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A review and reassessment of diffraction, scattering, and shadows in electrodynamics

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ABSTRACT

The concepts of diffraction and scattering are well known and considered fundamental in optics and other wave phenomena. For any type of wave, one way to define diffraction is the spreading of waves, i.e., no change in the average propagation direction, while scattering is the deflection of waves with a clear change of propagation direction. However, the terms “diffraction” and “scattering” are often used interchangeably, and hence, a clear distinction between the two is difficult to find. This review considers electromagnetic waves and retains the simple definition that diffraction is the spreading of waves but demonstrates that all diffraction patterns are the result of scattering. It is shown that for electromagnetic waves, the “diffracted” wave from an object is the Ewald–Oseen extinction wave in the far-field zone. The intensity distribution of this wave yields what is commonly called the diffraction pattern. Moreover, this is the same Ewald–Oseen wave that cancels the incident wave inside the object and thereafter continues to do so immediately behind the object to create a shadow. If the object is much wider than the beam but has a hole, e.g., a screen with an aperture, the Ewald–Oseen extinction wave creates the shadow behind the screen and the incident light that passes through the aperture creates the diffraction pattern. This point of view also illustrates Babinet’s principle. Thus, it is the Ewald–Oseen extinction theorem that binds together diffraction, scattering, and shadows.

1. Introduction

Diffraction can be thought of as the spreading of a wave into the geometrical shadow behind an impervious obstacle [1–3]. The *mechanism* of diffraction depends upon the type of wave. Generally, waves divide into two types; those that require a material medium in which to propagate and those that do not. For those propagating in a material medium, e.g., water and sound waves, a wave is blocked by an obstacle and the portion of the wave passing near the edge of the obstacle spreads into the geometrically shaded region due to the elastic nature of the medium. In this context, “blocking” refers to a discontinuity in the medium that supports the wave propagation wherein propagation is not allowed. Waves that require no material medium, such as electromagnetic (EM) waves, fundamentally cannot be blocked because a discontinuity in a medium does not change the fact that these waves require no medium to propagate. Said less formally, there is no medium to be blocked. What then is the mechanism that creates an optical diffraction pattern? Here, it is shown that secondary radiation from an obstacle in the path of incident light, which is induced by that light, produces a scattering pattern identical to the diffraction pattern predicted by Huygens’ description. Thus, for EM waves, *secondary radiation is the mechanism of diffraction*.

A *clear* definition of what optical diffraction *is* and, in particular, how it may be different, or not, from scattering is rare in the literature. One could propose that diffraction relates to waves at sharp edges of two-dimensional (2D) objects, while scattering relates to three-dimensional (3D) objects. Such delineation, however, leads to ambiguity. For example, it would be difficult to understand the striking, albeit qualitative, similarity of the angular spread of light in the far-field from an opaque circular *disk* and a transparent *sphere* of the same diameter. Indeed, some references state that there is no logical separation between the two concepts [1,4]. An aim of this review is to clearly illustrate that the general concepts of diffraction and scattering relate to the *same* physical phenomenon.

The focus here is on EM waves due to the enduring interest in the topic and because these waves require no medium to propagate. As a consequence, optical shadows can form from destructive interference only, and definitely not due to obstacles in the medium “blocking” the wave in a mechanical-like sense. A novel insight revealed by this description is that the interference process creating shadows is always active, whether an object is absorbing

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or not, is larger than the wavelength or not, and it is fundamentally linked to the observed phenomena associated with diffraction or scattering. It is also shown that these phenomena are produced from secondary radiation emanating throughout the *entire* volume of an obstacle. Thus, statements often encountered in the literature like "light diffracts around the obstacle," are misleading as they imply only a surface effect. Given the extensive amount of study on these concepts, this review cannot summarize all previous work. Rather, the focus will be on the mathematical treatments involved and their physical interpretations.

2. Huygens–Fresnel and Babinet principles: conceptual basis

It is helpful to first review the common description of optical diffraction. Begin with the familiar example of light of wavelength λ incident upon a rectangular aperture Σ_a, or slit, of width $2w$ and length 2ℓ with $\ell \gg w$ in an otherwise opaque screen Σ_s infinite in extent. The term "opaque" will refer to a perfectly conducting screen. Alternatively, a perfectly absorbing screen could be considered, but due to complications with the concept of a perfect absorber in electrodynamics, this case is not considered, cf. [5,6]. Suppose that the incident light is a well-collimated laser beam propagating along the positive z-axis. A good approximation for this wave is a Gaussian beam with a waist-width of $2w_o$ [7]. At the beam waist, the wave fronts are planar, but the beam profile is finite in size. In Section 6, this will allow the intrinsic angular spreading of the beam with distance from the waist to be incorporated in the analysis. At the waist, the beam encounters the aperture, which is much smaller than the waist, $w_o \gg w$ and $w_o \gg \ell$. Consequently, the aperture may – despite use of a beam – be regarded as uniformly illuminated by a plane wave following the customary treatment. The first objective is to examine the distribution of light beyond the aperture across an observation plane σ that is parallel to Σ_s located a distance $z = d$ from it as shown in Fig. 1. Also, σ will be assumed to be in the far-field zone of the aperture, which is defined by $d \gg kw^2/2$, where $k = 2\pi/\lambda$ [8]. This condition is commonly known as the Fraunhofer approximation [1].

The incident beam at the aperture appears blocked by Σ_s and across σ one observes a spread of light intensity modulated by a series of band-like interference maxima and minima, i.e., fringes, commonly called the single-slit diffraction pattern. It is thus customary to say that the light "diffracts into the shadow." The diffraction pattern can be approximately calculated in the far-field zone from the Huygens-Fresnel principle [1,9,10]. One imagines fictitious point sources of light that span the aperture Σ_a where each radiates a spherical wave of wavelength λ into the $z > 0$ region. A point source, located at $\mathbf{r}'$ in Fig. 1, is driven in-phase and in magnitude with the incident wave across the aperture; this is the Kirchhoff approximation [4]. Adding the contributions from these sources at $\mathbf{r}$ on σ approximates the observed diffraction pattern. With reference to Fig. 1 and following the treatment of [1], the normalized pattern in the far-field zone is given by:

$$\frac{I(\mathbf{r})}{I_o} = \left| \iint_{\Sigma_a} e^{ik\hat{\mathbf{r}}\cdot\mathbf{r}'} \mathrm{d}a' \right|^2, \tag{1}$$

where I is the diffracted light-intensity (irradiance) and I_o is the intensity along the z-axis (beam direction). The fringe structure of the pattern is then explained from the phase difference introduced by each source-point's differing location within Σ_a. In other words, the Huygens-Fresnel principle explains the diffraction pattern as interference from radiation emitted across a *free-space region*, i.e., the aperture. Eq. (1) also shows that the diffraction pattern is the absolute square of the Fourier transform of the aperture; another characteristic of the Huygens–Fresnel treatment.

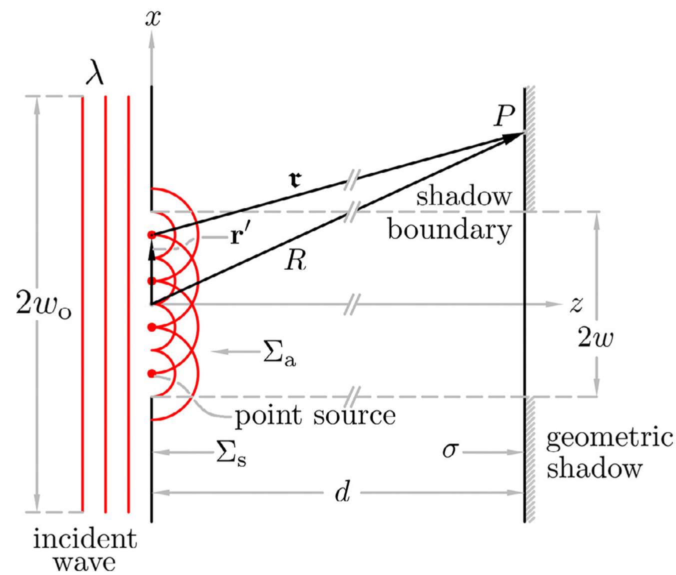

Fig. 1. Diffraction from a slit aperture. An aperture Σ_a in an opaque screen Σ_s is illuminated by a plane wave traveling along the positive z-axis. The aperture length is much larger than its width, i.e., $\ell \gg w$, whereas both dimensions are smaller than the beam waist w_o. Spanning the aperture are fictitious "Huygens" point-sources (red dots) that each emit a spherical wave into the region beyond the screen. Adding these waves across σ in the far-field zone gives an approximate description for the linear fringes of diffracted light observed on σ. In particular, the outcome predicts the observation of light in the geometric shadow of the aperture, shown in dash, and is a classic phenomenon associated with diffraction [1]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Diffraction is said to occur not only through apertures but also around barriers [1]. In 2D, any barrier may be envisioned as a screen that is the inverse of, or compliment to, an aperture. The complimentary screen to the rectangular aperture is a thin, opaque rectangular strip with dimensions $2w \times 2\ell$. If a screen Σ_s is combined with its complimentary screen Σ_s', the result is a complete opaque screen Σ, i.e., $\Sigma_s + \Sigma_s' = \Sigma$. Diffraction of a beam from an aperture and its complimentary screen is related by Babinet's principle [1]. As stated by [11],"the diffraction patterns which are produced by two complementary screens are identical excepting the central spot, which is diffraction angle zero."

A demonstration of Babinet's principle is instructive wherein two distinct scenarios, labeled 1 and 2, are compared. In scenario 1, an infinite screen $\Sigma_s^{(1)}$ containing aperture $\Sigma_a^{(1)}$ is illuminated by the beam and the resulting pattern is observed on σ. In scenario 2 however, only the complimentary screen is present, $\Sigma_s^{(2)}$, which is illuminated by the same beam and the resulting pattern is again observed on σ. If E_1 and E_2 are the *scalar* light-fields at the same point $\mathbf{r}$ on σ in scenario 1 or 2 respectively, then Babinet's principle states that [1,3]

$$E_1(\mathbf{r}) + E_2(\mathbf{r}) = E_o(\mathbf{r}). \tag{2}$$

Here, $E_o(\mathbf{r})$ is the (complex-valued) scalar light-field amplitude of the beam at $\mathbf{r}$ on σ when *neither* screen is present, i.e., when the beam is freely illuminating σ. Conceptually, one can understand Eq. (2) from the Huygens-Fresnel principle. As stated, the diffracted light (E_1) for scenario 1 from screen $\Sigma_s^{(1)}$ is given in Eq. (1) by an integral over the aperture opening, $\Sigma_a^{(1)}$. In scenario 2, Eq. (1) provides the diffracted light (E_2) as an integral over the planar region of free space *not* occupied by the complementary screen $\Sigma_s^{(2)}$, which could be regarded as a large aperture $\Sigma_a^{(2)}$, see Fig. 2. Adding these two surface integrals in Eq. (2) amounts to an integral of fictitious Huygens point sources over a complete plane Σ in empty space, and thus, reproduces the incident beam. Note