Research Article

BIOMEDICAL Journal of Scientific & Technical Research

ISSN: 2574 -1241

DOI: 10.26717/BJSTR.2020.27.004436

Effective Focusing of Radiation in the Medium Non-Linear Dielectric Film

Glushchenko AG*, Glushchenko EP and Glushchenko AA

Department of Physics Povolzhsky State University of Telecoimmunications and Informatics, Russia

***Corresponding author:** Alexander Glushchenko AG, Department of Physics Povolzhsky State University of Telecommunications and Informatics, Russia

ARTICLE INFO

Received: March 28, 2020

Published: April 13, 2020

Citation: Glushchenko AG, Glushchenko EP, Glushchenko AA. Effective Focusing of Radiation in the Medium Non-Linear Dielectric Film. Biomed J Sci & Tech Res 27(1)-2020. BJSTR. MS.ID.004436.

Keywords: Film; Kerr Nonlinearity; Flat Lens; Focusing; Light; Aperture

Annotation

The effect of focusing a light beam of finite cross section when passing through flat films with Kerr type nonlinearity is considered. The focusing conditions are obtained, which depend on the film thickness, nonlinear refractive index, and field distribution over the beam cross section. It is shown that for effective focusing it is necessary to ensure a special distribution of the field over the cross section, approaching the Gaussian distribution. The focusing method under consideration is more effective than other methods for focusing radiation at points of media located in the internal cavities of material bodies in the frequency regions transparent to radiation, including biological objects. The features of light diffraction by holes in the screen are considered taking into account the in homogeneity of the field distribution in the region of the holes associated with the inhomogeneous distribution of the field intensity over the beam cross section. A relation is obtained for calculating the field distribution during diffraction by the opening of a waveguide in media with a non-linear dielectric film on the surface.

Introduction

Lenses are a basic element of optical systems and are used to control the shape of the wave surface, in particular, the focus of the radiation [1,2]. Another important to practice to the scope of the lenses is ophthalmology [3,4], enables the use of lenses to correct people's impairments. There are many other applications of lenses: a dielectric lens for radio astronomy [5-7], gravitational lenses [8,9], acoustic lenses to focus the energy of shock waves [10] etc. Usually a lens is transpar- ent for waves of a body bounded by two spherical surfaces or a spherical and flat surfaces [1, 11-13]. While for good quality images you need a very high quality of the surfaces of the lens. This is ensured by a complex technology of manufacturing lenses and holds to their high cost. The lens, for example, due to the physical effect of aberrations [1,2] have several shortcomings which cannot be eliminated. The image of the remote point source produced by a wide beam of rays, refracted by a lens, is blurred. This limits the possibility of obtaining high-quality images using conventional op- tics. Technology coating of any profile to ensure a good convergence of the beam is limited.

Relatively recently, it was obtained a medium with negative refractive index that enables the use of a plane layer of optically negative environment, metamaterials get rid of the problems of aberrations and to obtain (at least in theory) a perfect lens [14,15]. The most practical use of this flat lens, how- ever, is difficult [16,17]. The use of metamaterials imposes significant restrictions on the desired position of the object relative to the lens for the realization of the positive properties of the lens. Even greater problems arise when the decision is important in medical practice the tasks of input of radiation in specific points inside a transparent for radiation of solids or any fluids. This article shows that, despite the possibilities of modern technology for coating any profile, it is more expedient to ensure beam convergence by changing the parameters of the signals them- selves using films with nonlinear parameters. This allows, in addition, it is relatively easy to control the focus area of the radiation. Here, the possibility of self-control of beam convergence due to the transverse distribution of the field intensity of the beam itself is considered. The focusing effect is realized using a layer or film of a dielectric with non-linear dielectric constant.

 DOI: 10.26717/BJSTR.2020.27.004436

Methods

Using the Maxwell equations, we consider the problem of passing a beam of light of finite width, limited in the transverse direction, through a thin layer (film) of a dielectric of thickness *d* with a nonlinear Kerr type refractive index:

$$n(r) = nL(r) + \chi_{1NL}\left|E(r)\right|^2 + \chi_{3NL}\left|E(r)\right|^4 + \ldots \quad (1)$$

The nonlinearity coefficients $\chi_{1NL}, \chi_{3NL\ldots}$ of which can reach gigantic values [18,19], especially nanoscale films [20,21], which allows one to create effective focusing by thin films. The main interest from the point of view of practical use is represented by layers with a thickness substantially less than the wavelength $(d << \lambda)$ of the incident radiation. Therefore, in the future we will call such a layer a nonlinear film. The distribution of the electric field strength over the beam cross section is generally inhomogeneous and is described by the function $E(r)$. Due to the dependence of the refractive index on the signal intensity over the cross section $n\left(r,|E|^2\right)$, the non-linear film acquires the properties of an optically inhomogeneous medium and can, under certain conditions, acquire the properties of a collecting lens provided provided:

$$\frac{dn(r=0)}{dr} > 0$$

And scattering lenses subject to:

$$\frac{dn(r=0)}{dr} < 0,$$

where n(r) is the refractive index of the film.

Main results and Discussion

The optical path difference of two parallel rays in different parts of the layer (in the center and at a distance r) to the observation point can be compensated by the path difference of these rays outside the film (Figure 1). In this case, the convergence of the rays at one point in the half-space un- der the film is observed, and the structure with a nonlinear film at the interface is acquiring the properties of a collecting lens. Consider the optical difference of the two rays shown in Figure 1 (passing through the center of the structure and at a distance r from the center):

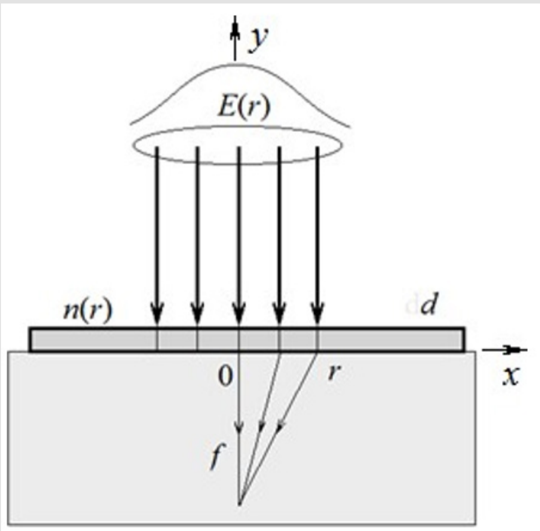

Figure 1: Passage of a light beam through a film with nonlinear parameters.

$$\Delta = \left[n(r=0)d(r=0) + f\right] - \left[n(r)d(r) + \sqrt{f^2 + r^2}\right].$$

At points in space for which the relation holds:

$$\left[n(r=0)d(r=0) + f\right] - \left[n(r)d(r) + \sqrt{f^2 + r^2}\right] = m\lambda, \quad (2)$$

Where m=0,1,2,... interference maxima are observed. The condition for focusing on the central optical axis (interference maximum for all parallel rays incident on the film surface) has the form:

$$n(r=0)d(r=0) - n(r)d(r) = \sqrt{f^2 + r^2} - f, \quad (3)$$

where *f* is the focal length, *d (r)* is the thickness of the layer, in the general case, depending on the distance to the center.

Relation (3) shows that the convergence of rays at one point (their focus) in the medium in the region y <0 can be achieved in several ways:

1) By changing the film profile (changing the layer thickness d(r)), for materials or medium with a uniform refractive index. The focusing condition has the form:

$$d(r) = d(r=0) + \frac{f - \sqrt{f^2 + r^2}}{n}.$$

The use of layer thickness heterogeneity d (r) is well known and is used in conventional lenses [1,2].

2) Focusing due to the creation of a stationary radial inhomogeneity of the refractive index

$N(r)$ for films with a constant thickness d = const, at ($r << f$)

$$n(r=0) = n(r) + \frac{f}{d}\left(\sqrt{f^2 + r^2} - f\right) \approx n(r)\frac{2r^2}{df}. \qquad (4)$$

The use of artificially created inhomogeneities in the refractive index n(r) is possible by alloying the film material. This method makes it possible to create flat lenses with a thickness of several tens of nanometers [2]. The parameters of such lenses, as well as conventional lenses, are station- ary. The production technology is quite complicated.

3) In this work, focusing in the medium is proposed by creating a radial inhomogeneity of the refractive index $n\left(r,|E|^2\right)$. this, radiation with a nonuniform cross section of the beam is used due to the use of films with nonlinear parameters. In this case, the dependence of the refractive index of the film material $n\left(r,|E|^2\right)$ on the intensity level of the radiation incident on the film, which is generally inhomogeneous in the cross section, is used. In the case of Kerr type nonlinearity, the refractive index has the form (1). Relation (3), taking into account (1), can be used to calculate the field distribution E(r) which ensures beam focusing. The field distribution function, providing the condition of phase matching of the rays for the first-order Kerr nonlinearity, is determined by the expression:

$$E(r) = \sqrt{|E(r=0)| - \frac{\sqrt{f^2 - r^2 - f}}{\chi_{NL} d}}. \qquad (5)$$

Considering that the relation f>>r is usually fulfilled, the field distribution function can be represented by the expression:

$$E(r) \approx E_0^2 - \frac{2r^2}{\chi_{NL} df} \text{H}\pi\text{H} E(r) \approx \sqrt{|E(r=0)|^2 - \frac{2r^2}{\chi_{NL} fd}}. \qquad (6)$$

From relation (6) it follows that for non-linearity of the type parallel $\chi_{NL} > 0$, the condition for focusing a parallel light beam takes the form:

$$|E(r=0)|^2 > \frac{2r^2}{\chi_{NL} fd} \qquad (7)$$

For the field level of the incident radiation and

$$d > \frac{2r^2}{\chi_{NL} f |E(r=0)|^2} \qquad (8)$$

for film thickness.

It follows that with a small coefficient of nonlinearity $|\chi_{NL}|$, focusing is ensured: 1)by increasing the intensity of the radiation field, 2) by increasing the thickness of the nonlinear film. With a decrease in the thickness of the nonlinear film, an increase in the radiation level is required to ensure focusing of the light.

Conversely, a decrease in the level of radiation to ensure focusing requires an increase in the thickness of the

nonlinear film. The focal length at which the conver- gence of the rays is observed is inversely proportional to the layer thickness, the magnitude of the nonlinearity coefficient and the radiation intensity. This value can be adjusted over a wide range.

Normalized field distribution E(r=0)/E(r) that ensures focusing by a layer of a nonlinear dielectric depending on the generalized parameter (squared distance from the axis of the radiation beam $\alpha(r) = r^2 / \left[2\chi_{NL} f^2 d |E(r=0)|^2\right]$, characterizing the structure parameters is shown in Figure 2 (curve 1). The energy distribution in a Gaussian beam is also shown here (curve 2).

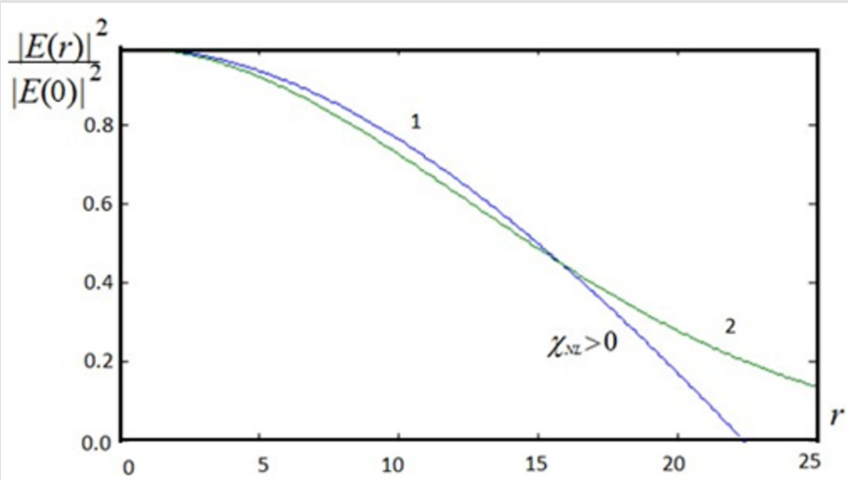

Figure 2: Field distribution function, focusing radiation.

A comparison of the functions of the field distribution in the beam (6) required for focusing and the Gaussian distribution shows their good agreement. The main difference between these dis- tributions is observed in the peripheral regions of the beam; therefore, to improve the convergence of a pulse with a Gaussian field distribution in the cross section, some correction is required by sup- pressing the peripheral region of the beam. Note that relation (4) allows us to find the intensity dis- tribution necessary to ensure the properties of the collecting lens for the layer and with other types of nonlinearity function of the refractive index, in particular, high-order Kerr nonlinearity $(\chi < 0)$, the layer acquires the properties of a scattering lens.

The radius of the beam should be limited: $r \le |E(r=0)|\sqrt{\chi_{NL} fd/2}$ and depends on the field intensity. When using a medium with a nonlinearity of the refractive index $\chi_{NL} < 0$, the film of the non linear dielectric acquires the property of a scattering lens.

For effective focusing of light with a film, both separate and combined changes in parameters are possible d(r), n(r,E).

Thus, films with nonlinear parameters can be used to concentrate radiation in bodies by de- positing films on the surface of these bodies and introducing radiation, for example, with a horn antenna or an aperture of the end of the waveguide (Figure 3). The proposed focusing method is more convenient than other known methods in the problem of introducing dosed radiation into specific areas of solid or liquid bodies to the required depth by applying films to the necessary surface areas of these bodies (including multilayer ones).

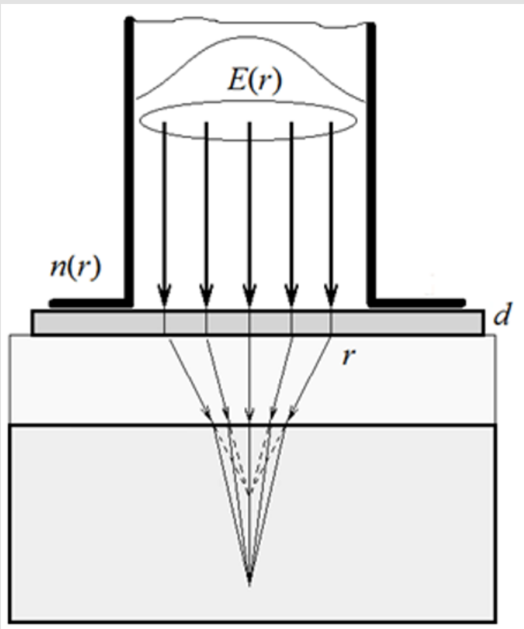

Figure 3: Focusing of waveguide radiation in a multilayer structure.

The Influence of the Field Structure in the Aperture on the Distribution of Radiation in the Medium

Of great importance for the focusing efficiency in the medium is the distribution of the structure of the field of the introduced radiation in the aperture of the antenna or from the open end of the waveguide**.** The problem of beam diffraction from the open end of a waveguide with a film of a nonlinear dielectric with an inhomogeneous field distribution at the end of the waveguide in the region $y=0, -a \le x \le a$ considered. For simplicity, we consider the Fraunhofer diffraction (Figure 4) We divide the open part of the wave surface $(y=0, -a \le x \le a)$ into elementary radiation zones with a width dx parallel to the edges of the aperture. The waves sent by the secondary sources of zones in the direction of the angle ϕ will be collected at one point at the focal length of the lens (Figure 4). Each secondary source dx in the region $y=0, -a \le x \le a$ creates oscillation dE_φ at this point. Its amplitude is proportional to the width of the zone dx.

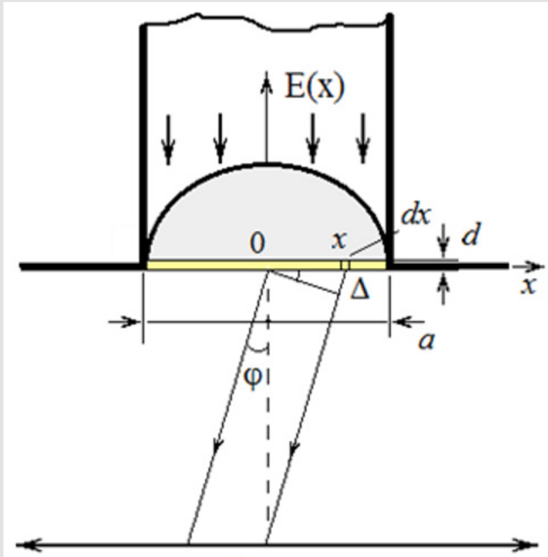

Figure 4: Aperture field distribution and beam path.

The resulting amplitude of the oscillations created by the secondary waves of all parallel rays over the entire width of the emitter 2*a* is determined by the ratio:

$$E_\phi = \int dE_\phi = \int_{-a}^{a} E(x)\exp\left[i(\omega t - \Delta\phi_1(x) - \Delta\phi_2(x))dx\right],$$

Where $\Delta\phi_1(x) = k\Delta = \frac{2\Pi}{\lambda} x \sin\varphi$ is the phase difference between the beam coming from the center of the waveguide and the beam coming from the aperture element with the coordinate x, $\Delta\phi_2(x) = k\Delta_2 = kd\left(\chi_1 |E(x)|^2 + ...\right)$ is the phase difference formed by the dependence of the refractive index of different parts of the wave surface of the film in the aperture plane on the field intensity $k = 2\pi/\lambda$ is the wave number , λ is the wavelength.

With a uniform field distribution in the region of the waveguide aperture $E(x) = E_{0,}$ we have the field distribution in the diffraction zone:

$$E_\varphi = E_0\left(\frac{\sin u}{u}\right)\cos(\omega t - u),$$

Where $u = (\pi/\lambda)a\sin\varphi$. For the radiation intensity in the direction of the angle φ , we have

 DOI: 10.26717/BJSTR.2020.27.004436

$$I_{\varphi} = I_0 \left(\frac{\sin u}{u}\right)^2.$$

In the particular case when the inhomogeneous field distribution in the region $y = 0, -a \le x \le a$ is described by function(6)

$$E(x) = E_0\left(1-\alpha x^2\right),$$

Then

$$E_{\varphi} = \int_{-a}^{a} E_0(1-\alpha x^2)e^{i(\omega t - kx\sin\varphi)}dx = E_0\left\{\int_{-a}^{a} e^{i(\omega t-kx\sin\varphi)}dx - \int_{-a}^{a}\alpha x^{2(\omega t-kx\sin\varphi)}dx\right\}$$

Or

$$E_{\varphi} = 2E_0 e^{i\omega t}\left[\frac{\sin(x)}{x}\left(1+\alpha a^2 - \frac{2\alpha a^2}{x^2}\right)+\frac{2\alpha a^2}{x^2} - \cos(x)\right],$$

Where $x = ka\sin\varphi$. The transmission coefficient of a wave with an inhomogeneous field distribution in the region $-a \le x \le a$ at the open end of the waveguide has the following form:

$$k_{\varphi} = \left(\frac{E_{\varphi}}{E_0}\right)^2 = 4e^{i2\omega t}\left[\frac{\sin(x)}{x}\left(1+\alpha a^2 - \frac{2\alpha a^2}{x^2}\right)+\frac{2\alpha a^2}{x^2}\cos(x)\right]^2.$$

Figure 5 shows a graph of the distribution of the radiation intensity as a function of the gener- alized parameter x, including the diffraction angle and the wavelength aperture normalized to the wavelength for various parameters α of the field inhomogeneity in the gap region. From the graph it follows that the maximum wave intensity depends on the degree of field inhomogeneity over the beam cross section (characterized by the parameter α). The angles of diffraction minima do not de- pend on the degree of field inhomogeneity.

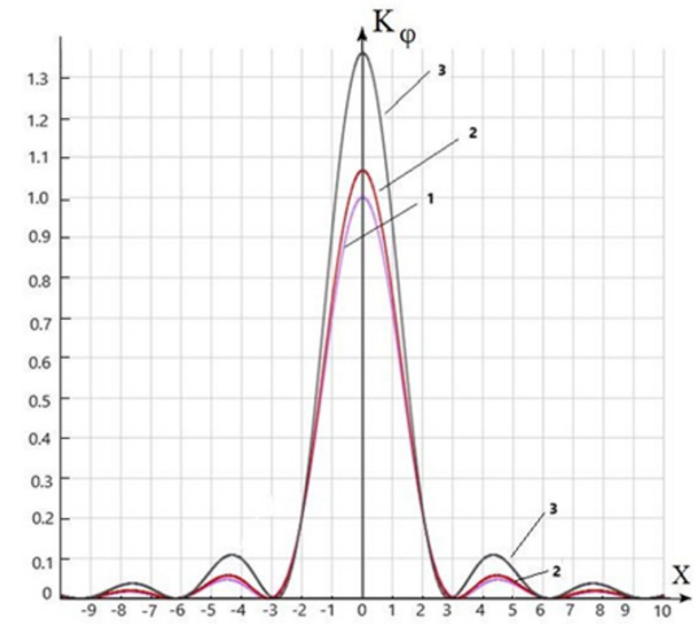

Figure 5: The dependence of the transmission coefficient on the parameter $x = ka\sin\phi : 1-\alpha a^2 = 0$ is a homogeneous field, $2-\alpha a^2 = 0.1, 3-\alpha a^2 = 0.5.$

The graphs show that the field non-uniformity in the gap plane leads to an additional redistri- bution of the field intensity compared to a uniform field. The intensity of the maxima increases and shifts to the center of the diffraction pattern. An even greater dependence of the field structure in the diffraction region is observed when the higher modes of the waveguide and other types of light intensity distribution in the region of the waveguide aperture fall for different modes of various types of waveguides [22-24]. Thus, the field unevenness in the region of the openings in the screens can significantly affect diffraction pattern. The structure of the diffraction field, taking into account the inhomogeneity of the field in the aperture of the waveguide and the nonlinearity of the film parameters, can be calculated by numerical methods. For a uniform field distribution in the region of the waveguide aperture, an analytical relation can be obtained for the wave to pass through the film, taking into account the nonlinearity of the refractive index of the film

$$\frac{E_{\varphi}}{E_0} = \int_{-a}^{a} e^{i(\omega t - kx\sin\varphi - kd\chi_1 x^2)}dx = e^{i\omega t}\frac{\sqrt{\pi}\exp\left(\frac{i(kx\sin\varphi)^2}{4kd\chi_1}\right).erf\left(\sqrt{ikd\chi_1}x + \frac{ikx\sin\varphi}{2\sqrt{ikd\chi_1}}\right)}{2\sqrt{ikd\chi_1}}.$$

Conclusion

It is established that when radiation passes through a flat layer or a dielectric film with non- linear parameters, radiation is focused in the medium on whose surface they are deposited. The depth of the focusing region depends on the parameters of the refractive index of the nonlinear film, the distribution function of the beam intensity over the cross section, and the film thickness. The field distribution in the medium depends on the field intensity distribution in the aperture of the emitter, which is especially pronounced when using higher types of waveguide waves, as well as on the parameters of the nonlinear film. Focusing radiation by nonlinear films makes it possible to use them for point focusing of radiation in the internal regions of various radiation-transparent media, in particular, biological bodies. In this case, it is possible to effectively control the depth of focus of radiation in the medium by changing the intensity of the input radiation, its field structure. The gi- ant nonlinearity of nanoscale films shows their promise for focusing radiation in media. The results obtained can be used both in single-layer and in multilayer media.

References

1. Steck DA (2010) Classical and Modern Optics. Publisher University of Oregon pp. 276.
2. Howard G (2007) The Physics of Waves Publisher. Prentice Hall: pp. 465.
3. Schmidt-Erfurth U, Kohnen T (2018) Encyclopedia of Ophthalmology. Springer-Verlag GmbH: p. 1954.
4. Barnett M, Johns KL (2017) Contemporary Scleral Lenses: Theory and Application. Benthem Science Publishers pp. 463.
5. Thornton J, Huang K-C (2013) Modern lens antennas for communications engineering. IEEE Press Wiley pp. 272.
6. Zhang Y, Christie S, Fusco V (2012) Reconfigurable beam formimg using phase-aligned Rotman lens. IET Microwaves Antennas and Propagation 6(3): 326-330.
7. Dong J, Zaghloul AI (2010) Extremely high-frequency beam steerable lens-fed antenna for vehicular sensor applications. IET Microwaves Antennas & Propagation 4: 1549-1558.
8. Chneider P, Ehlers J, Falco, Emilio E (1992) Gravitational Lenses-Springer-Verlag Berlin Heidel- berg, New York Press: pp. 321.
9. Refregier A (2003) Weak gravitational lensing by large-scale structure. Annual Reviews. 41(1): 645-668.
10. Rossing T (2014) Springer Handbook of Acoustics. Springer-Verlag New York: p. 1182.
11. Geddes C (2015) Reviews in Plasmonic. Springer pp. 441.
12. https://www.rp-photonics.com/lenses.html
13. Walther A (2006) Optical Software. NET The Ray and Wave Theory of Lenses. Cambridge Univer- sity Press: pp. 206.
14. Veselago V (1968) Sov Phys Usp 10: 509.
15. Pendry IB (2000) Negative refraction makes a perfect lens. Phys Rev Lett.85(18): 3966-3969.
16. Powell DA, Shadrivov IV, Kivshar YS (2009) Nonlinear electric metamaterials. Applied Physics Letters 95: 084102.
17. Gu J, Singh R, Tian Z, Cao W, Xing Q, et al. (2010) Terahertz superconductor metamaterial. Appl Phys Lett 97: 071102.
18. Si-Cong T, Ren-Gang W, Cun-Zhu T, Yong-Qiang N, Li Q, et al. (2014) Giant Kerr nonlinearity induced by tunneling in triple quantum dot molecules. J Opt Soc Am B 31(7): 1436-1442.
19. Qian H, Li S, Chen CF, Hsu SW, Bopp SE, et al. (2019) Large optical nonlinearity enabled by coupled metallic quantum wells. Light Sci Appl 8: 13.
20. Chen H, Ren J, Gu Y, ZhaoD, Zhang J, et al. (2015) Nanoscale amplification of Kerr nonlinearity using spontaneously generated coherence in a plasmon nanoresonator. Sci Rep 5: 18315.
21. Tohari MM, Lyras A, Alsalhi MS (2018) Giant Self-Kerr Nonlineari- ty in the Metal Nanoparticles-Graphene Nanodisks-Quantum Dots Hybrid Systems Under Low-Intensity Light Irradiance. Nanomaterials, 8 (7): 521.
22. Sheppard CJ R, Hrynevitch M (1992) Diffraction by a circular aperture: A generalization of Fresnel diffraction theory. J Opt Soc Am 9(2): 274-281.
23. Sheppard CJ R, Gu M (1993) Imaging by a high aperture optical system. J Mod Opt 40: 1631- 1651.
24. Glushchenko AG, Glushchenko EP (2018) The dependence of the distributed light intensity distri- bution on the structure of the field in the hole of the flat screen. Scientific Review. Technical Science 6: 11-16.

ISSN: 2574-1241

DOI: 10.26717/BJSTR.2020.27.004436

Glushchenko AG. Biomed J Sci & Tech Res