Mulith

Overview of Reference Distribution Real Image Formation Technology

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ABSTRACT

A semi-qualitative overview of RIF (reference distribution real image formation) technology is presented. The physics that underlies RIF has been developed (elsewhere) from basic principles. As part of that development, the previously unknown result that *two illuminated object points are required to form light waves that contribute to real image formation* was identified. This cooperative phenomenon has been used to form real images with resolution that far exceeds the commonly accepted optical diffraction limit. RIF technology is a practical application of the science linked to the cooperative phenomenon. Real time formation of enormously magnified (or demagnified) full-color optical real images with a very large depth of field and complete resolution is predicted to be achievable by means of RIF.

PLAN OF THE PAPER

I. INTRODUCTION

A nonlocal theory of optical real image formation, based on fundamental quantum physics, has been developed[1]. Reference distribution real image formation (RIF) technology is being established as a practical application of the new theory.

Applications of RIF technology to advanced optical microscopy, optical nanolithography, and passive ghost imaging have been identified and partially developed. Expectations are that many currently unknown applications of RIF technology will be identified and developed as time progresses.

With RIF, light that propagates away from a reference distribution, in addition to light that propagates away from a subject distribution, occurs. The reference distribution is usually (but not necessarily) separated physically from the subject distribution. A real image of both the subject and the reference distribution is formed. When RIF is used, no known fundamental resolution limit exists.

Historically, it has been widely assumed that only one illuminated point (a mathematical point that is infinitely small) in the subject is needed to support image-forming light. However, in accord with the new theory, at least two separate illuminated points are needed to support image-forming light. The consequences of this discovery are far-reaching and profound.

Laboratory demonstrations[2] have verified principal predictions of the new theory. No contrary results have been observed. Real time formation of enormously magnified (or demagnified) full-color optical real images with a very large depth of field and complete resolution is predicted to be achievable by means of RIF.

II. RIF CONCEPT

Consider the conceptual illustration of transmission RIF provided in Figure 1. Initially, light is incident (from the left) upon an opaque screen with two apertures in it. The side of the screen nearest to the imaging system (shown as a lens) serves as an object plane.

Incident light passes through the apertures to form two distributions of light on the object plane. The distributions of light are designated as the subject distribution and the reference distribution.

Taken separately, the propagation angles of the light that travels away from either of the two distributions of light are larger than the acceptance angle of the imaging system. Such light does not pass through the imaging system and consequently does not contribute to image formation.

Taken together, the propagation angles of the light that travels away from the combined distributions of light are smaller than the acceptance angle of the imaging system. This light defines a finite bandwidth and is transferred, without amplitude or phase distortion, through the imaging system. Consequently, light that propagates away from the combined distributions of light contributes to undistorted image formation.

No two points in either the subject distribution or the reference distribution are sufficiently separated to contribute to image formation. Every pair of points such that one point is in the subject distribution and one point is in the reference distribution is sufficiently separated to contribute to image formation.

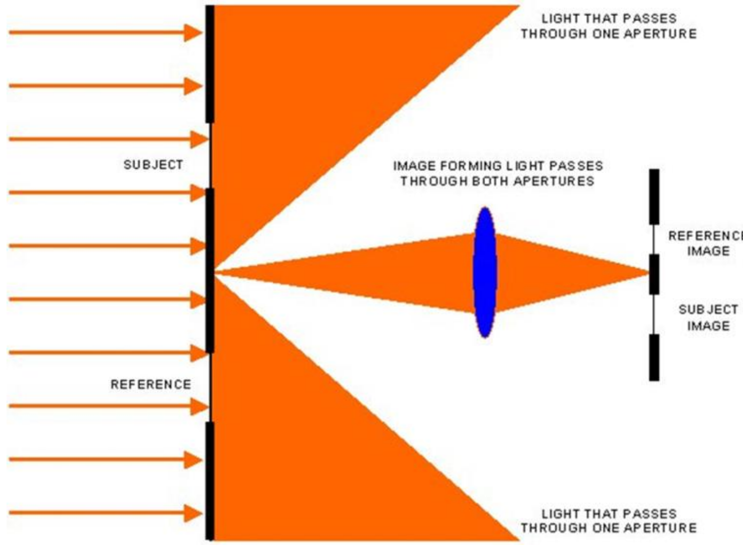


FIGURE 1. CONCEPTUAL RIF PROCESS

III. REAL IMAGE FORMATION

A return to first principles was used to develop the fundamental real image formation optics that underlies RIF[3]. Development of fundamental optics is ordinarily based upon the Huygens-Fresnel principle and various improvised approximations. This conventional approach differs substantially from the approach used to develop the theoretical underpinnings of RIF.

The Huygens-Fresnel principle is not a law of physics and is furthermore known to be problematic[4]. In addition, a series of *Ad hoc* approximations (such as initial approximations, the Fresnel approximations, the Fraunhofer approximation, etc.) are invoked in derivations that are based upon the Huygens-Fresnel principle. None of these derivations can be considered to be fundamentally correct.

Fundamental principles of optics are independent of the Huygens-Fresnel principle. Accordingly, the Huygens-Fresnel principle and its attendant approximations were avoided in the development of the nonlocal optical real image formation theory. Rather, the new theory is based on fundamental quantum physics.

Real image formation is achieved by means of an image formation apparatus. Consider the simple image formation apparatus illustrated in Figure 2. A plane subject, shown as a small green arrow, exists in the object plane; an image of this subject, shown as a large green arrow, exists in the image plane. The image is formed by light that interacts with the subject, then propagates through the imaging system and ultimately arrives at the image plane. The image closely resembles an unchanged or resized and possibly inverted version of the subject.

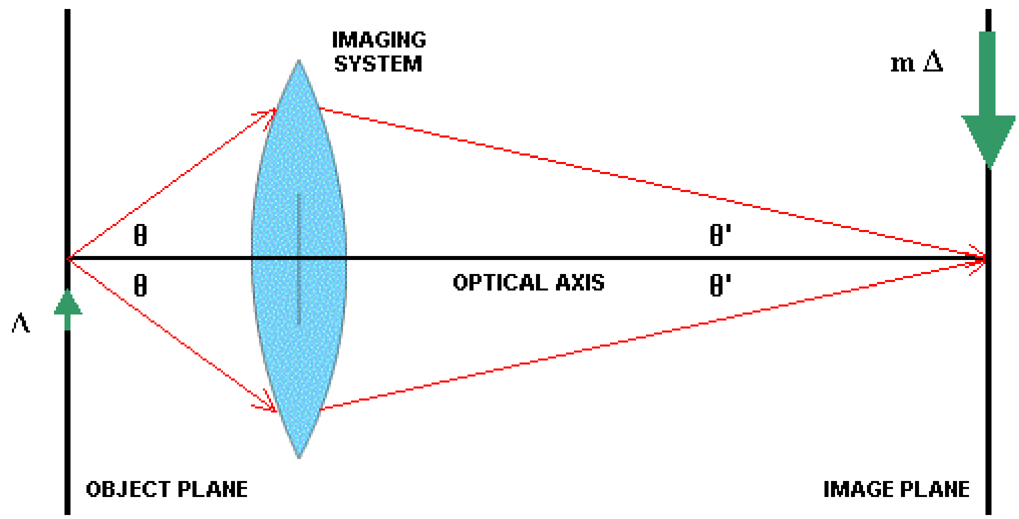


FIGURE 2. SIMPLE IMAGE FORMATION

Initially, light is reflected from or transmitted through the object plane. Light that interacts with various subjects in the object plane forms a configuration of light. This configuration of light – the subject distribution – exists on the side of the object plane nearest to the imaging system.

The length Δ of the small green arrow illustrated in Figure 2 separates two arbitrary illuminated points in the subject distribution. Two equi-amplitude plane waves that travel from the object plane to the image plane are linked to this pair of illuminated points. Referring to Figure 2, red arrows indicate the directions of propagation for these light waves. The directions of propagation change when the light passes through the imaging system.

The propagation direction and a wavefront that is perpendicular to the propagation direction are illustrated in Figure 3 for an individual plane wave component. The wavefront is an infinite plane that is perpendicular to the plane of the figure and that extends out of the plane; only the trace of the wavefront on the plane of the figure is shown in the figure. The propagation direction of the wave lies in the plane of the figure.

As shown in the new theory, the quantum amplitude spatial period associated with two illuminated points separated by the distance Δ in a distribution of light is given by

$$T = \frac{\Delta}{2} \tag{1}$$

The quantum amplitude spatial period associated with two illuminated points in a distribution of light is illustrated in Figure 3 as the hypotenuse of a right triangle.

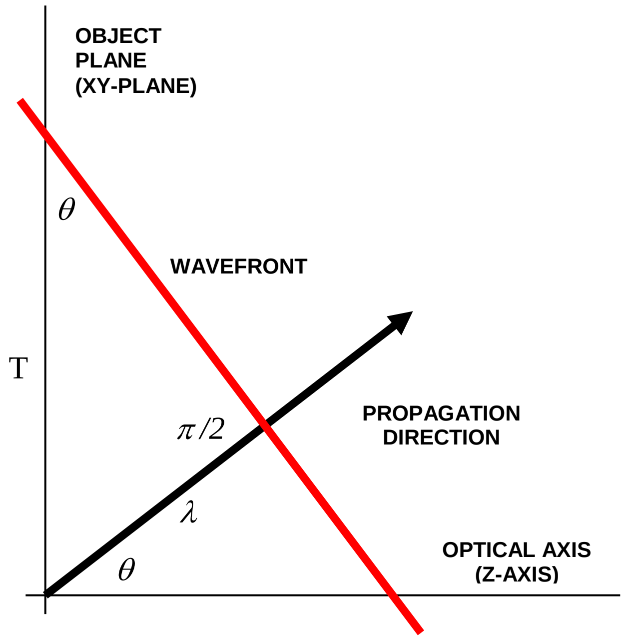


FIGURE 3. PLANE WAVE PROPAGATION GEOMETRY

Referring to Figure 3, the direction of propagation and the optical axis define a propagation angle. In the region between the object plane and the imaging system, the object side propagation angle is given by

$$\theta = \sin^{-1}\left(\frac{2\lambda}{\Delta}\right) \tag{2}$$

where λ is the wavelength of light involved. This relationship is illustrated graphically in Figure 4.

Small distances between points in a subject distribution are associated with large object side propagation angles. The minimum separation distance required for light to propagate away from the object plane exceeds two wavelengths of the light used, i.e.,

$$\Delta > 2\lambda \tag{3}$$

> **Two illuminated points in the object are required to form light waves that contribute to real image formation.**

The index of refraction of the medium on the image side of the imaging system may be different than its counterpart on the object side of the imaging system. Consequently the wavelength of the light on the image side of the imaging system may be different than its counterpart on the object side of the imaging system.

Let λ' be the wavelength of light in the region between the imaging system and the image plane. The image side propagation angle is given by

$$\theta' = \sin^{-1}\left(\frac{2\lambda'}{m\Delta}\right) \tag{4}$$

where *m* is the magnification achieved by the image formation apparatus. The magnification *m* is related to the angles θ and θ' in accord with the equation

$$m = \frac{n\sin\theta}{n'\sin\theta'} \tag{5}$$

The imaging system's object side index of refraction is n and its imaging side index of refraction is n'. The foregoing relationship is known as the optical invariant.

At the image plane, the component light waves add together to form a configuration of light. This configuration of light closely approximates a magnified (enlarged, reduced or unchanged and possibly, but not necessarily, inverted) version of the initial configuration of light associated with the subject. Consequently,

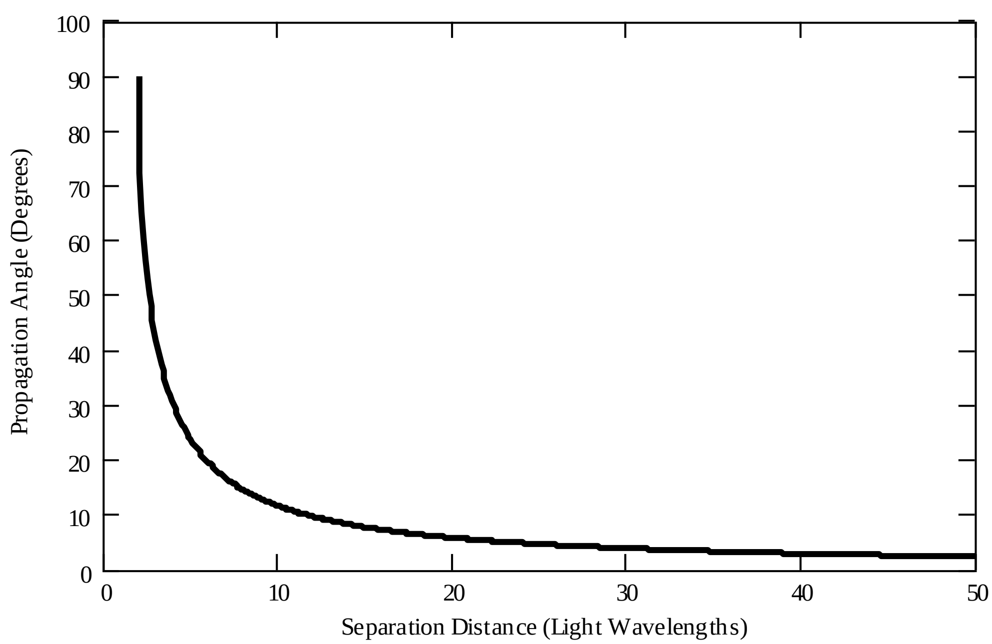


FIGURE 4. OBJECT SIDE PROPAGATION ANGLE θ AS A FUNCTION OF THE SEPARATION DISTANCE Δ BETWEEN TWO POINTS IN THE OBJECT

$$\Delta' = m\Delta \tag{6}$$

is the length of the large green arrow shown in Figure 2.

PROJECTION MAGNIFICATION

Referring to Figure 2, projection magnification can be understood in terms of the well-known Gaussian Lens Formula

$$\frac{1}{s_o} + \frac{1}{s_i} = \frac{1}{f} \tag{7}$$

where s_o is the distance between the object and the lens, s_i is the distance between the image and the lens, and *f* is the focal length of the lens. After recalling the magnification *m*

$$s_i = m\, s_o \tag{8}$$

can be obtained. Furthermore, after introducing the proportionality factor *q*

$$s_o = q\, f \tag{9}$$

can be obtained. Substitution of the foregoing two results into the Gaussian Lens Formula yields

$$\frac{1}{q\, f} + \frac{1}{m\, q\, f} = \frac{1}{f} \tag{10}$$

readily. After multiplying each term in this equation by *q f*, it reduces to

$$1 + \frac{1}{m} = q \tag{11}$$

or

$$m = \frac{1}{q-1} \tag{12}$$

following modest manipulation. After combining this result and equation (9)

$$m = \frac{f}{s_o - f} \tag{13}$$

follows. Enormous magnification can be achieved when the value of q is adjusted to be near unity.

COMPLETE RESOLUTION

Consider conventional optical real image formation. Let $\sigma\left(\frac{\mathbf{r}}{m}\right)$ be the coherent impulse response, as measured on the image side, of the real image formation apparatus. Furthermore, let $\psi_o\left(\frac{\mathbf{r}}{m}\right)$ and $\psi_i(\mathbf{r})$ be the quantum amplitudes of the image forming light on the object plane and image plane, respectively. The location of an arbitrary point in the object plane is denoted by $\mathbf{r}$ while m denotes the lateral magnification of the image relative to the object; m may be either negative or positive, depending upon whether the real image is inverted or not inverted relative to the object. The quantum amplitude on the image plane is related to the quantum amplitude on the object plane by

$$\psi_i(\mathbf{r}) = \left(\frac{1}{m}\right)^2 \psi_o\left(\frac{\mathbf{r}}{m}\right) \otimes \sigma\left(\frac{\mathbf{r}}{m}\right) \tag{14}$$

where $\otimes$ denotes the convolution operator. Such imaging, when done very well, is said to be diffraction limited.

As a direct result of the convolution operation, the size of each image feature is roughly the same as the size of the undistorted (ideal) image feature plus the size of the spot formed by the imaging system (lens). Magnification is significantly limited; with sufficiently large magnification the spot can dominate the entire image in addition to distorting any detail that might otherwise be present.

The foregoing equation arises as a straightforward consequence of the assumption that image forming light propagates from single points in the object plane. However, in accord with the physics that underlies RIF technology, this assumption is unwarranted. Propagation of light away from a single object point (as hypothesized by the Huygens-Fresnel principle) does not occur. Pairs of illuminated points in the object, where the points are separated by a distance that exceeds two wavelengths of the light involved, are required to form light waves that contribute to real image formation.

When done in accord with the precepts for RIF, the quantum amplitude on the image plane is given by

$$\psi_i(\mathbf{r}) = \left(\frac{1}{m}\right)^2 \psi_o\left(\frac{\mathbf{r}}{m}\right) \sigma\left(\frac{\mathbf{r}}{m}\right) \tag{15}$$

which is the RIF real image equation. No convolution operation is involved and no spot is formed by the imaging system. Enormous magnification is possible because no image-destroying spot exists.

IV. IMAGING SYSTEM

Most imaging systems are circular. Although non-circular imaging systems exist, little would be gained by considering them in the present context. Consequently, attention will be restricted to circular imaging systems.

Circular imaging systems are endowed with a definite diameter. Accordingly, a circular imaging system restricts the propagation angle of the light that can enter it to a maximum allowed value θ_c. Similarly, a circular imaging system restricts the propagation angle of the light that can leave it to a maximum allowed value θ'_c. The cutoff propagation angles θ_c and θ'_c are the entrance angle (also known as the acceptance angle) and the exit angle, respectively, of the imaging system.

The imaging system's object side numerical aperture $(\mathrm{NA})_o$ and image side numerical aperture $(\mathrm{NA})_i$, given by

$$\begin{pmatrix} (\mathrm{NA})_o \\ (\mathrm{NA})_i \end{pmatrix} = \begin{pmatrix} n \sin\theta_c \\ n' \sin\theta'_c \end{pmatrix} \tag{16}$$

are linked to the cutoff angles. In terms of these numerical apertures, the optical invariant becomes

$$m = \frac{(\mathrm{NA})_o}{(\mathrm{NA})_i} \tag{17}$$

when evaluated at cutoff.

V. FIELD DEPTH

As introduced earlier, Δ is the distance between two points in the object plane and Δ' is the corresponding distance (magnified) in the image plane. As shown in the new theory

$$\begin{pmatrix} D \\ D' \end{pmatrix} = \begin{pmatrix} \dfrac{\Delta\sqrt{\Delta^2 - 4\lambda^2}}{2K\lambda} \\ \dfrac{\Delta'\sqrt{\Delta'^2 - 4\lambda'^2}}{2K\lambda'} \end{pmatrix} \tag{18}$$

where the depth of object field has been designated as D and the depth of image field has been designated as D'. K is a subjectively determined constant. Selecting a suitable value for K is perhaps best done on the basis of experience. Possibly the value $K = 16$ may be suitable as a tentative useful value for K. The depth of object field and the depth of image field are both independent of the imaging system that is used.

VI. OBJECT PLANE CONFIGURATION

RIF is achieved by means of two distributions of light – a subject distribution and a reference distribution. These distributions of light can be thought of as a single distribution of light that is separated into two bright regions by a dark region. An image of both distributions of light is formed. An image of the reference distribution may or may not be desired. An image of the subject distribution is desired.

A configuration of light that is suitable for achieving RIF is illustrated in Figure 5. The configuration of light exists on the side of the object plane nearest to the imaging system and is confined to the interiors of the circles shown in the figure.

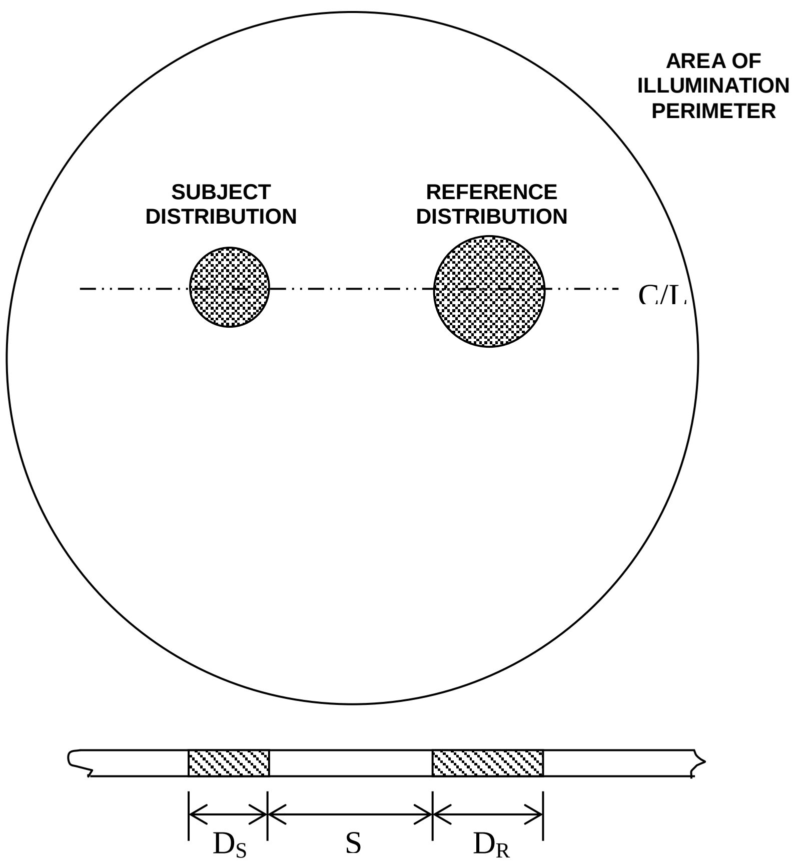


FIGURE 5. RIF OBJECT PLANE CONFIGURATION: PLAN AND FRONT ELEVATION VIEWS

As indicated in the figure, the subject distribution exists inside a circular area of diameter D_S while the reference distribution exists inside a circular area of diameter D_R. Let λ_s be the wavelength of light used as measured in vacuum. Ideal RIF occurs when the criteria

$$S > \frac{2\lambda_s}{(\mathrm{NA})_o} \quad (19)$$

$$D_S \le \frac{2\lambda_s}{(\mathrm{NA})_o} \quad (20)$$

and

$$D_R \le \frac{2\lambda_s}{(\mathrm{NA})_o} \quad (21)$$

are realized physically. Noisy RIF occurs when either D_S or D_R or both D_S and D_R do not satisfy the foregoing inequalities.

VII. CONVENTIONAL IMAGE DISTORTION

Figure 6 illustrates the real image that is formed by a circular imaging system when it is

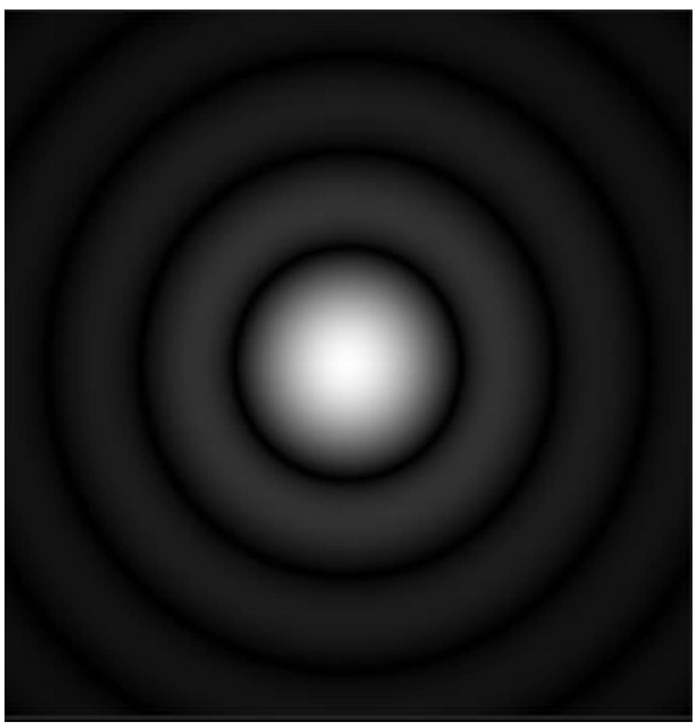


FIGURE 6. AIRY PATTERN. SOURCE: WIKIPEDIA *AIRY DISK*

illuminated by a plane wave propagating along the optical axis. The image is known as an Airy pattern. As shown in the figure, this image consists of a central bright region that is surrounded by a number of much fainter rings. The exposure associated with the central bright region is very much greater than that associated with any other region in the image. The central bright region is known as the Airy disk produced by the imaging system. The diameter of the Airy disk, given by

$$\delta = \frac{1.22\lambda'}{(\mathrm{NA})_i} \tag{22}$$

is often referred to as the imaging system's spot size.

Dimensions of image features that are formed by conventional means (not RIF) are larger than their geometrical size. As indicated in Figure 7, the linear dimensions of such an image feature are increased in size by an amount equivalent to the imaging system's spot size.

A minimum separation distance between two conventionally formed and distinguishable image features exists. Conventionally, the minimum separation distance such that the image of two features that are distinguishable as two features is equivalent to the imaging system's spot size. Two image features that can be distinguished as two image features are said to be resolved.

RIF is being developed to eliminate the adverse effects associated with an imaging system's spot size. This includes optical real image formation that has no resolution limit.

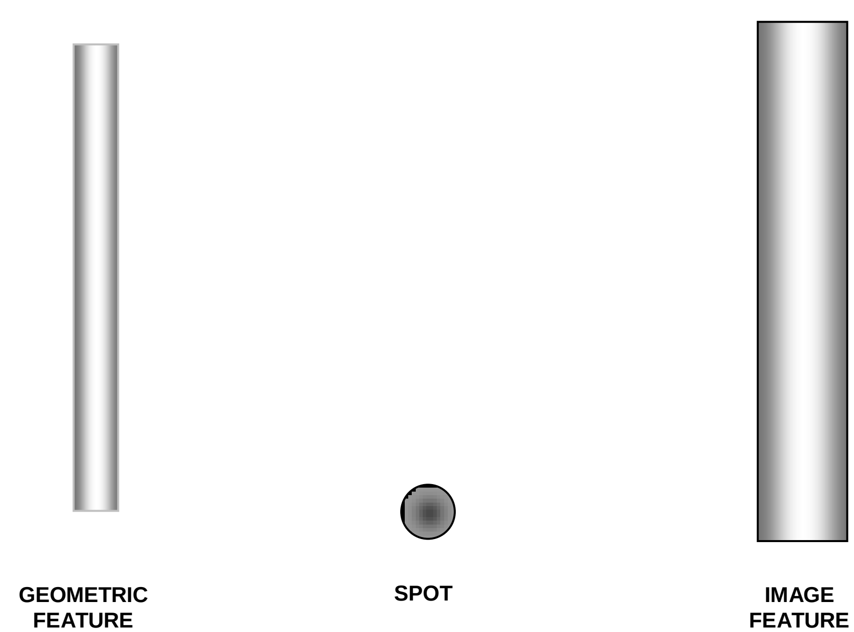


FIGURE 7. GEOMETRIC FEATURE DIMENSIONS ARE INCREASED BY THE IMAGING SYSTEM SPOT DIAMETER

FIGURE 8. RIF DEMONSTRATION UNIT

VIII. RIF DEMONSTRATIONS

A versatile RIF demonstration unit[5] has been constructed and used to demonstrate reference distribution real image formation (RIF). In addition, the unit has been used to demonstrate microscopy that is based on RIF technology. A photograph of the RIF demonstration unit is shown in Figure 8. The RIF demonstration unit was designed, constructed, and used under the auspices of Mulith, Inc. The unit can be and has been used as a reflection microscope and as a transmission microscope.

Primarily, the RIF demonstration unit was developed to provide a means for demonstrating RIF and serve as a RIF based microscope. In addition, a vigorous attempt was made to achieve design simplicity, ease of construction, and ease of operator use when the demonstration unit was being developed.

The RIF demonstration unit is an optical real image formation system. Ordinarily, real images of a subject are formed with light that propagates from the subject alone. With RIF, a distribution of light – a reference distribution – that is usually (but not necessarily) separated from the subject is introduced. A real image of both the subject and the reference distribution is formed on the image plane.

An iterative process was used to develop the RIF demonstration unit. RIF was demonstrated at various stages of the development process.

SLIT APERTURES

RIF was first demonstrated[6] on 12 July 2006. This simple demonstration was achieved by using optical transmission microscopy and a special microscope slide.

The microscope slide featured a slit aperture that was 2.5 micron wide by 25 micron long. The slit aperture was separated into two segments by means of a human hair.

(A) BOTH SEGMENTS OPEN

(B) RIGHT SEGMENT PARTIALLY CLOSED
LEFT SEGMENT NOT DIRECTLY CHANGED

(C) RIGHT SEGMENT REOPENED
LEFT SEGMENT NOT DIRECTLY CHANGED

FIGURE 9. SLIT APERTURE SEPARATED INTO TWO SEGMENTS: THE DARK REGION THAT SEPARATES THE SEGMENTS IN (A) AND (C) IS THE SHADOW OF THE HAIR THAT SEPARATES THE SEGMENTS

Referring to Figure 9, the dark regions that separate the two bright regions in micrograms (A) and (C) are recordings of the hair's shadow.

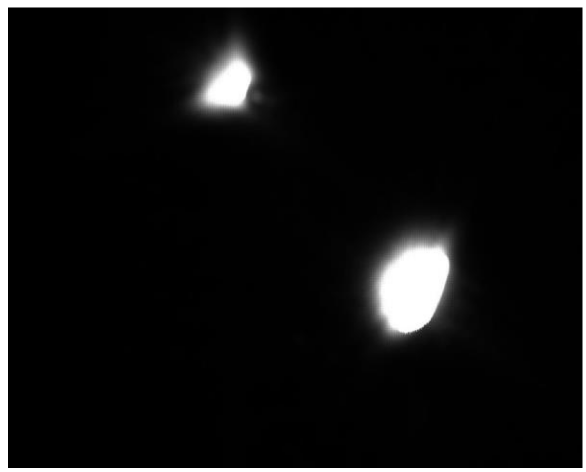
A subject distribution (an object of interest) is defined by the slit segment that corresponds to the images shown on the left in micrograms (A) and (C). A reference distribution is defined by the slit segment that corresponds to the images shown on the right in micrograms (A) and (C). The image shown in microgram (B) is not an image of the subject distribution and is also not an image of a satisfactory reference distribution.

Without RIF, the slit segment on the left in the foregoing sequence of micrograms was too small to be imaged. However, when the slit segment on the right was extended sufficiently far from the hair (thus forming a satisfactory reference distribution), an image of the region on the left was formed. These facts are all directly observable without recourse to theoretical understanding.

The micrograms presented in Figure 9 are overexposed. As a result, distortion of feature dimensions that is attributable to the image recording process (not the image formation process) occurs. Consequently, any attempt to obtain quantitative dimensional information from the micrograms is inappropriate.

White light was used with a 0.10 NA lens for the foregoing demonstration. The smallest wavelength of the light involved approximated 0.4 micron. The corresponding minimum separation of two points in the object that could be imaged without RIF would approximate 5 micron, a distance that is far greater than any of the distances that exist inside the subject distribution in the foregoing demonstration.

(A) BOTH APERTURES OPEN



(B) LEFT APERTURE PARTIALLY CLOSED; RIGHT APERTURE NOT DIRECTLY CHANGED

(C) LEFT APERTURE CLOSED; RIGHT APERTURE NOT DIRECTLY CHANGED

FIGURE 10. TWO SEPARATED APERTURES

CIRCULAR APERTURES

A cooperative phenomenon such that reference distribution changes are linked to subject distribution changes occurs when RIF is used. This phenomenon has been demonstrated by using two circular apertures in a thin metal screen. When light was transmitted through the apertures, one aperture served as a subject distribution of light and the other aperture served as a reference distribution of light.

Micrograms of two separated circular apertures are shown in Figure 10. White light was used with a 0.10 NA lens to record these micrograms. The nominal diameters of the apertures approximate 10 micron; their effective diameters are unknown.

Both apertures were completely open in microgram (A). In microgram (B), the aperture on the left was partially closed while the aperture on the right was not directly changed. In microgram (C), the aperture on the left was completely closed while the aperture on the right was not directly changed. This progression illustrates the cooperative phenomenon that occurs.

Gradual closure of the reference distribution (the aperture on the left) was used to demonstrate the cooperative phenomenon. Thus, the subject distribution of light was kept open and the reference distribution was partially closed in a progressive manner. Changes in the distribution of light associated with the subject distribution occurred when the distribution of light associated with the reference distribution was changed.

QUANTIFOIL GRID

Consider the microgram of a Quantifoil S7/2 Micromachined Square Mesh Holey Carbon Grid on 200 Mesh Copper shown in Figure 11. The grid consists of 7 micron X 7 micron square holes that are separated by bars that are 2 microns wide; the repeat distance (pitch) is 9 micron. Typically, Quantifoil grids are used to support specimens for electron microscopy examination.

White light was used with a 0.25 NA lens to obtain the Quantifoil grid microgram shown in Figure 11. The smallest wavelength of the light involved approximated 0.4 micron.

In accord with conventional real image formation theory, the imaging system's spot size approximated 2 micron. Images of the bar widths would be increased from 2 micron (magnified) to 4 micron (magnified) while images of the distances between the bars would decrease from 7 micron (magnified) to 5 micron (magnified). This is clearly contraindicated by Figure 11.

Conventional optical real image formation theory does not support understanding the microgram in Figure 11. However, this image is easily understood as an example of noisy RIF. Images of the bars were created in accord with RIF; contrast was sacrificed because light from the spaces between the bars (optical noise) was present in the image.

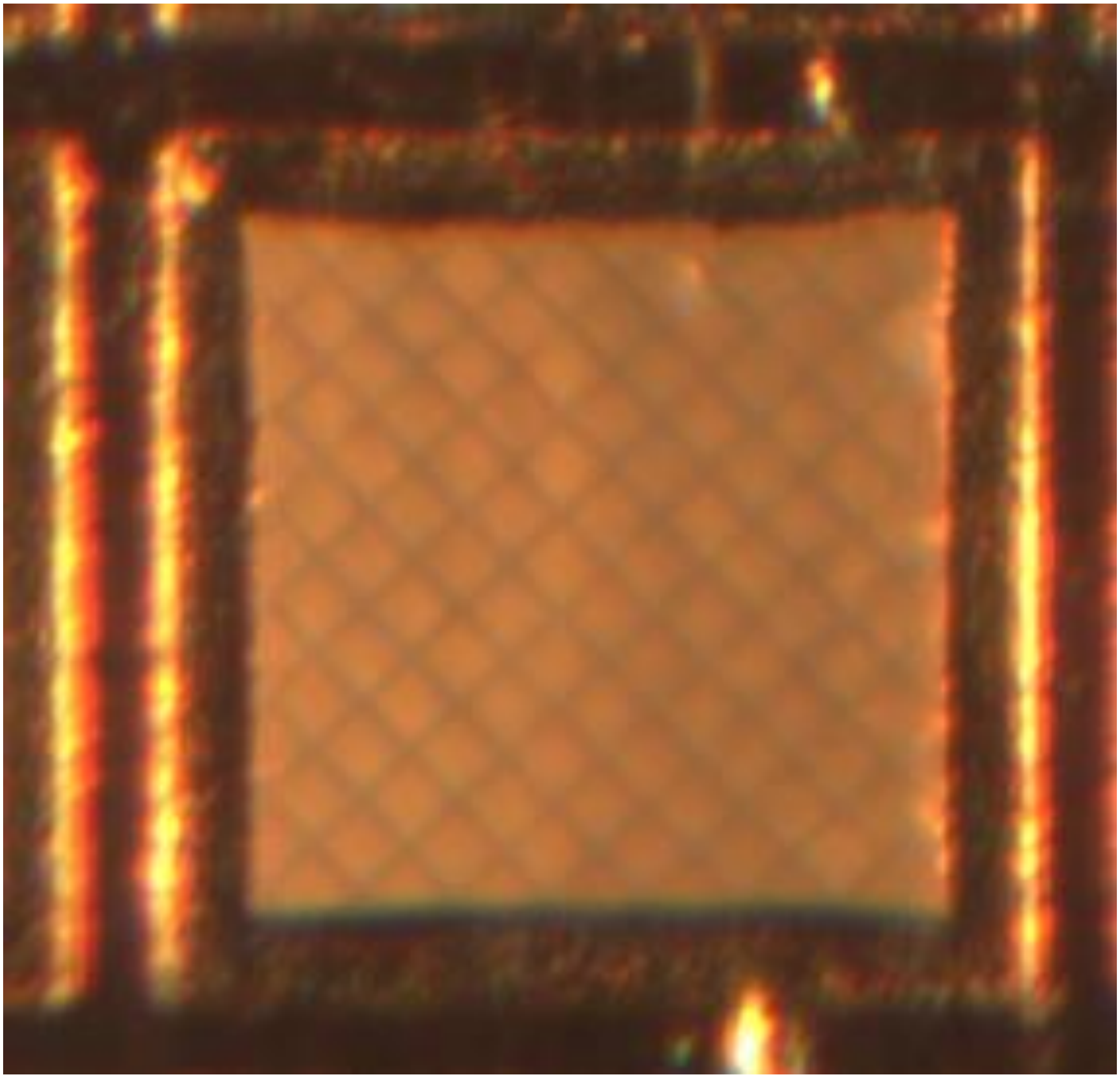


FIGURE 11. QUANTIFOIL S7/2 MICROMACHINED SQUARE MESH HOLEY CARBON GRID

IX. CONCLUSION

RIF (reference distribution real image formation) technology is being developed to provide precise optical real images. These images are of practical importance to high-resolution optical microscopy, high-resolution optical nanolithography, and passive ghost imaging.

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