’ technique depends on the character of the surface, lateral resolution of the electron microscope, magnification of the micrograph, the data-processing method used, and other factors. In the best cases, it is possible to measure surface features with lateral and height resolutions of the order of 10 Å.

A new direct method that has a sensitivity comparable to that of the Rasignis has recently been developed.48 The “scanning tunnel microscope” uses an extremely sharp field-emission-type probe to follow the contours of the surface. The probe is translated and at the same time held a constant distance away from the surface by keeping the potential between the probe and the surface constant. Thus the probe position gives a direct measure of the surface topography, and two-dimensional maps can be made that show detail never before seen on optical surfaces. Since the offset distance between the probe and the surface is proportional to the work function of the material, the work function must remain constant to obtain a true surface profile. This requires that the surface materials be very pure, single phase, and free of grain boundaries, partial oxide coverage, etc.

**Absorption**

Absorption is also detrimental for optical systems and can be measured by a variety of techniques, some of which are listed in Table I. Any of the methods that will give the optical constants of a film49 will of course also yield the film absorptance, since the absorption coefficient \( \alpha = 4\pi k/\lambda \), where \( k \) is the extinction coefficient (imaginary part of the complex index of refraction) and \( \lambda \) the wavelength.

Perhaps the simplest method to obtain the absorption of a thin film on a substrate is to measure the transmittance of the film-covered substrate as a function of wavelength. The real part of the refractive index can be obtained from the wavelengths of the interference maxima or minima. The transmittance can then be calculated at these wavelengths. Any decrease in the transmittance from the calculated value is caused by absorption in the film and/or substrate, or scattering. If the substrate is known to be smooth and nonabsorbing, the decrease in transmittance can be attributed to film absorption.

Ellipsometry50 is also an excellent method of obtaining optical constants and, hence, absorption of films on substrates of known optical properties. The ellipsometer measures the product of the film optical constants and thickness, so an independent measurement of film thickness is also needed.

The absorptance of opaque samples having a high reflectance can be obtained by subtracting the measured reflectance from unity. Since the absorptance is a small number, the reflectance must be measured very accurately, typically to a tenth of a percent or better.51 The sample must also be very uniform and have a low scatter. A very sensitive technique used particularly by manufacturers of laser gyro mirrors is the so-called “ring-down” technique,52 which in-

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**Figure 10.** Surface topography and autocovariance function for an evaporated silver film (subsequently baked in vacuum at 250°C for 2 hrs) obtained from microdensitometer scans of an electron micrograph replica of the surface. The technique is described in Ref. 47.
FIGURE 11. Absorptance data for a hot-pressed, forged CaF$_2$ prism using two different HF wavelengths (from Ref. 55).

volves counting the number of multiple reflections a pulsed laser beam can make between two mirrors, one of which is the mirror being tested, before the intensity reaches a predetermined level. This method measures total mirror loss, i.e., transmission, absorption, and scattering, and is generally used only for comparison purposes.

Calorimetry measures absorption directly by recording a temperature rise when a sample is irradiated with a laser beam or other intense light source. Conventional rate calorimetry requires that various properties of the material such as geometrical dimensions, heat capacity, thermal diffusivity, etc. be known. The sample surroundings are also important and must be carefully controlled.

Adiabatic calorimetry is a technique in which the sample is irradiated a short time by a laser beam. The sample is contained in an evacuated chamber, and the temperature of the walls is kept the same as the sample. The technique eliminates most of the problems present with rate calorimetry and enables measurements to be made under well-controlled conditions; no knowledge of geometric dimensions or thermal properties of the sample, sample mass, specific heat, or thermal diffusivity of the sample is necessary. Absolute electrical calibration is provided by equivalent joule heating of the sample. One adiabatic calorimeter has a sensitivity of measuring absorption to parts in $10^5$ using low power (<1-W) laser sources, the absorptance data are absolute with high accuracy, samples can be spatially scanned with a small spot diameter laser beam, and the calorimeter can be operated from the far infrared to the ultraviolet.

Since absorption can be measured as a function of position with an adiabatic calorimeter, a wedge-shaped film or substrate can be used to obtain bulk absorption in a substrate material, in a film, or interface absorption on the surfaces of a film. Figure 11 shows recent measurements of the infrared absorption in a prism-shaped sample of fusion-cast calcium fluoride. Note that the absorption is different at two closely spaced wavelengths, one in the water band and one outside of it. An earlier calorimetric study showed that it is possible to have film-substrate interface absorption which is larger than the absorption within the film.

The chemical species of absorbing molecules or radicals can be obtained by using internal reflection spectroscopy in the infrared. This technique obtains its sensitivity from the suitable choice of polarization, angle of incidence, and refractive index of the coupling prism to enhance the magnitude of the electric field vector at the surface; multiple reflections between the material of the coupling prism also increase the effect. Figure 12 illustrates how internal reflection microscopy can be used to identify OH absorption in a thin SiO film.

Another technique which is specific for detecting...
the presence of water in a film or at an interface has been developed by Donovan et al.\textsuperscript{58} This method makes use of a nuclear reaction between fluorine and hydrogen atoms to produce oxygen and helium and release gamma radiation. By using fluorine atoms having energies between 16 and 19 MeV to vary the penetration into a material, it is possible to depth profile a film and determine the location of the water and its approximate concentration. In Fig. 13(a), such a profile shows that most of the water is located within a film; in Fig. 13(b), the water is located at the interface between the film and the substrate.

Laser-stimulated desorption, which can be thought of as short-pulse calorimetry, has been developed by Allen and co-workers\textsuperscript{59} to detect very thin films of water and other materials on surfaces. As shown in Fig. 14, it uses a pulsed laser beam to desorb a thin adsorbed water film. The amount of water that is desorbed depends on the amount present on the surface and also on the energy in the laser pulse. By removing the water film with repeated laser pulses, it is possible to improve the damage threshold of a material and also to explain why the multiple pulsed (N/1) damage threshold is higher than the single pulse (1/1) damage threshold.

Photoacoustic spectroscopy\textsuperscript{60} is another sensitive new technique for measuring absorbing areas in films or on substrates. In this method, a small-diameter chopped light beam is absorbed by a material. The reradiated energy is also pulsed, heats the surrounding air in an oscillating manner, and thus produces an acoustic signal which can be detected with a sensitive microphone. Although absolute calibration is difficult, photoacoustic spectroscopy has been successfully used to measure absorbing defects in a material which later damaged when exposed to an intense laser beam. Figure 15 shows the correlation between absorbing

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**FIGURE 13.** Hydrogen profile data for (a) a ThF\textsubscript{4} film showing concentration of water within the film and (b) a ZnS film showing large film-substrate interface absorptance (from Ref. 58).

**FIGURE 14.** Laser-stimulated desorption of water from CaF\textsubscript{2} at 2.7 µm (from Ref. 59).

**FIGURE 15.** Photoacoustic spectroscopy measurements of thin film absorbing defects that subsequently damaged in a CO\textsubscript{2} laser beam (from Ref. 60).
sites that were identified by photoacoustic spectroscopy and sites that later damaged when exposed to a high intensity CO_2 laser beam. Interestingly, not all photoacoustic spectroscopy sites were visible before laser damage occurred.

Summary

In this review, we have discussed scattering, surface imperfections, and absorption—all problems associated with optical surfaces and coatings. We have discussed the origins of scattered light and have mentioned scalar and vector scattering theories used to predict scattering from correlated surface microirregularities. Sensitive techniques for measuring hemispherical and angle-resolved scattering, surface microstructure, and absorption in coatings, at interfaces, and in bulk material have been described. By combining sensitive evaluation techniques with state-of-the-art methods for fabricating optical surfaces and coatings, the quality of the optics can be improved, and the optics of the future will come closer to the present.

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