A METHOD OF NORMALIZING THE MEASURED
SCATTERED LIGHT FROM A SURFACE DEFECT
LOCATED ARBITRARILY IN A GAUSSIAN
INTENSITY DISTRIBUTION INCIDENT ON THE
SURFACE

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ABSTRACT

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. 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 TEM₀₀ 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 beam. Experimental data was obtained which verifies the theory.

I. INTRODUCTION

The TEM₀₀ mode of operation is the most commonly employed mode for a laser. 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 and 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 Fig. 1 in which a collimated laser beam of $1/e^2$ diameter $2a$ passes through a beamsplitter and is incident normally on 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 light energy. However, a small defect occurring near the central portion of the incident beam may produce scattered light

energy equal to or greater than a large defect illuminated by the outer portion of the 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 Fig. 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 useable power of the laser beam 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 the present paper a method is described which makes direct use of the Gaussian intensity distribution in Eq. (1) to provide a means of normalizing in the presence of the Gaussian intensity, without requiring a uniform beam intensity. In this method the highly stable Gaussian intensity distribution of the TEM₀₀ beam provides a basis for the normalization. In this approach the Gaussian intensity is an asset instead of a hindrance.

II. THEORY

A. Multiple Detections of a Defect

The method of normalization developed below requires that there be multiple detections of a given defect with an arrangement of the type shown in Fig. 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 Fig. 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 insure 100% 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% inspection, as indicated in Fig. 2. Therefore, even in the case of minimum overlap in Fig. 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 Fig. 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 theory given below 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 3 detections. Two detections are not sufficient, as will be shown. Consider a defect at point P_d in Fig. 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 Fig. 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

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

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 Eq. (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.

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

As the surface under test in Fig. 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 as in Fig. 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 Fig. 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 and 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

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

and

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

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 Eqs. (3) and (4), the result can be written

in the form

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

Similarly, W_0 can be eliminated from Eqs. (3) and (5) to give

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

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 Fig. 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 Eqs. (6) and (7) together with Eqs. (8) through (11) constitute six equations in the six unknowns r_1 , r_2 , r_3 , α , β , and ψ . Eqs. (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 Eqs. (9) and (10) and then eliminating the quantity $r_1 \cos \beta$ from Eqs. (8) and (11). Also, r_1 can be eliminated between Eqs. (6) and (7). Finally, r_1 and β can be eliminated among Eqs. (10), (11), and (6) by squaring both sides of (10) and (11) and adding and combining with Eq. (6). This procedure yields the four equations in the four unknowns r_2 , r_3 , α , and ψ

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

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

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

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

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

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 Eqs. (12) and (15) and then between Eqs. (13) and (15). Eqs. (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 Eqs. (17) and (18) are solved for $\cos \alpha$ and $\sin \alpha$, and the results are squared, added, and combined with Eq. (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 Eq. (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 Fig. 4 can be obtained by substituting Eq. (20) into Eq. (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 Eq. (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 Fig. 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 (Fig. 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 Eq. (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 Eq. (20) can be used to solve for the distance r_2 from Eqs. (19) and (16), and the distance r_1 can then be obtained from Equation (6). The angles α , ψ , and β can also then be determined from Eqs. (18), (13), and (11), thereby fully defining the position of the defect relative to the illuminated spots. However, the expression for W_0 in Eq. (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 .

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

Consider Fig. 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 scans are offset by a known amount h . Inspection of Fig. 5 shows that the group of Eqs. (6) through (11) considered earlier in reference to Fig. 4 also apply to the geometry in Fig. 5 provided Eq. (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 Eq. (22) is used in place of Eq. (11) then the 6 equations in 6 unknowns can be solved as before to yield expressions for r_3 and W_0 which correspond to those in Eqs. (20) and (21). When this is done, the results are

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

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

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

III. EXPERIMENTAL

The foregoing theory was tested experimentally by measuring the scattered light from small isolated defects on a highly reflective surface with an arrangement similar to that indicated schematically in Fig. 1. Light from a helium-neon laser was incident normally on a very smooth metal surface which had an arithmetic average (AA) surface finish of approximately $0.008 \mu\text{m}$. The light reflected from the surface was diverted by a beamsplitter and a lens was used to focus the light to a point P shown at the origin of a coordinate system designated by $x'-z'$ in Fig. 1. As the surface is moved in the $x-y$ plane and a small defect passes into the path of the incident beam, a certain amount of light is scattered outside the focussed spot at point P . The amount of scattered light depends not only on the size of the defect but also on its position relative to the center of the illuminated spot. A small stop was used to block the focussed spot of light and a photodetector was placed behind the stop at

point P which allowed the light scattered outside the focussed spot to be detected and measured. The output from the photodetector was interfaced with a computer and hence the detector could be sampled at variable but precisely known time intervals by making use of the 10^5 Hz clock of the computer. The motion of the surface in the x and y directions in Fig. 1 was controlled and monitored by the computer and therefore the mapping of the illuminated spots on the surface corresponding to the distances L and h in Eqs. (20) and (20A), was accurately known.

A. Determination of the $1/e^2$ Diameter of the Illuminated Spot on the Surface

In order to perform the normalization with the aid of Eqs. (20) and (21), or Eqs. (20A) and (21A), it is necessary to know the value of the $1/e^2$ radius a of the illuminated spot on the surface in Fig. 1. In the optical arrangement used, the raw beam of $1/e^2$ diameter d_r from a helium-neon laser was passed through a spatial filter to remove unwanted variations in the intensity, and the light emerging from the pinhole of the filter was recollimated with a lens of focal length such that the illuminated spot diameter 2a was somewhat less than the raw beam diameter d_r . On the basis of geometrical optics, the value of 2a was given by

$$2a = 0.3 d_r \quad , \quad (23)$$

where 0.3 is the factor by which the raw beam diameter was de-magnified. The $1/e^2$ diameter d_r of the laser beam was 0.8 mm and therefore according to Eq. (23) the $1/e^2$ radius a of the illuminated spot on the surface in Fig. 1 was

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

The latter method of determining a is somewhat indirect and therefore a more direct measurement was made as follows. A small defect was selected on the reflective surface and the position of the surface was adjusted in the y -direction of Fig. 1 so that the defect would pass through the center of the illuminated spot as the surface was subsequently moved in the x -direction. Next, the surface was moved in the x -direction and the computer was used to measure the scattered light at point P by sampling the photodetector at closely spaced intervals as the defect was moved through the illuminated spot. This corresponded to a very small value of L and provided a very large number of samples of the scattered light versus position of the defect within the illuminated spot. The measurements of scattered light versus position of the defect within the illuminated spot are given in Fig. 6. 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 Fig. 6 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 Eq. (24) determined indirectly on the basis of geometrical optics is within 15% of the latter best-fit measured value. In all the calculations of normalization referred to below, 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.

B. Normalization and Comparison of Experiment with Theory

Eq. (21), and the counterpart Eq. (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. This predicted value of scattered light can then 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 Fig. 4. The general case is shown in Fig. 7. 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 a distance $ML - Nh$ horizontally to the right of O_4 as indicated in Fig. 7. Let $u = (u_x^2 + u_y^2)^{1/2}$ be the distance from point P_d 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

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

where W_0 is the normalized value determined earlier. From Fig. 7 it can be seen that

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

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

(Eq. (27) includes the effect of the offset h and is analogous to Eq. (18) for a square.) Therefore, the scattered light corresponding to the illuminated spot with center at $O_{N,M}$ can be calculated from Eq. (25) with u_x , u_y , and α given by Eqs. (26) and (27).

Data was obtained from a number of isolated defects and the results are summarized in Table I. 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 Eq. (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 Fig. 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 and 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 is the case as indicated by the data of Table I giving the ratio of the calculated normalized value W_0 to the maximum observed value of W . Also given in Table I are the calculated and observed values of W_4 . The calculated value of W_4 was obtained from Eqs. (25)-(27), with $N = M = 0$ corresponding to point O_4 in Fig. 7. From the table,

the agreement between the observed and calculated values of W_4 is better than 11% except in one case.

The calculation of W_4 involves setting $N = M = 0$ in Eq. (26). Data was also obtained comparing the theory with experiment for the case in which $N \neq 0$ and $M \neq 0$, and the results are summarized in Table II. 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 Fig. 7. The data in Table II show that the observed and calculated values of $W_{N,M}$ agree within 9% 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 5 defects, and two different values of L were used in each case. The results are given in Table III. The offset h was zero in each case. The normalized values of W_0 , calculated from Eqs. (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% or better for each defect.

IV. SUMMARY

When a highly reflective surface containing small isolated defects and illuminated with a Gaussian intensity beam as in Fig. 1 is moved in an automated fashion in the x-y plane, the isolated defects can be detected by monitoring the scattered light at point P with a photodetector which is sampled at appropriate equal intervals to avoid missing any of the surface. Any given defect will appear at an arbitrary point relative to the mapping of the centers of the illuminated spots on the surface and

therefore the scattered light does not in general provide a good measure of the defect size because a relatively large defect appearing near the edge of the Gaussian spot may not scatter as much light as a smaller defect appearing near the center of the spot. However, if at least three measurements W_1 , W_2 , and W_3 are made of the light scattered from a given defect then the scattered light can be normalized to the value it would have if the defect were located at the center of the Gaussian intensity distribution of the illuminated spot. The normalization is accomplished with the aid of Eqs. (16), (20), and (21) for the case in which the centers of adjacent illuminated spots form a square of known sides L (see Fig. 3) and the $1/e^2$ radius a of the incident Gaussian intensity is also known. If the centers of adjacent illuminated spots do not lie on the vertices of a square but instead there is a known offset h as indicated in Fig. 5, then the normalization can be accomplished with Eqs. (16), (20A), and (21A) provided L and a are known and three measurements of the scattered light from a given defect are made. Experimental data verifying the theory was obtained.

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LIST OF FIGURES

- Figure 1. An arrangement in which a collimated laser beam of $1/e^2$ diameter $2a$ is incident normally on a reflective surface. The retroreflected light from the surface is diverted by a beamsplitter and brought to focus at point P by a lens. A small defect on the surface will scatter light outside the focussed spot at P, in the $x'z'$ plane, but the amount of scatter for a given defect is dependent on the position of the defect relative to the center O of the Gaussian intensity distribution.
- Figure 2. Mapping of illuminated spots on the surface of Figure 1 showing the geometry for the case of minimum overlap (at the $1/e^2$ diameter of $2a$) so that no part of the surface is missed. A defect at point P_d would be detected by the two spots S_1 and S_2 .
- 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 centers of adjacent illuminated spots lie on the vertices of a square which has its sides of length L.
- Figure 4. A defect at point P_d is illuminated by four adjacent spots S_1 , S_2 , S_3 , and S_4 . The centers O_1 , O_2 , O_3 , and O_4 of the illuminated spots form a square of side L. The defect is at distances r_1 , r_2 , and r_3 from the centers of spots S_1 , S_2 , and

S_3 , respectively.

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. The distance between adjacent spots on a given scan is L and adjacent scans are also separated by the distance L , but the centers on adjacent scans are offset by the distance h .

Figure 6. Ratio of measured scattered light at distance r to scattered light at $r = 0$, versus the distance r of a small defect from the center of the Gaussian illuminated spot of $1/e^2$ radius a . The open circles represent the measured intensity ratios and the solid curve is a best-fit Gaussian with $a = 0.1419$ mm.

Figure 7. Mapping of the centers of illuminated spots for the case in which there is an offset h . The signals obtained from the spots with centers at points O_1 , O_2 , and O_3 are used for calculating the normalization from Eq. (21A). The signal from an illuminated spot with center at point $O_{N,M}$ can be calculated from Eqs. (25)-(27), where u is the distance from the defect at point P_d to the point $O_{N,M}$. If $N = M = 0$, the value of u is the distance to the point O_4 .

TABLE I. Comparison of Observed and Calculated Values of W_4 for Six Different Defects. The $1/e^2$ Radius of the Incident Laser Beam was 0.1419 mm.

Defect No.	h (mm)	L (mm)	Calculated Value of W_0 Expected if Defect Were at Center of Illuminated Spot	Ratio of W_0 to Maximum Value of W Observed	W_4		
					Observed	Calculated	Percentage Difference
1	.0145	.0629	1.74 μW	1.01	1.67 μW	1.60 μW	- 4%
2	.0140	.0898	8.09	1.15	4.68	4.33	- 7
3	.0048	.0898	13.51	1.22	7.45	7.83	5
4	.0721	.0898	2.90	1.12	2.71	2.55	- 6
5	.0132	.0898	9.85	1.13	5.91	5.49	- 7
6	-.0346	.0898	17.40	1.11	6.85	7.59	11

TABLE II. Comparison of Observed and Calculated Values of $W_{N,M}$ for Three Different Defects. The Data was Obtained with an Incident Laser Beam of $1/e^2$ Radius Equal to 0.1419 mm.

Defect No.	h (mm)	L (mm)	Calculated Value of W_0 Expected if Defect Were at Center of Illuminated Spot	N,M	$W_{N,M}$		
					Observed	Calculated	Percentage Difference
I.	0	.0629	2.81 μW	0,0	2.37 μW	2.28 μW	- 4%
	"	"	"	0,1	1.81	1.68	- 7
	"	"	"	-1,1	1.84	1.75	-4.7
	"	"	"	0,-2	2.05	2.00	-2.5
	"	"	"	-1,-2	2.30	2.14	- 7
II.	0	.0629	1.78	0,0	1.69	1.71	1%
	"	"	"	0,1	1.63	1.49	-8.7
	"	"	"	1,-1	1.65	1.55	- 6
III.	-.0214	.0898	2.71	0,0	1.81	1.68	- 7%
	"	"	"	-1,-2	1.90	1.84	- 3
	"	"	"	-2,-1	1.69	1.56	-8.7

TABLE III. Comparison of Normalized Values W_0 Determined with Two Different Distances L Between Adjacent Illuminated Spots, for Each of Five Different Defects.

Defect No.	L (mm)	Calculated Value of W_0 Expected if Defect Were at Center of Illuminated Spot	Percentage Difference between Calculated Values of W_0 Corresponding to the Two Values of L , for Each Defect
1	.0898	2.27 μW	2%
	.0629	2.32	
2	.0898	1.96	0.5%
	.0629	1.97	
3	.0898	2.15	1.9%
	.0629	2.19	
4	.0898	3.20	1.9%
	.0629	3.14	
5	.0898	2.71	1.8%
	.0629	2.76

Fig 7