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**Normalization of the Scattered
Light From an Isolated Defect
Illuminated by a Gaussian Beam**

By P. E. Klingsporn

Published July 1980

Topical Report

Prepared for the United States Department of Energy
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**Kansas City
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The intensity distribution of the beam from a laser operated in the TEM₀₀ mode is Gaussian in a plane perpendicular to the axis of the beam. A method of normalization is described which makes direct use of the Gaussian intensity distribution of the TEM₀₀ mode. The normalization requires that three measurements be made of the scattering by the defect for an arbitrary location of the defect relative to the center of the beam.

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CONTENTS

Section	Page
SUMMARY.	6
DISCUSSION	7
SCOPE AND PURPOSE.	7
ACTIVITY	7
<u>Concepts and Analysis.</u>	9
<u>Comparison Between Analysis and Results.</u>	16
ACCOMPLISHMENTS.	25
FUTURE WORK.	26
REFERENCES	27

ILLUSTRATIONS

Figure		Page
1	A Collimated Laser Beam of $1/e^2$ Diameter $2a$ Is Shown Incident Normally on a Reflective Surface.	8
2	Mapping of Illuminated Spots on the Surface of Figure 1, Showing the Geometry for the Case of Minimum Overlap.	10
3	Mapping of the Illuminated Spots on the Surface of Figure 1 for the Case of Arbitrary Overlap of the Illuminated Spots of $1/e^2$ Diameter $2a$	12
4	A Defect at Point P_d Is Shown Illuminated by Four Adjacent Spots S_1 Through S_4	13
5	Mapping of Illuminated Spots on the Surface of Figure 1 for the Case in Which the Centers of Adjacent Spots Do Not Lie on the Vertices of a Square	15
6	Optical Arrangement Used in Testing the Theory of Normalization for Small Isolated Defects on a Reflective Spherical Surface. .	17
7	Details of the Geometry for Determining the $1/e^2$ Radius of the Illuminated Spot on the Spherical Surface in Terms of the Raw Laser Beam Diameter d_r , the Spherical Radius R , and the Focal Length f of the Lens	18
8	Ratio of Measured Scattered Light at Distance r to Scattered Light at $r = 0$, Versus the Distance of a Small Defect From the Center of the Gaussian Illuminated Spot of $1/e^2$ Radius a	20
9	Mapping of the Centers of Illuminated Spots for the Case in Which There Is an Offset h .	21

TABLES

Number		Page
1	Comparison of Observed and Calculated Values of W_4 for Six Different Defects.	23
2	Comparison of Observed and Calculated Values of $W_{N,M}$ for Three Different Defects.	24
3	Comparison of Normalized Values of W_0	25

SUMMARY

The intensity distribution of the beam from a laser operated in the zero order configuration for the transverse electromagnetic field (TEM_{00} mode) is Gaussian in a plane perpendicular to the axis of the beam. In some applications it is desirable to have a uniform intensity over a certain region in space. For example, when a Gaussian beam is incident on a smooth surface containing small isolated defects, the light scattered by a defect will depend on the position of the defect relative to the center of the beam. In the past, several techniques have been devised to convert a Gaussian intensity profile into a uniform intensity over a specified region in space. In the present work a different approach is taken. A method of normalization is described which makes direct use of the Gaussian intensity distribution of the TEM_{00} mode. By this method the amount of light scattered by a defect can be normalized to the value which would be observed if the defect were located at the center of the beam, for a defect small in size compared with the $1/e^2$ diameter of the Gaussian profile. The normalization requires that three measurements be made of the scattering by the defect for an arbitrary location of the defect relative to the center of the Gaussian beam, and that the $1/e^2$ radius of the Gaussian beam and the interval between adjacent illuminated spots on the surface are known. Experimental data verifying the theory was obtained from isolated defects on a superfinished spherical surface.

DISCUSSION

SCOPE AND PURPOSE

A method was developed for normalizing the light scattered by a defect located arbitrarily in a Gaussian intensity distribution, to the value of scattering expected if the defect were located in the center of the Gaussian distribution of intensity. The technique of normalization was developed to provide a modification which can be made to existing computer programs for the purpose of possibly improving repeatability of pit defect analysis with the semi-automated laser surface inspection system.

ACTIVITY

The TEM₀₀ mode of laser operation is the one most commonly employed. The intensity distribution of the beam from a laser operated in the TEM₀₀ mode is Gaussian in a plane perpendicular to the direction of propagation; therefore, the intensity $I(r)$ in a transverse plane is

$$I(r) = I_0 e^{-2r^2/a^2}, \quad (1)$$

where I_0 is the intensity at the center of the beam, r is the radial distance from the center, and a is the radial distance from the center at which the intensity is $1/e^2$ times its value at the center. In many applications it is desirable that the TEM₀₀ beam intensity be "flattened" or made uniform over a region of space for purposes of normalization. For example, consider the simple application shown diagrammatically in Figure 1 in which a collimated laser beam of $1/e^2$ diameter $2a$ passes through a beamsplitter and is incident normal to a reflective surface. After reflection from the surface, the beam is diverted by the beamsplitter and brought to focus at point P by a lens. This arrangement can be used to detect the presence of isolated defects on the otherwise smooth surface.

The beam can be made to sample an entire given area on the surface by moving the surface in a programmed manner alternately along the y and x directions in the plane of the surface. When an isolated defect on the reflective surface appears in the illuminated spot on the surface, some light will be scattered outside the central focussed spot of light at point P in the $x-z'$ plane. In general, the larger the defect the greater the scattered energy. However, a small defect illuminated by the central portion of the beam may produce a scattered light energy equal to or greater than a relatively large defect occurring near

Figure 1. A Collimated Laser Beam of $1/e^2$ Diameter $2a$ Is Shown Incident Normally on a Reflective Surface .

the outer portion of the incident beam. This poses a problem in normalization when it is desired to distinguish between large and small defects based on the amount of light scattered by the defect. The problem poses itself particularly in an application in which the surface of Figure 1 is moved in an automated fashion in the x and y directions; because, in general, a surface defect will appear at an arbitrary point in the Gaussian distribution. If the intensity were uniform, the light scattered by a given defect would be independent of the position of the defect within the illuminated spot and normalization would not be a problem.

In the past, methods have been devised to transform a region of the Gaussian intensity into a uniform intensity. Some methods involve selective high absorption at the center of the beam, with proportionately less at increasing distance from the center.^{1,2} Others involve expanding the beam and using only a small region near the center where the variation in intensity is sufficiently small to be tolerable.³ These methods result in a substantial loss of usable laser beam power and require a high

degree of precision in aligning absorptive lens elements relative to the beam. Another method would result in very little loss in energy but would require high precision in aligning aspheric or graded refractive index elements relative to the incident Gaussian beam.⁴

In this report a method is described which makes direct use of the Gaussian intensity distribution in Equation 1 to provide a means of normalizing in the presence of the Gaussian intensity, without requiring a uniform beam intensity. In this approach the highly stable Gaussian intensity distribution of the TEM₀₀ beam provides a basis for the normalization. By this method the Gaussian intensity is an asset instead of a hindrance.

Concepts and Analysis

Multiple Detections of a Defect

The method of normalization developed here requires that there be multiple detections of a given defect with an arrangement of the type shown in Figure 1. However, multiple detections arise in a natural way when a circular spot of illumination is used to inspect an entire region of a surface without missing any of the surface. Consider the case in Figure 2. Even if the intensity of the laser beam were uniform so that the light scattered by a defect would be independent of its position in the illuminated spot, there would still have to be an overlap of the spots to ensure 100 percent inspection of the surface. In fact, if the illuminated spot is circular with $1/e^2$ diameter $2a$, the centers of adjacent spots cannot be separated by more than $\sqrt{2}a$ for 100 percent inspection, Figure 2. Therefore, even in the case of minimum overlap in Figure 2, there will be multiple detections of a given defect. A defect at point P_d would be detected by illuminated spots S_1 and S_2 , and a defect at point P' would be detected by four adjacent illuminated spots.

In an automated system in which a computer is used to sample the output of a photodetector placed at point P in Figure 1, the registration of multiple detections of a given isolated defect can be handled by a computer program designed to keep track of the positions of the illuminated spots on the reflective surface. A computer program of the latter type for recognizing the presence of a given isolated defect can be modified on the basis of the following theory to determine the normalized photodetector signal expected if the defect were located at the center of the Gaussian illuminated spot.

First, in order for the normalization to be accomplished with multiple detections in a Gaussian intensity beam, it is necessary that there be at least three detections. Two detections are not sufficient, as will be shown. Consider a defect

Figure 2. Mapping of Illuminated Spots on the Surface of Figure 1, Showing the Geometry for the Case of Minimum Overlap

at point P_d in Figure 2 which is detected twice by the two adjacent illuminated spots S_1 and S_2 , and let r_1 and r_2 be the distances of the defect from the centers of the two illuminated spots S_1 and S_2 , respectively. The scattered light observed with a photodetector placed at point P in Figure 1 is proportional to the light energy falling on the defect, which depends on its position relative to the center of the illuminated spot. Therefore, the scattered light signals W_1 and W_2 observed with the photodetector for the detections registered by the illuminated spots S_1 and S_2 , respectively, are

$$\begin{aligned} W_1 &= W_0 e^{-2r_1^2/a^2} \\ W_2 &= W_0 e^{-2r_2^2/a^2}, \end{aligned} \tag{2}$$

where W_0 is the scattered light which would be measured if the defect were positioned at the center of an illuminated spot of known $1/e^2$ radius a . For normalization, the value of W_0 is desired. The measured values W_1 and W_2 are known, but the values r_1 and r_2 are not known. If either were known, then W_0 could be calculated by solving the appropriate relation in Equation 2 for W_0 . However, when only two detections of the defect are considered, there are three unknowns r_1 , r_2 , and W_0 , but only two equations in these variables. Therefore, to determine the normalized value W_0 , more than two detections of a given defect must be considered.

Normalization for the Case in Which the Centers of Adjacent Spots Lie on the Vertices of a Square

As the surface under test in Figure 1 is moved in a plane perpendicular to the path of the incident laser beam, and a photodetector at point P is sampled at equal time intervals, the succession of illuminated spots on two adjacent scans on the surface can be represented schematically (Figure 3). The length L is the distance the surface moves in the time interval between successive readings of the photodetector. The quantity a is the $1/e^2$ radius of the illuminated spot on the surface, and the time interval between successive readings of the detector must be adjusted so that the overlap of adjacent spots on the surface is sufficient to avoid missing any region of the surface. A more detailed view is shown in Figure 4 in which a defect at point P_d , for example, will be detected by the illuminated spots S_1 and S_2 on one scan and by spots S_3 and S_4 on the adjacent scan. When the defect is illuminated by spot S_1 , the defect lies at an arbitrary distance r_1 from the center O_1 of the Gaussian intensity distribution of spot S_1 ; hence, the scattered light W_1 measured with the photodetector will be

$$W_1 = W_0 e^{-2r_1^2/a^2}, \quad (3)$$

where W_0 is the scattered light which would be measured if the defect were located at the center O_1 of the spot S_1 . Similarly, the defect at point P_d is located at distances r_2 and r_3 from the centers of the illuminated spots S_2 and S_3 , respectively. Therefore, the scattered light corresponding to spots S_2 and S_3 will be

$$W_2 = W_0 e^{-2r_2^2/a^2} \quad \text{and} \quad (4)$$

$$W_3 = W_0 e^{-2r_3^2/a^2}, \quad (5)$$

respectively, where W_0 is the scattered light which this particular defect would register if it were positioned at the center of any of the spots. When W_0 is eliminated between Equations 3 and 4, the result can be written in the form

$$r_2^2 - r_1^2 = 1/2a^2 \ln(W_1/W_2). \quad (6)$$

Similarly, W_0 can be eliminated from Equations 3 and 5 to give

$$r_3^2 - r_1^2 = 1/2a^2 \ln(W_1/W_3). \quad (7)$$

Figure 3. Mapping of the Illuminated Spots on the Surface of Figure 1 for the Case of Arbitrary Overlap of the Illuminated Spots of $1/e^2$ Diameter $2a$

The segments of lengths r_1 , r_2 , and r_3 joining the position of the defect with the centers of the illuminated spots S_1 , S_2 , and S_3 make angles β , ψ , and α , respectively, with the directions shown in Figure 4. The following relations can be written connecting r_1 , r_2 , and r_3 with the angles β , ψ , α , and the distance L between adjacent illuminated spots.

$$r_1 \cos \beta + r_2 \cos \psi = L \quad (8)$$

$$r_3 \cos \alpha + r_1 \sin \beta = L \quad (9)$$

$$r_1 \sin \beta = r_2 \sin \psi \quad (10)$$

$$r_1 \cos \beta = r_3 \sin \alpha \quad (11)$$

The quantities L and a are known in advance, and W_1 , W_2 , and W_3 are measured with the photodetector. Thus, Equations 6 and 7 together with Equations 8 through 11 constitute six equations in the six unknowns r_1 , r_2 , r_3 , α , β , and ψ . Equations 6 through 11 can be reduced to four equations in the four unknowns r_2 , r_3 , ψ , and α by first eliminating the quantity $r_1 \sin \beta$ from Equations 9 and 10 and then eliminating the quantity $r_1 \cos \beta$ from Equations 8 and 11. Also, r_1 can be eliminated between Equations 6 and 7. Finally, r_1 and β can be eliminated among Equations 10, 11, and 6 by squaring both sides of (10) and (11) and adding and combining with Equation 6. This procedure yields the four equations in the four unknowns r_2 , r_3 , α , and ψ

Figure 4. A Defect at Point P_d Is Shown Illuminated by Four Adjacent Spots S_1 Through S_4

$$L - r_3 \cos \alpha = r_2 \sin \psi \quad (12)$$

$$r_3 \sin \alpha + r_2 \cos \psi = L \quad (13)$$

$$r_2^2 - A = r_3^2 - B \quad (14)$$

$$r_2^2 \sin^2 \psi + A = r_2^2 - r_3^2 \sin^2 \alpha \quad (15)$$

$$\text{where } A = \frac{1}{2} a^2 \ln(W_1/W_2) \text{ , } B = \frac{1}{2} a^2 \ln(W_1/W_3). \quad (16)$$

The latter group of equations can be reduced to three equations in the three unknowns α , r_2 , and r_3 by eliminating ψ between Equations 12 and 15 and then between Equations 13 and 15. Equations 12 through 15 then yield

$$2Lr_3 \cos \alpha - A = L^2 + r_3^2 - r_2^2 \quad (17)$$

$$L^2 - A = 2Lr_3 \sin \alpha \quad (18)$$

$$r_2^2 - A = r_3^2 - B. \quad (19)$$

When Equations 17 and 18 are solved for $\cos\alpha$ and $\sin\alpha$, and the results are squared, added, and combined with Equation 19, the following expression for r_3^2 is obtained.

$$r_3^2 = \frac{(L^2 - A)^2 + (L^2 + B)^2}{4L^2} \quad (20)$$

But, $W_3 = W_0 \exp(-2r_3^2/a^2)$ from Equation 5 and, therefore, the scattered light W_0 , which the defect would produce if it were located at the center of an illuminated spot in Figure 4, can be obtained by substituting Equation 20 into Equation 5 and solving for W_0 to give

$$W_0 = W_3 \exp \left[\frac{(L^2 - A)^2 + (L^2 + B)^2}{2a^2 L^2} \right]. \quad (21)$$

In the latter, the quantities A and B are defined in Equation 16 in terms of the measured values W_1 , W_2 , W_3 , and the $1/e^2$ beam radius a. Therefore, when the surface of Figure 1 is illuminated normally with a Gaussian beam of known $1/e^2$ radius a, and the spots of illumination are mapped on the surface at equal known adjacent distances L (Figure 3), the normalized scattered light W_0 which would be measured if the defect were located at the center of any spot can be calculated from Equation 21 in which A and B are defined in terms of three measurements W_1 , W_2 , and W_3 of the scattered light corresponding to an arbitrary position of the defect relative to the center of a spot.

The expression for r_3^2 in Equation 20 can be used to solve for the distance r_2 from Equations 19 and 16, and the distance r_1 can be obtained from Equation 6. The angles α , ψ , and β can then be determined from Equations 18, 13, and 11, thereby fully defining the position of the defect relative to the illuminated spots. However, the expression for W_0 in Equation 21 is sufficient to determine the normalized value W_0 in terms of the measured quantities W_1 , W_2 , and W_3 and the known values of a and L.

Case in Which the Centers of Adjacent Illuminated Spots Do Not Lie on the Vertices of a Square

Consider Figure 5 in which the centers of the adjacent illuminated spots mapped on the surface under consideration do not lie on the vertices of squares. The distance between successive illuminated spots on any scan is L and the distance between adjacent scans is also L, but the centers of illuminated spots on two adjacent

Figure 5. Mapping of Illuminated Spots on the Surface of Figure 1 for the Case in Which the Centers of Adjacent Spots Do Not Lie on the Vertices of a Square

scans are offset by a known amount h . Inspection of Figure 5 shows that the group of Equations 6 through 11, considered earlier in reference to Figure 4, also apply to the geometry in Figure 5 provided Equation 11 is replaced by the expression

$$r_1 \cos \beta = r_3 \sin \alpha - h, \quad (22)$$

where h is the known amount of offset. If Equation 22 is used in place of Equation 11 then the six equations in six unknowns can be solved as before to yield expressions for r_3 and W_0 which correspond to those in Equations 20 and 21. When this is done, the results are

$$r_3^2 = \frac{[(L+h)^2 - A - h^2]^2 + \{B + L^2 + h^2 - h/L[(L+h)^2 - A - h^2]\}^2}{4L^2} \quad (20A)$$

$$W_0 = W_3 \exp \left[\frac{[(L+h)^2 - A - h^2]^2 + \{B + L^2 + h^2 - h/L[(L+h)^2 - A - h^2]\}^2}{2a^2 L^2} \right], \quad (21A)$$

where A and B are the same quantities defined earlier in Equation 16. When $h = 0$, the latter two equations reduce to Equations 20 and 21.

Comparison Between Analysis and Results

The derived procedure for normalization is in reference to flat surfaces. The particular application discussed here and the data given are for a spherical surface, but the theory given previously applies equally well to the spherical surface for the case in which the illuminated spot size is much smaller than the radius of the sphere. The experimental arrangement is shown schematically in Figure 6. Light from a helium-neon laser is passed through a spatial filter to remove unwanted intensity variations. A lens is used to collimate the beam emerging from the pinhole of the spatial filter, and a lens of focal length f brings the collimated beam to a virtual focus at the center of a highly reflective sphere of radius R . With this arrangement, each ray in the converging cone of light is incident normally on the spherical surface and is, therefore, retroreflected from the surface. The retroreflected light is diverted 90 degrees by a thin membrane beamsplitter (pellicle), and a lens brings the light to focus at point P, which is analogous to the focused point P in Figure 1.

The theory of normalization was tested experimentally by measuring the scattered light from small isolated defects on a highly reflective 18-mm diameter spherical surface. The very smooth spherical metal surface had an arithmetic average (AA) surface finish of approximately $0.008 \mu\text{m}$. The sphere was positioned in a two-axis rotary fixture which made it possible to rotate the sphere accurately about two perpendicular intersecting axes as indicated in Figure 7. Complete revolutions were made about the horizontal axis and incremental rotations were made about the vertical axis. The sphere was set into motion at an appropriate speed about the axis and this was maintained constant. The computer received a signal representing "go", corresponding to an arbitrary zero on the angle θ . When the computer received the go signal, corresponding to $\theta = 0^\circ$, it then sampled the output of the detector at point P at equal time intervals. When one revolution was completed, the computer signaled the rotary table to rotate through the increment $\Delta\phi$ about the vertical axis and the sequence was then repeated.

The motion of the surface in the θ - and ϕ -directions in Figure 7 was controlled and monitored by the computer; therefore, the mapping of the illuminated spots on the spherical surface was accurately known. That is, as the surface was moved in the θ -direction relative to the incident beam, the time interval between successive samplings of the detector was controlled by the 100 kHz clock of the computer and thus the distance L was accurately known. Moreover, for a given position of the surface in the ϕ -direction, the starting point of the scan in the θ -direction was accurately known and hence this precisely determined the value of the offset h for any two adjacent scans in the θ -direction.

Figure 6. Optical Arrangement Used in Testing the Theory of Normalization for Small Isolated Defects on a Reflective Spherical Surface

Further details of the equipment for semi-automated inspection of superfinished spherical surfaces have been reported previously.⁵

Determination of the $1/e^2$ Radius of the Illuminated Spot on the Surface of the Sphere

In order to perform the normalization with the aid of Equations 20 and 21, or Equations 20A and 21A, it is necessary to know the value of the $1/e^2$ radius a of the illuminated spot on the surface of the sphere in Figure 7. The value of a can be approximated by assuming geometrical optics related to a thin lens and calculating a in terms of the known values of the spherical radius R and diameter of the raw laser beam before its expansion. From the geometry of Figure 7, the relationship between similar triangles gives

$$\frac{a}{R} \approx M \frac{d_r}{2f}, \quad (23)$$

Figure 7. Details of the Geometry for Determining the $1/e^2$ Radius of the Illuminated Spot on the Spherical Surface in Terms of the Raw Laser Beam Diameter d_r , the Spherical Radius R , and the Focal Length f of the Lens

where M is the factor by which the raw laser beam is expanded after it passes through the spatial filter and is re-collimated. In the arrangement used, $M = 10/3$, the spherical radius $R = 9$ mm, $f = 100$ mm, and $d_r = 0.8$ mm. Therefore, the value of the $1/e^2$ radius a of the illuminated spot on the spherical surface, according to Equation 23, is

$$a = 0.12 \text{ mm.} \quad (24)$$

The value of a was determined more directly by the following experimental technique. A sphere with a defect small in comparison with the value of a in Equation 24 was aligned in the two-axis rotary fixture in Figure 7 in such a way that the defect on the spherical surface could be rotated through the center of the illuminated spot. Then, the sphere was set into motion at a constant rate sufficiently low that the computer received approximately 20 signals of the scattered light during the passage of the defect into one edge of the Gaussian spot, through the center,

and finally out through the other edge of the spot. The experimentally-measured signals versus arc length on the spherical surface are given in Figure 8. The open circles represent the ratio of the measured scattered light to that measured at the center, $r = 0$, versus the distance r from the center of the illuminated spot. The solid curve in Figure 8 is a best-fit Gaussian of the form $I = I_0 \exp(-2r^2/a^2)$, where $a = 0.1419$ mm.

The value of a in Equation 24 determined indirectly on the basis of geometrical optics is within 15 percent of the latter best-fit measured value. In all the following calculations of normalization, the best-fit value of $a = 0.1419$ mm was used, because this value is based on direct measurement of the Gaussian profile of the illuminated spot on the surface.

Normalization and Comparison of Experiment With Theory

Equation 21 and the counterpart Equation 21A, for the case of offset scans, provide the basis on which the normalized scattered light W_0 , corresponding to the defect centered in the illuminated spot, can be calculated from three measured signals obtained from an arbitrary defect position. After the normalized value, W_0 , is determined from this procedure, a check of the theory and the consistency of the data can be made by using the normalized value, W_0 , and the corresponding known position of the defect relative to the illuminated spots to calculate the expected scattered light from an illuminated spot different from any of the three spots from which W_0 itself was determined. Then, this predicted value of scattered light can be compared with that observed experimentally for the corresponding illuminated spot. The most obvious case is the calculation of the scattered light expected from the illuminated spot forming the fourth vertex of the square which has O_1 , O_2 , and O_3 as the other three vertices in Figure 4. The general case is shown in Figure 9. The measured values W_1 , W_2 , and W_3 from which W_0 is calculated correspond to illuminated spots S_1 , S_2 , and S_3 , respectively, with centers at O_1 , O_2 , and O_3 . The fourth spot forming the fourth vertex has its center at point O_4 and gives a measured value W_4 . In general, consider the illuminated spot $S_{N,M}$ which gives a measured value $W_{N,M}$. The center of this spot is at point $O_{N,M}$ located N units of the interval L in the vertical direction from O_4 and M units of L horizontally to the right of O_4 as indicated in Figure 9. Let $u = (u_x^2 + u_y^2)^{1/2}$ be the distance from point O_4 to point $O_{N,M}$. The value of scattered light $W_{N,M}$ corresponding to the illuminated spot $S_{N,M}$ is thus given by

$$W_{N,M} = W_0 e^{-2(u_x^2 + u_y^2)/a^2}, \quad (25)$$

Figure 8. Ratio of Measured Scattered Light at Distance r to Scattered Light at $r = 0$, Versus the Distance of a Small Defect From the Center of the Gaussian Illuminated Spot of $1/e^2$ Radius a

Figure 9. Mapping of the Centers of Illuminated Spots for the Case in Which There Is an Offset h

where W_0 is the normalized value determined earlier. From Figure 9 it can be seen that

$$u_x = NL + r_3 \cos \alpha, u_y = ML + L - Nh - r_3 \sin \alpha, \quad (26)$$

$$\text{where } \alpha = \arcsin \left[\frac{(L+h)^2 - A - h^2}{2Lr_3} \right]. \quad (27)$$

Therefore, the scattered light corresponding to the illuminated spot with center at $O_{N,M}$ can be calculated from Equation 25, with u_x , u_y , and α given by Equations 26 and 27.

Data was obtained from a number of isolated defects and the results are summarized in Table 1. The value of L , which is the distance between successive illuminated spots on a given scan and also the distance between adjacent scans, is given in the table, along with the value of offset h . The normalized value, W_0 , corresponding to the value which would be measured if the defect were located at the center of the illuminated spot is given in the table. For each defect, the values of A and B in Equation 16 were calculated from the three largest measured values W_1 , W_2 , and W_3 obtained for the particular defect. It should be noted that the photodetector gave a background signal even when the Gaussian spot in Figure 1 was incident on a defect-free region of the reflective surface. The background signal resulted from residual scattering from the minute undulations of the very smooth (but not perfect) test surface. The measured values W_1 , W_2 , and W_3 obtained when defects were present were corrected for the background signal prior to performing the calculations of normalization, but the values of W_0 given in the table include the background because it would be present in any measurement made. All the measurements were obtained under automated conditions; therefore, only by chance would a defect appear at the center of any illuminated spot. It follows that the normalized value, W_0 , for each defect should be greater than any of the measured values W_1 , W_2 , W_3 , or W_4 . This case is indicated by the data of Table 1 giving the ratio of the calculated normalized value W_0 to the maximum observed value of W . Also given in Table 1 are the calculated and observed values of W_4 . The calculated value of W_4 was obtained from Equations 25 through 27 with $N = M = 0$ corresponding to point O_4 in Figure 9. From the table, the agreement between the observed and calculated values of W_4 is better than 11 percent except in one case.

The calculation of W_4 involves setting $N = M = 0$ in Equation 26. Data was also obtained by comparing the theory with experiments for the case in which $N \neq 0$ and $M \neq 0$, and the results are summarized in Table 2. The position of the illuminated spot for which the reading $W_{N,M}$ was obtained, relative to the three spots from which the readings W_1 , W_2 , and W_3 were obtained, can be determined from Figure 9. The data in Table 2 show that the observed and calculated values of $W_{N,M}$ agree within 9 percent or better.

Finally, a further check on the theory was made by comparing the calculated normalized values of W_0 obtained under experimental conditions in which different sampling intervals L were used. This was done for five defects, and two different values of L were used in each case. The results are given in Table 3. The offset h was zero in each case. The normalized values of W_0 , calculated from Equations 20 and 21 for each defect for both intervals of L used, are given in the table. The normalized values W_0 obtained with the two different values of L agree within 2 percent or better for each defect.

Table 1. Comparison of Observed and Calculated Values of W_4 for Six Different Defects

Defect (Number)	h (mm)	L (mm)	Calculated Value of W_0^* (μW)	Ratio of W_0^{**}	W_4		
					Observed (μW)	Calculated (μW)	Difference (Percent)
1	0.0145	0.0629	1.74	1.01	1.67	1.60	- 4
2	0.0140	0.0898	8.09	1.15	4.68	4.33	- 7
3	0.0048	0.0898	13.51	1.22	7.45	7.83	5
4	0.0721	0.0898	2.90	1.12	2.71	2.55	- 6
5	0.0132	0.0898	9.85	1.13	5.91	5.49	- 7
6	-0.0346	0.0898	17.4	1.11	6.85	7.59	11

*expected if defect was at center of illuminated spot

**to maximum value of W observed

The $1/e^2$ radius of the incident laser beam was 0.1419 mm.

Table 2. Comparison of Observed and Calculated Values of $W_{N,M}$ for Three Different Defects

Defect (Number)	h (mm)	L (mm)	Calculated Value of W_0^* (μW)	N,M	$W_{N,M}$		Difference (Percent)
					Observed (μW)	Calculated (μW)	
1	0	0.0629	2.81	0,0	2.37	2.28	-4
	0	0.0629	2.81	0,1	1.81	1.68	-7
	0	0.0629	2.81	-1,1	1.84	1.75	-4.7
	0	0.0629	2.81	0,-2	2.05	2.00	-2.5
	0	0.0629	2.81	-1,-2	2.30	2.14	-7
	0	0.0629	2.81	-1,-2	2.30	2.14	-7
2	0	0.0629	1.78	0,0	1.69	1.71	1
	0	0.0629	1.78	0,1	1.63	1.49	-8.7
	0	0.0629	1.78	1,-1	1.65	1.55	-6
3	-0.0214	0.0898	2.71	0,0	1.81	1.68	-7
	-0.0214	0.0898	2.71	-1,-2	1.90	1.84	-3
	-0.0214	0.0898	2.71	-2,-1	1.69	1.56	-8.7

*expected if defect was at center of illuminated spot

The data was obtained with an incident laser beam of $1/e^2$ radius equal to 0.1419 mm.

Table 3. Comparison of Normalized Values of W_0

Defect (Number)	L (mm)	Calculated Value of W_0 * (μW)	Difference (Percent)**
1	0.0898	2.27	2
	0.0629	2.32	
2	0.0898	1.96	0.5
	0.0629	1.97	
3	0.0898	2.15	1.9
	0.0629	2.19	
4	0.0898	3.20	1.9
	0.0629	3.14	
5	0.0898	2.71	1.8
	0.0629	2.76	

*expected if defect was at center of illuminated spot

**between calculated values of W_0 corresponding to the two values of L

The data was determined with two different L distances between illuminated spots, for each of five different defects.

ACCOMPLISHMENTS

A method was developed for normalizing the scattered light from a surface defect, located at an arbitrary point within a Gaussian illuminated spot on the surface, to the value of scattering which would occur if the defect were located at the center of the Gaussian intensity distribution. The method is useful in the automated detection of surface defects illuminated with the Gaussian intensity of a TEM₀₀ laser beam, because a defect will, in general, appear at an arbitrary location within the Gaussian distribution of intensity. Past methods of normalization have been directed at transforming the Gaussian intensity into a uniform intensity over a certain region in space. These methods result in substantial loss of light energy from the beam and require a high degree of precision in aligning optical elements relative to the beam. The method of normalization developed in the present work makes direct use of the stable Gaussian distribution of intensity from a laser operated in the TEM₀₀ mode and does not require selective absorption or other alteration of the

beam. The present method requires only that there be three measurements of the scattered light from a given defect and that the distances between adjacent illuminated spots and the $1/e^2$ radius of the illuminated spot are known.

Experimental data was obtained which verified the theory. First, the normalized value of scattered light for several defects was determined from three measurements for each defect, and then the normalized value was used to predict the scattered light expected from illuminated spots different from those on which the normalization was based. The calculated values were within a few percent of the experimentally observed values. Also, the normalization was performed for several defects, each of which was measured with two different intervals between adjacent illuminated spots. The normalized values corresponding to the measurements made with two different intervals agreed with each other for each defect, as expected from the theory.

FUTURE WORK

No further work is planned at present. If it becomes necessary to seek means of improving the repeatability of the semi-automated laser surface inspection system, then the method of normalization developed in the present work should be used to modify the existing computer programs for defect recognition and analysis.

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The intensity distribution of the beam from a laser operated in the TEM₀₀ mode is Gaussian in a plane perpendicular to the axis of the beam. A method of normalization is described which makes direct use of the Gaussian intensity distribution of the TEM₀₀ mode. The normalization requires that three measurements be made of the scattering by the defect for an arbitrary location of the defect relative to the center of the beam.

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