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Revisiting Young's edge diffracted wave: Diffraction of light by fractured plane wave-front

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ABSTRACT

Based on the Young's boundary diffraction wave (BDW) idea and the inherent concept of singularity in it, we would be able to look at certain unforeseen aspects of scalar diffraction, especially for phase objects. In order to give a basic and necessary perception, we consider diffraction from a Fresnel's bi-prism which produces two crossing plane wave-fronts. This approach permits the mathematical treatment to be done with much ease. Experimental results are both in excellent agreement with our theoretical predictions which are accompanied by numerical simulations and validate our strategy. This will raise the present level of the diffraction phenomena study to a however, vast area with many applications.

1. Introduction and overview

The development of the main part of classical physics, such as classical wave fields, the wave theory of light in optics, some branches of both physics and engineering, which deal with wave propagation, the fundamental basis for quantum mechanical uncertainty relations, and the different types of matter-waves interactions as the essence of quantum mechanics, are all indebted to the leading role of diffraction. Hence, for more than three centuries from its systematic and regular starting point, many theoretical and experimental researchers have directed extensive attention on this important phenomenon [1]. It is common belief that diffraction as an elementary phenomenon well understood for many years. However, if the problematic nature of it was concerned, scalar diffraction theory in general and scalar diffraction from phase objects as a special case, are extremely open to original investigation and unsettled. Except for a finite practical field which is concerned mainly with electron, neutron and X-ray microscopy and other imaging techniques based on diffraction, in almost all investigations have been performed thus far, the chief aim was to test the validity of the diffraction theories by attempting to compare their predictions with that given by diffraction patterns quantitatively. Out of these, a few researchers attracted directly or indirectly to the effects observed when a part of a coherent wavefront bears an abrupt change in its phase as a result of interaction with phase objects; but they are quite rare [2–6]. Unfortunately, for some unknown reasons this type of diffraction attracted little attention and few followers and hence, is an open field.

In the process of ion exchange between a soda-lime glass slide and ion-containing solution, Tavassoly and his collaborators found that to study the interaction of a coherent laser light with this glass, Fresnel diffraction (FD) from a phase object plays a role of utmost importance [7]. Extensive researches on FD from phase objects in reflection and transmission modes have been carried on since that time and provides a powerful technique for the measurements of phase and physical quantities

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that can be converted into phase change, since similar to that of interference one can desirably change the optical path difference in diffraction. Consequently, it opens up unprecedented possibilities which may well go beyond the conventional framework of ordinary diffraction and is a very rich subject with many applications which provides numerous interesting metrological applications including high-precision measurements; and as time goes on new outlooks are found [8–25]. Surely, unlike the Michelson interferometer which produces a linear phase change, due to nonlinear phase change in FD, it seems not to be so easily and reasonable to put the latter in practice. But based on what has been done during the recent years, we strongly believe that it affords a convenient means to get ahead the borderline of the diffraction, remarkably.

2. Singularity in the phase of a wavefront

Historically, however, both the interference and diffraction phenomena nearly originated concurrently at about the middle of the 17th century [briefly discussed in Ref. [1], Historical introduction], and have been subject to the same extensive study after a long time since then; but amazingly enough, quite remarkable growth and more technological advances have been made in the field of interference and optical interferometry rather than diffraction and optical diffractometry [26]. We feel that, this gross discrepancy is due mainly to the unknown potential capability of diffraction. This feature is especially noticeable in the scalar diffraction from phase objects by allowing more flexibility in design and for much ease in practice. Young, the founder of the wave theory of light, formulated his own idea of diffraction in a rough qualitative way [Ref. [1], Historical introduction]. After a short time interval and based on the principle of interference, discovered by Young, mathematical approach of Fresnel's theory which successfully gave a sound foundation to the wave theory, soon dominated the field and Young's explanation of diffraction was not taken seriously by others and putting aside. Hence, diffraction was naturally described in terms of the prevailing Huygens-Fresnel theory; until Kirchhoff in his theory of diffraction quite automatically arrived at a development of Fresnel's ideas. It was not until Sommerfeld showed quite naturally that the diffracted electromagnetic wavefield by a conducting half plane is the superposition of a geometric and a boundary wave [27] and very soon after, Lord Rayleigh indicated certain singularities will then occur at the edge of the diffracting screen [28]. Therefore, the truth and the adequacy of the Young's theory became appear. The fact that was stressed again later by many researchers in theoretical and experimental investigations [29–38]. Thus, in practice, physical existence of the BDW in Young's theory was delayed until about the beginning of the 20th century and in this way could not get the proper path and hence, could not get its most valuable place. It is clear now that, Young's theory of diffraction represents a sound physical model than that of Huygens and Fresnel [39,40].

In what follows, inspired by the Young's theory, we shall lay the foundation of our definition of diffraction. What we require in diffraction is that at least one of the interfering beams arises in the course of encountering a kind of singularity with an obstacle, either opaque or transparent, by reason of light scattering due to local variations in the amplitude and/or phase in a region of the wavefront after reflecting or transmitting. By singularity of some auxiliary or physical functions that are used to describe or measure the physical quantities, we mean that they are indeterminate, or they become infinite or nondeterministic and the next behavior cannot be predicted at a point or along a line. In mathematical words, a single-valued function is said to have a singularity at a point if the function is not analytic at that point. The singularity may be classified depending on the behavior of the function around that point or line [41].

Consequently, diffraction can be divided into two overall categories according to some convenient scale of the structure of materials. Hence, it may be studied either:

(i) On the macroscopic scale by light scattering from singularities due to inhomogeneity of a continuum opaque or transparent matter or
(ii) On the atomic scale by light scattering from an atom or assemblies of atoms which comes from singularities due to heterogeneity [42] of matter.

It should be noted that, at the atomic level, everything except a vacuum is heterogeneous. But, what we are concerned with, in ordinary diffraction and in this context is the scattering of light beam at the level which are much larger than the atomic one and are due to the scattering arises from inhomogeneity of obstacles and not heterogeneity of matter. In effect, scattering is due principally to the presence of any discontinuity or singularity in a physical quantity. Although, both mathematics and physics are rendered unable in describing the singularity, but a wide class of phenomena with many different kinds of behavior in the immediate neighborhood of singular points is associated with singularities. Thus, in general, as an important result and in accordance with the Young's idea, it is an expectation that diffraction phenomena will occur when a part of the unobstructed coherent beam interfere with the leftover part of it encountering a kind of singularity -e.g. singularity in one of its properties like amplitude, phase, polarization, and coherency- which after interaction, scattered out toward the observation point. Consequently, as a result of forward scattering with a given obstacle, beams of greater wavelength are diffracted more strongly than that of shorter wavelength [43].

Therefore, with respect to the inhomogeneity of a reflector or a transparent obstacle, FD from phase objects can be divided into two classes, FD due to:

(i) "Discontinuous rapid change" in the phase of a wavefront: Until now, the majority of our earlier studies in FD from phase objects was focused on the cases in which a wavefront undergoes a discontinuity in its phase in the interaction with a