The experimental verification of how light spreads at large distances - A missing experiment at foundation

Corneliu I. Costescu (✉ corneliucostescu@gmail.com)

Agora Lab

Ruxandra M. Costescu

National Institute of Materials Physics

Doina M. Costescu

Agora Lab

Research Article

Keywords: light spreading at large distances, missing experiment for the wave approach.

Posted Date: July 26th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-242447/v2>

License: This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

The experimental verification of
How light spreads at large distances -
A missing experiment at foundation

Corneliu I. Costescu^{1,*}, Ruxandra M. Costescu^{1,2}, Doina M. Costescu¹

¹*Agora Lab, 1113 Fairview Ave, Urbana, IL 61801, USA,*

²*National Institute of Materials Physics, Romania*

**Corresponding author, corneliucostescu@gmail.com*

Received July, 2021

Abstract. We recognize that the spreading of light at large distances (the whole space) is the only property which can decide by yes or no if light really behaves physically like waves, while the fit of the waves for describing the diffraction fringes is insufficient for this purpose. Indeed, the fringe space is too limited and hence, brings the possibility of misinterpretation. Hence, the experiment for the verification if light is spreading like waves at large distances is necessary in principle, and is crucial. However, very surprisingly and tragically, this experiment was totally missing in history. This experiment uses the simplest diffraction case, in which a beam of light falls perpendicularly with its axis on the line and the plane of a straight edge. Practically, this experiment verifies if there is a dependence of the diffracted light at large distances in the geometrical shadow on the changes in beam thickness traversal to a single straight edge, while the distribution of light along the straight edge remains the same. If this dependence exists, as the wave theory for light fundamentally predicts, then the wave approach to light is physically true. If there is no dependence then light cannot behave physically like waves. This experiment can clearly be developed and performed without any calculation from the wave approach, just by a careful measurement practice. However, for a broader view, we describe in detail wave results for spreading of light at large distance, which illustrate the experiment – what are the spatial points where the measurement must be done to see if the above dependence exists, and which is the big picture for the wave approach. We attempted this experiment for many years, but could not finish it because of the lack of resources to measure at 100 – 500 m. The present article will empower big labs to perform this experiment. However, we show alternatively that the answer to how light spreads also comes from comparing the well known data for the diffraction on macroscopic holes with relatively recent data for the diffraction on nanoscopic holes. This comparison clearly shows that light does not spread physically like waves, which makes necessary a new, non-wave but periodic structure for light. Such an alternative answer regarding the spreading of light also makes absolutely necessary to perform the above missing experiment, as a direct way that convinces anybody how light is spreading.

Key words: light spreading at large distances, missing experiment for the wave approach.

I. INTRODUCTION

We recognize an unsolved fundamental problem for nature of light, namely we recognize that the spreading of light at large distances (the whole space) is the only property which can decide by yes or no if light really behaves physically like waves in propagation, while the fit of the waves for describing the diffraction fringes is insufficient for this purpose. Indeed, the fringe space is too limited and hence, brings the possibility of misinterpretation regarding the nature of light. Hence, the experiment for the verification of how light is spreading at large distances is necessary in principle and it is crucial, but it is still missing. This experiment is as follows. A stable laser beam falls perpendicularly with its axis on a straight diffracting edge, with a constant distribution of light intensity along the edge, while the distribution of light transversal to the edge can be substantially broadened. For each case of transversal distribution of light, the intensity of the diffracted light is measured in a set of points at large distances in the geometrical shadow. If the results show a dependence of the intensity of light on the beam thickness transversally to the diffracting edge, as the Maxwell equations and the wave diffraction integral for light predict, then the wave theory of light is physically true. If there is no dependence, then light does not spread like the waves do, and a new physical approach is necessary for light, that is a diffraction mechanism that takes place only in the material edges. Hence, this experiment is crucial, and can be done without any wave calculation for defining the measurement points because these points can be found by a simple but systematic practice of light measurements at small and large distances.

The methods. Before introducing the methods for illustrative calculations and for the measurements used in this paper, we describe the method necessary for naturally recognizing this missing experiment for light and its results, and hence, for avoiding to repeat the case of the missing fact for heat, and other cases of missing facts in the future. From our lifetime work on light we found that both the case for light and for heat happened because the method of broad thinking on the major opposing views in a field, is not used systematically in the university, in society in general. For the case of light, the major opposing views are those on the origin of the diffracted light – as waves both inside and outside of the diffracting edge, or only inside the diffracting edge. A simple broad thinking on these opposing views shows to the regular student that there is no verification on how light spreads at large distance, and that the diffracted light is born only inside the diffracting edge, which makes impossible for light to physically behave like waves in diffraction (because if it did, the diffracted light would also be produced around the diffracting edges) ... Only by using this broad thinking, we realized that there is a missing experiment at the foundation of light: how light spreads at large distances: as waves or not as waves. For heat, the opposing views were how the heat is produced – only by the vicinity with hot body, or both by this vicinity and

by mechanical action ... If the student is taught and allowed to practice this broad thinking he/ she will see the missing fact/ experiment, and hence, the theories that are based on missing fact will not survive/ repeat ... On this line of thought, sooner or later this method will become a basic part in the education in science, for a scientist with the big-picture knowledge, in excess to the method for fast thinking for detailed knowledge ... This method is also necessary for the society sciences. For instance a broad thinking on the major opposing views in society, namely those of liberals and conservatives, shows quickly that a major and simple system is missing in society/ democracy - the system for growing/ developing common ground, functional and wise broad views. In such a system the Constitution requires that a party and a candidate, in order to participate in elections, must prove that they know the method and have some work for common ground/ functional and wise broad views with their counterpart. It would also be a requirement that a part of the government should enforce this system for common ground/ functional and wise broad views.

In Section II we use the wave approach to illustrate approximately how the waves intrinsically produce the above dependence of the diffracted light in the geometric shadow, on the wave front above the diffracting edge. For this purpose we use in Section II, the scalar Rayleigh-Sommerfeld wave diffraction integral in the Fresnel approximation [1, 2, 3] for a Gaussian laser beam. Such a diffraction integral is accurate in the wave picture (but not necessarily in the reality of light), if the following conditions are satisfied. (1) The diffraction aperture must be large as compared with the wavelength [1, Sec. 3.1], [3, Sec. 8.4]. (2) The diffracted light must be observed not too close to the aperture [1, Sec. 3.1]. (3) The laser beam comes from a low power, helium neon laser (a Micro-g Lacoste laser - a high quality He-Ne, 1mW, stable laser) for which it is justified to use a single transverse mode (also called a pure or fundamental mode) Gaussian beam, that is an ideal mode beam [4, pg. 10.6 – 10.9]. For higher power lasers, would be necessary to use more complex Gaussian beams. However, since for our experiment, the wave calculations are necessary only as an illustration, that is, not as strictly necessary calculations, it is sufficient to use the single transverse Gaussian beam. We do these calculations to illustrate the wave big picture for the experiment, and to suggest the measurement points at large distance in the geometrical shadow, which otherwise can be found by a systematic measurement practice.

In Section III we present a detailed description of the crucial experimental setup which is necessary for the measurement of the dependence between the light in the geometrical shadow and the light above the diffracting edge, a dependence that is crucial for the nature of light. Performing this experiment does not necessarily need the wave calculations from Section II because the measurement points in the geometrical shadow can be found by a systematic practice. However, such calculations clearly illustrate how the waves generate the above dependence.

Results. Section IV in this paper shows, that we designed and attempted this experiment for more than 10 years, with measurements up to 5 m distance in the geometrical shadow, from the diffracting edge. For these distances, we found no dependence of the diffracted light on the beam thickness above the diffracting edge, which is in accordance with the wave integral prediction. Due to the lack of resources to measure at 100 – 500 m, where the wave approach indicates the existence of such a dependence, we could not finish the experiment. But our documentation here for our experiment will allow that bigger labs develop and finish these measurements.

However, Section IV also shows that by using the method reported above, namely the broad thinking on the major opposing view, we found that alternatively, the proof for how light spreads in general, surprisingly comes by recognizing the real significance of relatively new experimental data existing for the diffraction on macroscopic holes, Section IV. This experimental data comes from relatively new measurements which analyze the role of the edges in the diffraction on nanoscopic and microscopic holes in nanoscopic walls. We describe here that the data from these measurements provides a simple case of reduction to absurd for the wave approach which demonstrates that light has physically a non-wave spreading. This conclusion makes necessary and important for the physics community to perform the above missing direct experimental verification, as a double-check. If correct, this conclusion makes necessary a new, non-wave but periodic, mechanism type structure for light. This situation would be similar but much more important than the case when the heat production by mechanical action was missing and then added in physics by the kinetic theory of heat instead of the model of the caloric fluid for heat. A new mechanism type structure for light would remove the non-mechanism, physically impossible ideas like “light spreads like waves, but nothing oscillates”, while still allowing to use the wave approach as a formal way, valid for practical quantitative evaluations in the limited space of the diffraction fringe zones.

II. ANALYTICAL AND NUMERICAL WAVE CALCULATIONS ILLUSTRATIVE FOR THE MISSING EXPERIMENT

The wave theory of diffraction shows, through the diffraction integral (an expression of the Huygens principle), that all the points above the diffracting edge contribute/ spread diffracted light in the geometrical shadow. We present the predictions of the diffraction integral for the light in the geometrical shadow of a straight diffracting edge. We underline here that in the wave view, all the points around the diffracting edge, not only those in the illuminated spot on the diffracting edge, contribute diffracted light in the geometrical shadow. This presentation also suggests where in geometrical shadow, we can measure the effect of increasing of the beam thickness transversal to the diffracting edge.

We use the Rayleigh-Sommerfeld (RS) formula for the diffraction integral [1] which is simpler than the Fresnel-Kirchhoff formula [1,2] and accurate at distances in the fringe zones [1 in Sec. 3.1, and 3 in Sec. 8.4], that is not close to

the diffracting . If U characterizes the electrical potential (a complex number) of the incident beam of light, in the electromagnetic theory of light, then the RS formula states that the electrical potential U at a point P_0 behind a screen with the aperture Σ of fig. 1, is given by an integral over the entire area of the aperture, with the elementary area ds [1],

$$U(P_0) = \frac{1}{j\lambda} \iint_{\Sigma} U(P_1) \frac{\exp(-jkr_{01})}{r_{01}} \cos(\vec{n}, \vec{r}_{01}) ds, \quad (1)$$

where $j = \sqrt{-1}$, $k = 2\pi/\lambda$ is the light wavelength of the wave. The other quantities in eq (1) are defined in fig. 1. $\cos(\vec{n}, \vec{r}_{01})$ is the cosine of the angle between the directions $\vec{n}$ and $\vec{r}_{01}$. In this formula one assumes that the values of U at the points P_1 on the surface Σ of the aperture are the same as when the screen and the aperture are not present. Here U could characterize a round or elliptic laser beam [3], or a plane wave beam [1].

Fig. 1 The diffraction of light on an aperture Σ in a non-transparent plate. To calculate the diffracted light by the aperture $U(P_0)$ we can use the Rayleigh-Sommerfeld formula where the electrical potential U is assumed known at point P_1 in the aperture – the value of U given by the Maxwell equations in the absence of the plate.

The formula (1) is an expression of the Huygens principle, and says that each point P_1 on the wave front Σ contributes a number of $U(P_1) \cos(\vec{n}, \vec{r}_{01})$ spherical waves $\exp(-jkr_{01})/r_{01}$ towards the point P_0 . In other words, in the wave theory any point P_1 in the aperture Σ contributes to a given point P_0 , even if this point is in the geometrical shadow, i.e. not in the area directly illuminated by the incident beam of light. In the wave theory of light, the

intensity of the optical field at a point P is the square of the modulus of the complex number $U(P)$,

$$I(P) = |U(P)|^2 \quad (2)$$

Fresnel Approximation. We use the Fresnel approximation [1] for the diffraction integral because its results are clearly valid at points of interest here, starting with points relatively far from the diffracting edge, but not too far from the beam axis. It would be simpler to use the Fraunhofer approximation (and the associated Fourier transform) but this approximation is valid only for too large distances from the diffracting edge – more than 1500 m from the diffracting edge, [1].

Assume that $U(x_1, y_1, z_1)$ on the aperture can be factorized

as $U(x_1, y_1, z_1) = F(x_1, z_1)G(y_1, z_1)$. In order to produce a closed form from eq. (1) we need an approximation that allows the exponential to be factorized in terms dependent only on one integration coordinate. According to Fig. 1,

$$r_{01} = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2 + (z_0 - z_1)^2} \quad (3)$$

Generally, we are interested in a diffraction pattern at large z_0 and we assume that $z_{01} = z_0 - z_1$ is much greater than the rest of the difference quantities in eq. (7). In this case,

$$\begin{aligned} r_{01} &= z_{01} \sqrt{1 + (x_0 - x_1)^2 / z_{01}^2 + (y_0 - y_1)^2 / z_{01}^2} \\ &\approx z_{01} (1 + (x_0 - x_1)^2 / 2z_{01}^2 + (y_0 - y_1)^2 / 2z_{01}^2) \end{aligned} \quad (4)$$

The above assumption is also consistent with assuming $\cos(\vec{n}, \vec{r}_{01}) \cong 1$. Therefore eq. (1) becomes,

$$\begin{aligned} U(P_0) &= \frac{\exp(-jkz_{01})}{j\lambda z_{01}} \iint_{\Sigma} U(x_1, y_1, z_1) \\ &\quad \cdot \exp(-j \frac{k}{2z_{01}} [(x_0 - x_1)^2 + (y_0 - y_1)^2]) ds \\ U(x_0, y_0, z_0) &= \frac{\exp(-jkz_{01})}{j\lambda z_{01}} \int dx_1 F(x_1) \exp(-j \frac{k}{2z_{01}} [(x_0 - x_1)^2]) \\ &\quad \cdot \int dy_1 G(y_1) \exp(-j \frac{k}{2z_{01}} [(y_0 - y_1)^2]) \end{aligned} \quad (5)$$

This formula is called the Fresnel approximation of eq. (1).

Gaussian Beam. According to [4, pg. 10.6 – 10.8] “the low power beam from helium-neon lasers are closely approximated by a Gaussian beam (also called a pure or fundamental mode beam)”. Indeed, the propagation factor M^2 for such helium-neon lasers, which measure the deviation of the beam propagation from a pure Gaussian beam, is close to 1. The higher the power of the laser, the more

complex is mathematical description necessary for the beam. Hence, for our illustrative purpose (not absolutely necessary) of the wave approach for the straight line diffraction, we can use a pure Gaussian beam. An elliptic Gaussian beam [5] is a solution of the Maxwell equations. A Gaussian beam that propagates along the z axis is defined [5, 6] by,

$$U^{laser}(x, y, z) = U_{inc} \frac{\sqrt{\omega_{0x}\omega_{0y}}}{\sqrt{\omega_x(z)\omega_y(z)}} \exp(j[kz + \beta(z)] - x^2[\frac{1}{\omega_x^2(z)} + \frac{jk}{2R_x(z)}] - y^2[\frac{1}{\omega_y^2(z)} + \frac{jk}{2R_y(z)}]) \quad (6)$$

Here,

$$\begin{aligned} r^2 &= x^2 + y^2, \quad k = 2\pi / \lambda, \\ \omega_x^2(z) &= \omega_{mx}^2 (1 + (2(z - z_{mx}) / b_x)^2), \\ \omega_y^2(z) &= \omega_{my}^2 (1 + (2(z - z_{my}) / b_y)^2), \\ \text{or, } \omega_x^2(z) &= \omega_{mx}^2 (1 + ((z - z_{mx}) / z_{0x})^2), \\ \omega_y^2(z) &= \omega_{my}^2 (1 + ((z - z_{my}) / z_{0y})^2) \\ R_x(z) &= (z - z_{mx})(1 + (b_x / (2(z - z_{mx})))^2), \\ R_y(z) &= (z - z_{my})(1 + (b_y / (2(z - z_{my})))^2), \\ \beta(z) &= \frac{1}{2} \tan^{-1}(2(z - z_{mx}) / b_x) + \frac{1}{2} \tan^{-1}(2(z - z_{my}) / b_y), \quad (7) \\ b_x &= 2\pi\omega_{mx}^2 / \lambda, \quad z_{0x} = b_x / 2, \quad b_y = 2\pi\omega_{my}^2 / \lambda, \\ z_{0y} &= b_y / 2 \end{aligned}$$

The quantities ω_{mx} and ω_{my} are the beam minimum waists (ellipse semi-axes) at the positions z_{mx} , z_{my} respectively, along the z axis. ω_{mx} and ω_{my} are the values at which the beam field amplitude $|U|$ decreases by a factor $1/e$ compared to its value on the beam axis. The beam is simply a circular beam along the z axis when $\omega_{mx} = \omega_{my} = \omega_m$, $z_{mx} = z_{my} = z_m$, and hence, when $\omega_x = \omega_y = \omega$. Its minimum waist of ω_m is at z_m .

The diffraction of an elliptic Gaussian beam. Assume that the diffracting half-plane edge/ screen is defined by the conditions $z = z_1$, $y_1 \leq \varepsilon$ and $-\infty < x_1 < \infty$, where ε is positive or negative number to position the half-screen off the axis of the circular Gaussian beam. The position of the screen for the diffraction pattern is

considered at $z_0 > 0$. The diffracted light in this case can be derived by using eq. (6) as $U(x_1, y_1, z_1) = F(x_1, z_1)G(y_1, z_1)H(z_1)$ in the Fresnel approximation - eq. (5) of the diffraction formula - eq. (1). The integration domain will be $-\infty < x_1 < \infty$ and $\varepsilon \leq y_1 \leq y_{\max}$, where “ $y_{\max}$ ” is normally very large (i.e., ∞). However, $y_{\max}$ can be chosen smaller than $\omega_y(z_1)$ for studying how the integration domain influences the diffracted light in a certain point (x_0, y_0, z_0) . In the latter case, the interval $(\varepsilon, y_{\max})$ defines in fact a one-dimensional slit.

$$U(x_0, y_0, z_0) = \frac{\exp(-jkz_{01})}{j\lambda z_{01}} U_{inc} \frac{\sqrt{\omega_{mx}\omega_{my}}}{\sqrt{\omega_x(z)\omega_y(z)}} \exp j[kz_1 + \beta(z_1)] \cdot$$

$$\cdot \int_{-\infty}^{\infty} dx_1 \exp(-x_1^2 [\frac{1}{\omega_x^2(z_1)} + \frac{jk}{2R_x(z_1)}]) \exp(-j \frac{k}{2z_{01}} [(x_0 - x_1)^2])$$

$$\cdot \int_{\varepsilon}^{y_{\max}} dy_1 \exp(-y_1^2 [\frac{1}{\omega_y^2(z_1)} + \frac{jk}{2R_y(z_1)}]) \exp(-j \frac{k}{2z_{01}} [(y_0 - y_1)^2])$$

$$U(x_0, y_0, z_0) = \frac{\exp(-jkz_{01})}{j\lambda z_{01}} U_{inc} \frac{\sqrt{\omega_{mx}\omega_{my}}}{\sqrt{\omega_x(z)\omega_y(z)}} \exp j[kz_1 + \beta(z_1)] \cdot$$

$$\cdot \int_{-\infty}^{\infty} dx_1 \exp(-(x_1^2 (\frac{1}{\omega_x^2(z_1)} + \frac{jk}{2R_x(z_1)}) + j \frac{k}{2z_{01}} (x_1^2 - 2x_0x_1 + x_0^2))) \quad (8)$$

$$\cdot \int_{\varepsilon}^{\infty} dy_1 \exp(-(y_1^2 (\frac{1}{\omega_y^2(z_1)} + \frac{jk}{2R_y(z_1)}) + j \frac{k}{2z_{01}} (y_1^2 - 2y_0y_1 + y_0^2)))$$

$$U(x_0, y_0, z_0) = \frac{\exp(jkz_{01})}{j\lambda z_{01}} U_{inc} \frac{\sqrt{\omega_{mx}\omega_{my}}}{\sqrt{\omega_x(z)\omega_y(z)}} \exp j[kz_1 + \beta(z_1)] \cdot$$

$$\cdot \int_{-\infty}^{\infty} dx_1 \exp(-(a_1x_1^2 + 2b_1x_1 + c_1)) \quad (9)$$

$$\cdot \int_{\varepsilon}^{\infty} dy_1 \exp(-(a_2y_1^2 + 2b_2y_1 + c_2))$$

In eq. (9) the coefficients are defined as follows,

$$\begin{aligned}
a_1 &= V_{1x}(z_1) + j(V_{2x}(z_1) + \frac{k}{2z_{01}}) = V_{1x} + j(V_{2x} + \frac{k}{2z_{01}}) \\
a_2 &= V_{1y}(z_1) + j(V_{2y}(z_1) + \frac{k}{2z_{01}}) = V_{1y} + j(V_{2y} + \frac{k}{2z_{01}}) \\
b_1 &= -j \frac{kx_0}{2z_{01}} \quad b_2 = -j \frac{ky_0}{2z_{01}} \\
c_1 &= j \frac{kx_0^2}{2z_{01}} \quad c_2 = j \frac{ky_0^2}{2z_{01}}
\end{aligned} \quad , \quad (10)$$

where

$$\begin{aligned}
V_{1x} &= V_{1x}(z_1) = \frac{1}{\omega_x^2(z_1)} & V_{2x} &= V_{2x}(z_1) = \frac{k}{2R_x(z_1)} \\
V_{1y} &= V_{1y}(z_1) = \frac{1}{\omega_y^2(z_1)} & V_{2y} &= V_{2y}(z_1) = \frac{k}{2R_y(z_1)}
\end{aligned} .$$

Hence,

$$U(x_0, y_0, z_0) = U_{inc} \cdot A \cdot I_1 \cdot I_2 . \quad (11)$$

with
$$A = \frac{\exp(-jkz_{01})}{j\lambda z_{01}} \frac{\sqrt{\omega_{mx}\omega_{my}}}{\sqrt{\omega_x(z)\omega_y(z)}} \exp j[kz_1 + \beta(z_1)] . \quad (12)$$

According to [7] the integrals in eq. (9) , and based on $erf(\infty) = 1$ and $erf(-\infty) = -1$, are

$$\begin{aligned}
I_1 &= \int_{-\infty}^{\infty} dx_1 \exp(-(a_1 x_1^2 + 2b_1 x_1 + c_1)) = \\
&\exp(\frac{b_1^2}{a_1} - c_1) \frac{1}{2} \sqrt{\frac{\pi}{a_1}} erf(\sqrt{a_1} x_1 + \frac{b_1}{\sqrt{a_1}}) \Big|_{-\infty}^{\infty} = \\
&\exp(\frac{b_1^2}{a_1} - c_1) \frac{1}{2} \sqrt{\frac{\pi}{a_1}} \cdot 2 = \exp(\frac{b_1^2}{a_1} - c_1) \sqrt{\frac{\pi}{a_1}} .
\end{aligned} \quad (13),$$

where,

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2) dt .$$

$$\begin{aligned}
I_2 &= \int_{\varepsilon}^{y \max} dy_1 \exp(-(a_2 y_1^2 + 2b_2 y_1 + c_2)) = \\
&= \int_{\varepsilon}^{\infty} dy_1 \exp(-(a_2 y_1^2 + 2b_2 y_1 + c_2)) - \\
&\quad \int_{y \max}^{\infty} dy_1 \exp(-(a_2 y_1^2 + 2b_2 y_1 + c_2)) \\
&= \frac{1}{2} \sqrt{\frac{\pi}{a_2}} \exp\left(\frac{b_2^2}{a_2} - c_2\right) \operatorname{erf}\left(\sqrt{a_2} y_1 + \frac{b_2}{\sqrt{a_2}}\right) \Big|_{\varepsilon}^{\infty} - \\
&\quad \frac{1}{2} \sqrt{\frac{\pi}{a_2}} \exp\left(\frac{b_2^2}{a_2} - c_2\right) \operatorname{erf}\left(\sqrt{a_2} y_1 + \frac{b_2}{\sqrt{a_2}}\right) \Big|_{\varepsilon}^{\infty} \\
&= \frac{1}{2} \sqrt{\frac{\pi}{a_2}} \exp\left(\frac{b_2^2}{a_2} - c_2\right) (1 - \operatorname{erf}(\sqrt{a_2} \varepsilon + \frac{b_2}{\sqrt{a_2}})) - \\
&\quad \frac{1}{2} \sqrt{\frac{\pi}{a_2}} \exp\left(\frac{b_2^2}{a_2} - c_2\right) (1 - \operatorname{erf}(\sqrt{a_2} y \max + \frac{b_2}{\sqrt{a_2}})) = \\
&= \frac{1}{2} \sqrt{\frac{\pi}{a_2}} \exp\left(\frac{b_2^2}{a_2} - c_2\right) (\operatorname{cerf}(\sqrt{a_2} \varepsilon + \frac{b_2}{\sqrt{a_2}}) - \operatorname{cerf}(\sqrt{a_2} y \max + \frac{b_2}{\sqrt{a_2}})) \quad (13')
\end{aligned}$$

where $\operatorname{cerf}(y) = 1 - \operatorname{erf}(y)$.

In order to express these equations in a more computational form let us define

$$\begin{aligned}
\cos \varphi_x &= V_{1x} / \sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2} > 0, \\
\sin \varphi_x &= (V_{2x} + k/2z_{01}) / \sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2} > 0, \\
\cos \varphi_y &= V_{1y} / \sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} > 0, \\
\sin \varphi_y &= (V_{2y} + k/2z_{01}) / \sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} > 0
\end{aligned} \tag{14}$$

Notice that since $\cos \varphi > 0$, $\sin \varphi > 0$, it follows that $\cos \varphi/2 > 0$, $\sin \varphi/2 > 0$.

Hence we have the following equations,

$$\begin{aligned}
a_1 &= V_{1x} + j(V_{2x} + \frac{k}{2z_{01}}) = \sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2} (\cos \varphi_x + j \sin \varphi_x), \\
\sqrt{a_1} &= \sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}} (\cos \varphi_x / 2 + j \sin \varphi_x / 2). \\
1/a_1 &= (V_{1x} - j(V_{2x} + k/2z_{01})) / (V_{1x}^2 + (V_{2x} + k/2z_{01})^2) \\
&= \frac{1}{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}} (\cos \varphi_x - j \sin \varphi_x), \\
b_1^2 / a_1 &= \frac{-k^2 x_0^2 / (4z_{01}^2)}{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}} (\cos \varphi_x - j \sin \varphi_x),
\end{aligned} \tag{15}$$

$$\begin{aligned}
a_2 &= V_{1y} + j(V_{2y} + \frac{k}{2z_{01}}) = \sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} (\cos \varphi_y + j \sin \varphi_y), \\
\sqrt{a_2} &= \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} (\cos \varphi_y / 2 + j \sin \varphi_y / 2). \\
1/a_2 &= (V_{1y} - j(V_{2y} + k/2z_{01})) / (V_{1y}^2 + (V_{2y} + k/2z_{01})^2) \\
&= \frac{1}{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} (\cos \varphi_y - j \sin \varphi_y) \\
b_2^2 / a_2 &= \frac{-k^2 y_0^2 / (4z_{01}^2)}{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} (\cos \varphi_y - j \sin \varphi_y),
\end{aligned} \tag{16}$$

$$\begin{aligned}
1/\sqrt{a_1} &= \frac{1}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} (\cos \varphi_x / 2 - j \sin \varphi_x / 2), \\
|\frac{\sqrt{\pi}}{\sqrt{a_1}}| &= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} |\cos \varphi_x / 2 - j \sin \varphi_x / 2| \\
&= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}}
\end{aligned} \tag{17}$$

$$\begin{aligned}
1/\sqrt{a_2} &= \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} (\cos \varphi_y / 2 - j \sin \varphi_y / 2), \\
|\sqrt{\frac{\pi}{a_2}}| &= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} |\cos \varphi_y / 2 - j \sin \varphi_y / 2| \\
&= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
b_2 / \sqrt{a_2} &= -j \frac{ky_0}{2z_{01}} \frac{\cos \varphi_y / 2 - j \sin \varphi_y / 2}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
&= -\frac{ky_0}{2z_{01}} \frac{\sin \varphi_y / 2 + j \cos \varphi_y / 2}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}}
\end{aligned} \tag{18}$$

Let us also define

$$\begin{aligned}
u_y + jv_y &= \sqrt{a_2} \varepsilon + \frac{b_2}{\sqrt{a_2}} = \varepsilon \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} \cos \varphi_y / 2 \\
&\quad + j \varepsilon \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} \sin \varphi_y / 2 \\
&\quad - \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \sin \varphi_y / 2 \\
&\quad - j \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \cos \varphi_y / 2
\end{aligned} \tag{19}$$

$$\begin{aligned}
p_y + jq_y &= \sqrt{a_2} y \max + \frac{b_2}{\sqrt{a_2}} = \\
&y \max \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} \cos \varphi_y / 2 +} \\
&\quad jy \max \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} \sin \varphi_y / 2} \quad (19') \\
&- \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \sin \varphi_y / 2 - \\
&\quad j \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \cos \varphi_y / 2
\end{aligned}$$

Hence,

$$\begin{aligned}
u_y &= \varepsilon \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} \cos \varphi_y / 2} \\
&\quad - \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \sin \varphi_y / 2, \\
v_y &= \varepsilon \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2} \sin \varphi_y / 2} \\
&\quad - \frac{ky_0}{2z_{01}} \frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \cos \varphi_y / 2
\end{aligned} \quad (20)$$

Similar expressions are true for p_y and q_y .

Notice that

$$\begin{aligned}
v_y^2 - u_y^2 &= (\varepsilon \sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}})^2 (\sin^2 \varphi_y / 2 - \cos^2 \varphi_y / 2) \\
&\quad + \frac{k^2 y_0^2}{4z_{01}^2} \left(\frac{1}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \right)^2 (\cos^2 \varphi_y / 2 - \sin^2 \varphi_y / 2) \\
&= -\varepsilon^2 \sqrt{(V_{1y}^2 + (V_{2y} + k/2z_{01})^2)} \cos \varphi_y \\
&\quad + \frac{k^2 y_0^2}{4z_{01}^2} \frac{1}{\sqrt{(V_{1y}^2 + (V_{2y} + k/2z_{01})^2)}} \cos \varphi_y \\
&= -\varepsilon^2 V_{1y} + \frac{k^2 y_0^2}{4z_{01}^2} \frac{V_{1y}}{(V_{1y}^2 + (V_{2y} + k/2z_{01})^2)}
\end{aligned} \quad (21)$$

and hence,

$$-\frac{k^2 y_0^2}{4z_{01}^2} \frac{V_{1y}}{(V_{1y}^2 + (V_{2y} + k/2z_{01})^2)} = u_y^2 - v_y^2 - \varepsilon^2 V_{1y} \quad (22)$$

Similarly,

$$-\frac{k^2 y_0^2}{4z_{01}^2} \frac{V_{1y}}{(V_{1y}^2 + (V_{2y} + k/2z_{01})^2)} = p_y^2 - q_y^2 - y \max^2 V_{1y} \quad (22')$$

From eq. (11)

$$|U(x_0, y_0, z_0)/U_{inc}| = |A| \cdot |I_1| \cdot |I_2| \quad (23)$$

where,

$$|A(z_1)| = \frac{\sqrt{\omega_{mx}\omega_{my}}}{\sqrt{\omega_x(z_1)\omega_y(z_1)}} \frac{1}{\lambda z_{01}}, \quad (24)$$

Based on eqs. (14), (22) and (22')

$$\begin{aligned} |I_1| &= |I_1(x_0)| = |I_1(x_0, z_0, z_1)| = \frac{\sqrt{\pi} |\exp((b_1^2/a_1) - c_1)|}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \\ &= \frac{\sqrt{\pi} |\exp(b_1^2/a_1)|}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \\ &= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \\ &\quad \cdot \exp\left(\frac{-k^2 x_0^2/(4z_{01}^2)}{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}} (\cos \varphi_x - j \sin \varphi_x)\right) \\ &= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \\ &\quad \cdot \exp\left(\frac{-k^2 x_0^2/(4z_{01}^2)}{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}} \cos \varphi_x\right) \\ &= \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \exp\left(\frac{-V_{1x} k^2 x_0^2/(4z_{01}^2)}{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}\right) \quad (25) \end{aligned}$$

Similarly,

$$\begin{aligned}
|I_2| &= |I_2(y_0)| = |I_2(y_0, z_0, z_1)| = \frac{1}{2} \frac{\sqrt{\pi} |\exp(b_2^2/a_2 - c_2)|}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
&\quad \cdot |(\operatorname{cerf}(\sqrt{a_2} \varepsilon + \frac{b_2}{\sqrt{a_2}}) - \operatorname{cerf}(\sqrt{a_2} y_{\max} + \frac{b_2}{\sqrt{a_2}}))| \\
&= \frac{1}{2} \frac{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
&\quad \cdot |\exp(\frac{-k^2 y_0^2/(4z_{01}^2)}{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}} (\cos \varphi_y - j \sin \varphi_y))| Y \\
&= \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} (\exp(\frac{-k^2 y_0^2/(4z_{01}^2)}{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}) \cos \varphi_y) Y, \\
&= \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} (\exp(\frac{-V_{1y} k^2 y_0^2/(4z_{01}^2)}{V_{1y}^2 + (V_{2y} + k/2z_{01})^2})) Y.
\end{aligned} \tag{26}$$

where,

$$Y = |(\operatorname{cerf}(u_y + jv_y) - \operatorname{cerf}(p_y + jq_y))| \tag{26'}$$

Therefore,

$$|I_1| = \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}}} \exp(\frac{-V_{1x} k^2 x_0^2/(4z_{01}^2)}{V_{1x}^2 + (V_{2x} + k/2z_{01})^2}), \tag{27}$$

$$\begin{aligned}
|I_2| &= \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
&\quad \cdot |\exp(-\varepsilon^2 V_{1y}) \exp(u_y^2 - v_y^2) \operatorname{cerf}(u_y + iv_y) - \\
&\quad \exp(-y_{\max}^2 V_{1y}) \exp(p_y^2 - q_y^2) \operatorname{cerf}(p_y + iq_y)|
\end{aligned} \tag{28}$$

Notice that when ymax goes to infinity then,

$$\begin{aligned}
|I_2| &= \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_{1y}^2 + (V_{2y} + k/2z_{01})^2}}} \\
&\quad \cdot \exp(-\varepsilon^2 V_{1y}) |\exp(u_y^2 - v_y^2) \operatorname{cerf}(u_y + iv_y)|
\end{aligned} \tag{28'}$$

The numerical calculations. The direct calculation of $\operatorname{cerf}(u+jv)$ from eq. (28') is difficult because it leads to multiplying very large numbers with very small numbers which results in very large errors. Rather, the calculation of $\operatorname{cerf}(u+jv)$

can be based on the calculation of the Fadeeva function $w(-v+ju)$ by the following derivation. From Ref. [7] we have,

$$\begin{aligned} w(z) &= \exp(-z^2) \operatorname{cerf}(-jz) \\ w(jz) &= \exp(z^2) \operatorname{cerf}(z) \end{aligned} \quad (29)$$

where $z = u+jv$, or $z = p+jq$

Hence,

$$\begin{aligned} w(-v+ju) &= \exp(u^2 - v^2) \exp(j2uv) \operatorname{cerf}(u+jv) \\ w(-q+jp) &= \exp(p^2 - q^2) \exp(j2pq) \operatorname{cerf}(p+jq) \\ \exp(u^2 - v^2) \operatorname{cerf}(u+jv) &= \exp(-j2uv) w(-v+ju) \\ \exp(p^2 - q^2) \operatorname{cerf}(p+jq) &= \exp(-j2pq) w(-q+jp) \end{aligned} \quad (30)$$

Therefore eq. (28) becomes

$$\begin{aligned} |I_2| &= \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_1^2 + (V_2 + k/2z_{01})^2}}} \\ &\quad \cdot |\exp(-\varepsilon^2 V_1) \exp(-j2uv) w(-v+ju) \\ &\quad - \exp(-p_{\max}^2 V_1) \exp(-j2pq) w(-q+jp)| \end{aligned} \quad (31)$$

Again, when $p_{\max}$ goes to infinity then,

$$|I_2| = \frac{1}{2} \frac{\sqrt{\pi}}{\sqrt{\sqrt{V_1^2 + (V_2 + k/2z_{01})^2}}} \exp(-\varepsilon^2 V_1) |w(-v+ju)| \quad (31')$$

A Fortran program for eqs. (23 – 31) : Edgediffraction_gaussianbeam.

We developed a computer program in Fortran for the calculation of the diffraction integral for a Gaussian beam based on eqs. (23-31). The calculation of the function $w(-v+ju)$ is done with the routine Function $w\operatorname{werf}(z)$ [8-11]. We tested the program in various ways.

a) For a perfectly round beam it produces the value of $A(z_1)/2$ for eq. (23) for $(x_0, y_0, z_0) = (0, 0, z_0)$ as it should. This means that the light intensity on the beam axis (i.e., the square value of eq. (23)) is $A(z_1) \cdot A(z_1) / 4$. The program shows that when ε is a large negative number, that is when there is no diffraction edge in the path of the beam, the program gives for the diffraction integral the values of the Gaussian beam, as it should. Also, when ε is a very large positive number, that is when the Gaussian beam of light is blocked by the diffracting edge, the program gives very small numbers for the diffraction integral, that is no beam passes the diffracting edge.

b) The graph in Fig. 2 compares the results for a thick beam with the results for a plane wave.

The amplitude for the diffraction of light on a half-plane - (x,y) plane. The Gaussian beam has its axis along the z-axis and its minimum waist is at $z=0$ while the diffracting half-plane is at $z = 1000$ mm and the diffraction pattern is calculated at $z = 5000$ mm.

FIG. 2 Testing the program for the diffraction of a Gaussian beam. The diffracted amplitude at 4000 mm behind the diffracting half-plane for a thick (10 mm diameter) Gaussian beam is compared with the standard case of the diffracted amplitude for a plane wave. The comparison shows that the numerical calculations are satisfactory.

III. THE EXPERIMENTAL SETUP

In this experiment a laser beam hits perpendicularly with its axis a fine diffracting edge, and the intensity of light is measured in the geometrical shadow of the diffracting edge. This experiment verifies systematically if the intensity of

the diffracted light in any point in the geometrical shadow, especially at large distances, increases when the thickness of the diffracting beam increases transversally to the diffracting edge. Surprisingly, this dependence, although is the most fundamental prediction for understanding the nature of light (more important than the diffracting fringes, for the nature of light) because a very large (infinite) volume, was not systematically measured yet. Our experimental setup includes three systems: a highly stable laser with a fine positioning/ orientation system, a fine edge/ slit system with micrometric positioning system, and a detector system: a linear detector - PDF10A, Femtowatt Photoreceiver from Thor, and a two-dimensional camera - the Little Guy beam profiler from Ankron, with a fine positioning system. Our laser is a Micro-g Lacoste laser - a high quality He-Ne, 1mW.

This experiment tests if the Huygens principle, or the wave diffraction integral is valid for the diffracted light in the geometrical shadow, that is if the later depends on the thickness of the beam transversal to the diffracting edge, while maintaining the same distribution of light along the diffraction edge. We answer the following questions. How the calculations and the experiment can vary this transversal thickness of the beam and maintain the longitudinal distribution of light along the diffracting edge? At what distance from the laser we need to measure the light in the geometrical shadow in order to see if there is a dependence on the beam thickness across the diffracting edge? By following a systematic measurement, or calculations with the elliptical Gaussian beam, naturally allows answering these questions.

Fig. 3. Gaussian beam diameter (where the beam intensity decreases at $1/e$ from the value on z axis) and the changes in the wave front with propagating distance along z axis. This is a circular beam and hence, the graph is the same on both x and y axis transversal to z axis.

http://www.mellesgriot.com/pdf/CatalogX/X_02_2-5.pdf.

Our Micro-g Lacoste laser, is a highly stable in intensity and direction 1mW laser, with a minimum beam radius (waist) $\omega_m = 0.3$ mm at the exit from the laser, and with a beam divergence 1.3 mrad, polarized beam. The diffracting edge is placed at distances 1500 mm where β of eq. (7) becomes proportional with z . For $z_{mx} = z_{my} = 0$ mm we have $\omega_x = \omega_y = 1$ mm at $z = 1500$ mm, while for $z_{my} = 0$ mm and $z_{mx} = 3000$ we have $\omega_y = 3$ mm and $\omega_x = 1$ mm at $z = 4500$ mm.

The laser and the origin of the beam is placed at $z = 0$ Fig. 3, the plane of the diffracting edge is placed in the semi-plane (x_1, y_1, z_1) where $-\infty < x_1 < \infty$, $y_1 \leq 0$, with z_1 a fixed point beyond z_R . The edge itself extends parallel with the x axis and touches the z axis at z_1 . The points where we calculate or measure the diffracted light are on the line $(0, y_0, z_0)$ with $y_0 < 0$ such that $z_0 - z_1$ is a large distance from the diffracting edge, that is a line parallel with the y axis, at large distance in the geometrical shadow. Below we show that the latter distance needs to be in a range difficult to measure, namely 100 m to 500 m, that is not in the 5 m which is normally accessible.

In the calculations, for a given position of the diffracting edge on the z axis, we compared two cases of traversal thickness but with the same longitudinal (along the diffracting edge) distribution of light. In the first case (case 1), which is the reference case, we use the same position along the beam axis $z_{mx} = z_{my} = 0$ in eq. (7) for the two minimum waists of the Gaussian beam – the one on the x axis (along the diffracting edge) and the one on the y axis (transversal to the diffracting edge). The diffracting edge is placed at the distance $z_1 - z_{mx} = 1.5$ m from the beam waists. In the second case (case 2) the position of the minimum waist on the y axis is kept as in the first case while the position of the minimum waist on the x axis is moved forward at larger values of z_{mx} along z axis. At the same time the position z_1 of the diffracting edge is also moved forward, so that the distance $z_1 - z_{mx}$ remains constant, which is the same as in the case 1. As a result of this variation the traversal (y axis) distribution of the light on the diffracting edge varies (the traversal thickness of the beam falling on the diffracting edge increases), but the distribution along the diffracting edge is similar and by normalization can be made the same. The comparison of the calculated diffracted light in these two cases characterizes the predicted effect of increasing the beam thickness, transversal to the diffracting edge, on the diffracted light in the geometrical shadow.

The numerical calculations with our Fortran program Edgediffraction Gaussianbeam show the following differences between the light intensities for the two cases: 1) Less than 1% for $z_0 - z_1 = 5$ m and y_0 in the range of 10 mm to 25

mm below z axis that is in the geometrical shadow. 2) 5% for $z_0 - z_1 = 50$ m and $y_0 = 10$ mm, and 5 % for $z_0 - z_1 = 50$ m and $y_0 = 25$ mm below z axis that is in the geometrical shadow. 3) Around 75 % for $z_0 - z_1 = 100$ m and y_0 in the range of 10 mm to 25 mm below z axis that is in the geometrical shadow. 4) Around 250 % for $z_0 - z_1 = 500$ m and y_0 in the range of 10 mm to 25 mm below z axis that is in the geometrical shadow. Therefore, these numerical results show that we need to measure the diffracted light in the geometrical shadow for $z_0 - z_1$ in the range from 100 m to 500 m, better for $z_0 - z_1$ close to 500 m. We needed a long time to explore by calculations where we need to measure. Initially we were looking at distances $z_0 - z_1$ from 5 m to 10 meters.

A quicker insight for where to calculate and measure can be obtained by evaluating the radius of the first Fresnel zone on the integration domain in the diffraction integral, which is the main contributor to the value of the diffraction integral for any given point $P0 (x_0, y_0, z_0)$ in the geometrical shadow. A point $P1 (x_1, y_1, z_1)$ from the integration domain in the diffraction integral, is in the first Fresnel zone if the difference of the distance between P0 and P1 and of the distance between P0 and $O(0,0, z_1)$ is smaller than $\lambda / 2$. For $(0, y_0, z_0)$ in the geometrical shadow with $y_0 = -10$ mm and $z_0 = 5$ m, 50 m, 100 m and 500 m, the results for the radius of the first Fresnel zone are of the order of 0.1 mm, 1mm, 2 mm and 8 mm respectively. This means that our Case 1 with a beam thickness of 1 mm on the diffracting edge and Case 2 with a beam thickness of 3 mm transversal to the diffracting edge, can be differentiated only at points in the geometrical shadow of $y_0 = -10$ mm and z_0 in the range 100 m to 500 m, better close to the latter.

Experimentally, the beam waists for our laser are in the same place $z_{mx} = z_{my} = 0$ mm on the z axis, as used in the Case 1 above. Reference [12, pg. 122-123], shows an example of how with a lens we can create a second beam waist along the x axis by using a lens of a focal distance f. This example can be adapted for our Case 2, by placing a divergent cylindrical lens of a certain focal distance f at a position z_l , before the diffracting edge for Case 1, with the axis of the cylindrical lens parallel with the x axis. Then the beam spreads more along y axis, as if a second beam waist ω_{new} along y axis (smaller than ω_{my} from the Case1) is created at the distance d before the lens, as necessary for the Case 2. By varying the position z_l and the focal distance f we can have the same distribution of light falling on the diffraction edge along the x axis, but a broader light beam falls transversally to the diffracting edge. Hence it is possible to reproduce experimentally the Case 1 and Case 2 above. Certainly the normalization of the

beam at the diffracting edge for the two cases is necessary in order that the distribution of light falling on the diffracting edge be the same in the two cases.

IV. RESULTS

1) The results from our experiment

Due to limited resources of our small lab, we could perform the measurements only at distances of about 5 meters from the diffracting edge. For these distances the differences between the above two cases for diffraction were very small, as the wave integral predicts. This means that we could not measure in the range of 100 m to 500 m where the wave approach illustrates a strong dependence of the diffracted light in the geometrical shadow on the beam thickness traversal to the diffracting edge. It took a long time, a lifetime for the authors to perform these steps. They could be the basis for future attempts to verify this dependence.

2) The alternative experimental proof that light does not spread like waves

As described above, the experimental verification of how light spreads at large distances is missing. In this context, we found that the experimental results from Ref. [2-9] are totally useful. These experiments analyze the role of the edges in the diffraction on nanoscopic and microscopic holes in nanoscopic walls. The results display a surprising extraordinary transmission-type of diffracted light, instead of the regular fringe pattern seen in the cases of macroscopic diffraction of light. The authors rightly conclude that the transmission, that is the spreading of light through the nanoscopic edges, have a major contribution to the diffracted light. And they extend the wave propagation in the nanoscopic walls to include this contribution and successfully describe the experimental results on nanoscopic and microscopic holes.

However, the authors of these measurements did not see that this important contribution from the edges in the diffraction on nanoscopic holes, brings the following absurd contradiction in the wave approach for the diffraction on macroscopic holes. Indeed, the edges in the macroscopic holes necessarily have a macroscopic surface area with nanoscopic terminal shapes, and hence, according to the above findings, these macroscopic edges necessarily contribute an important part of the diffracted light. Such an important contribution is also supported by the direct observations with the naked eye, from all directions and from all distances, around the illuminated spots on the diffracting edges in the macroscopic case. The brightness of these spots is even bigger than some of the diffraction fringes. This clearly shows that the brightly illuminated spots on the edges are a source of diffracted light both for the directly illuminated area of the diffraction pattern, and for the shadow area of the diffracted light. However, in the wave approach, the

diffracted light is sufficiently described by the diffraction integral applied only on the inner/ empty space of the macroscopic hole, that is without any illuminated spot on the diffracting edge. And what is the contribution from the edges in this wave approach? If the wave diffraction integral is extended inside the diffracting edges of the hole, the contribution from these edges to the wave diffraction integral is small as compared with the contribution of the wave front on the inner space of the hole. This is a direct result of the fact that the waves on the inner space of the hole can produce by itself the diffraction fringes, and is in total contradiction with the above conclusion from the experimental data of [13-20] that the diffraction edges have an important contribution to the diffracted light. (However, this result from the wave approach for the light diffracted inside the edges, is used in existing books and discussions to wrongfully claim that the edges have physically only a small contribution to diffraction, and hence, justifies ignoring the related questions on the wave nature of light.) Based on this contradiction of the wave approach with the results from [13-20] we have a clear case of reduction to absurd for the wave approach, and hence, light does not spread as the waves do.

This means that in the wave approach, the real problem is replaced by a formal approach valid only in the fringe zones: the fringes are formed mainly by the inherent capability of spreading and interfering of the wave-front which passes through the inner space of the hole. But even this formal fit which the waves give in the fringe zone of the macroscopic diffraction, leads to some poor results, as the diffraction on a simple straight edge (not a hole) shows. Indeed, there is a simple experimental proof [21] that the waves do not give the right position of the diffracting fringes.

These conclusions make necessary and important for the physics community to perform the above missing experimental verification, as a double-check that convinces everybody what the nature of light is. If correct, these conclusions make necessary a new, non-wave but periodic, mechanism type structure for light. In a separate development for a new physical model for light, that is for a non-wave but periodic model, we show that this model is feasible and brings mechanism-type explanations for all the optical phenomena. This would be similar but much more important than the case when recognizing the heat production by mechanical action made necessary and feasible a mechanism-type model, which is the kinetic theory of heat, instead of the model of the caloric fluid for heat.

V. CONCLUSIONS

This paper shows the experimental design of the missing experiment and crucially necessary at the foundation of the wave theory of light: the experiment for the verification if light spreads at large distances as the waves do. We could

not finish the experiment because of the lack of resources to measure at 100 – 500 m. This design makes easier for a lab, like the one in Magurele, Romania, to start and repeat this absolutely necessary experiment. The alternative experimental proof that light does not spread like the waves do, presented in Section IV, also makes necessary and important for the physics community to perform the above missing experimental verification, as a double-check that convinces everybody what the nature of light is. If correct, these conclusions make necessary a new, non-wave but periodic, mechanism type structure for light. In a separate development for a new physical model for light, that is for a non-wave but periodic model, we show that this model is feasible and brings mechanism-type explanations for all the optical phenomena. This would be similar but much more important than the case when recognizing the heat production by mechanical action made necessary and feasible a mechanism-type model, which is the kinetic theory of heat, instead of the model of the caloric fluid for heat.

Acknowledgements. We acknowledge the important help from Professor Anthony Leggett from UIUC in Urbana-Champaign, USA: criticism and advice for improving the form and content of this paper. He requested a self-contained paper, instead of an overview, for the missing experiment. Also, we acknowledge the help from Dr. Ionel Rata by many discussions which helped us to define the missing experiment for the measurement of the diffracted light in the geometrical shadow of the edge diffraction.

References

- [1] J.W. Goodman, *Introduction to Fourier Optics*, (McGraw-Hill, NY, 1968)
- [2] J.E. Pearson, T.C. McGill, S. Kurtin, A. Yariv, *Diffraction of Gaussian Laser Beams by a Semi-Infinite Plate*, *Journal of the Optical Society of America*, 11, 1140 (1969).
- [3] M. Born, E. Wolf, *Principles of Optics*, 2d rev, ed., Pergamon Press, New York, 1964.
- [4] The CVI Melles Griot Technical Guide, *All Things Photonic*, Vol 2, Issue 1, www.cvimellesgriot.com.
- [5] A. Yariv, *Optical Electronics in Modern Communications*, (Oxford University Press, 1997).
- [6] A. Siegman, *Lasers*, (Sausalito, CA: University Science Books, 1986).
- [7] M. Abramowitz, I. Stegun, *Handbook of Mathematical Functions*, National Bureau of Standards, 1964.

- [8] K.S. Kölbig, *C335: Complex Error Function*, Mathlib gen, CERN Library, Submitted 1970, Revised, 1993.
- [9] W. Gautschi, Algorithm 363, Complex Error Function, Collected Algorithms from CACM (1969).
- [10] W. Gautschi, Efficient Computation of the Complex Error Function, *SIAM J. Numer. Anal.* **7** (1970) 187-198.
- [11] K.S. Kölbig, *Certification of Algorithm 363 Complex Error Function*, *Comm. ACM* **15** (1972) 465-466.
- [12] A. Yariv, *Quantum Electronics*, (John Wiley & Sons, 1989).
- [13] T.W. Ebbessen, H.J. Lezec, H.F. Ghaemi, T. Thio, P.A. Wolff, "Extraordinary optical transmission through sub-wavelength hole arrays," *Nature*, vol. 391, 667 (1998).
- [14] D.E. Grupp, H.J. Lezec, T.W. Ebbessen, K.M. Pellerin, T. Thio, "Crucial role of metal surface in enhanced transmission through sub-wavelength apertures", *Appl. Phys. Lett.*, **77**(11), 1569 (2000).
- [15] H.J. Lezec, A. Degiron, E. Devaux, R.A. Linke, L. Martin-Moreno, F.J. Garcia-Vidal, T.W. Ebbessen, "Beaming Light from a Sub-wavelength Aperture", *Science*, vol 297, 820 (2002)
- [16] A Degiron, H.J. Lezec, W.L. Barnes, T.W. Ebbessen, Effects of hole depth on enhanced light transmission through sub-wavelength hole arrays", *Appl. Phys. Lett.* **81**(23), 4327 (2002).
- [17] L. Martin-Moreno, F.J. Garcia-Vidal, H.J. Lezec, A. Degiron, T.W. Ebbessen, "Theory of Highly Directional Emission from a Single Sub-wavelength Aperture Surrounded by Surface Corrugations", *Phys. Rev. Lett.*, **90** (16), 167401(4) (2003).
- [18] F.J. Garcia-Vidal, L. Martin-Moreno, H.J. Lezec, T.W. Ebbessen, "Focusing light with single sub-wavelength aperture flanked by surface corrugations", *Appl. Phys. Lett.*, **83**(22), 4500 (2003).
- [19] J.-M. Yi, F. de Leon-Perez, A. Degiron, E. Laux, E. Devaux, C. Genet, J. Alegret, L. Martin-Moreno, and T. W. Ebbessen, "Diffraction Regimes of Single Holes", *Phys. Rev. Lett.*, **109**, 023901 (2012).
- [20] J.-M Yi, "Diffraction of single holes through planar and nanostructured metal films." Other. Université de Strasbourg, 2013. English. NNT : 2013STRAF011. tel-01018454
- [21] R.A.L. Sullivan, "No quarter asked, but given!", *Phys. Educ.* Vol **18**, 90, 1983.