

# Physical foundation of optical smart antenna based on metamaterial and lithium niobate

К.А. Vytovtov<sup>1</sup>, Е.А. Barabanova<sup>1</sup>, М.А. Igumnov<sup>1</sup>

<sup>1</sup>Astrakhan State Technical University, Tatishchev Street 16, Astrakhan, Russia, 414056

**Abstract.** In this work we present the main physical foundations of optical antenna array. This antenna array is based on the mirror system and lens system. To provide the necessary phase shift we propose two kind of structures: based on lithium niobate and based on ferrite-garnet. The main analytical expressions describing system behaviour are found for the first time. The results of calculation of the lens system parameters in the program ZEMAX are presented also.

## 1. Introduction

Today optical communications are very perspective kinds of communication systems because of its high speed information transferring [1-10]. Now there are two main directions of optical system development: wireless [1-4] and fiber optic [5]. Optical fiber systems are quite developed for today, but we cannot say this about wireless optical systems. In particular in scientific literature it has been presented only one patent as for optical antenna array [4] in spite of the fact that this device is very important in communication lines. Obviously, optical antennas must be used in wireless optical communication systems for high speed signal transmission.

In modern technology optical antennas are used only for enhancing absorption cross sections and quantum yields in photovoltaics, releasing energy efficiently from nanoscale light-emitting devices, boosting the efficiency of photochemical or photophysical detectors, and increasing spatial resolution in optical microscopy. [6,9]. Also there are optical antenna-LED structure integrated into the chips of digital chips, enabling them to more quickly transmit information and increasing their computing power [6,10]. Such antennas have been called as optical nanoantennas. The detail description of nanoantennas can be found in [6]. The classification of optical nanoantennas has been given in that work also.

However note that there is only one work that describes an optical antenna array for optical signal transmitting in telecommunication networks [4]. This antenna has been built as an open section of optic cable. Each output of cable has been considered as an element of the antenna array. The main disadvantage of this antenna is its uncontrollability. Moreover the results of radar power calculations have not been presented in that work.

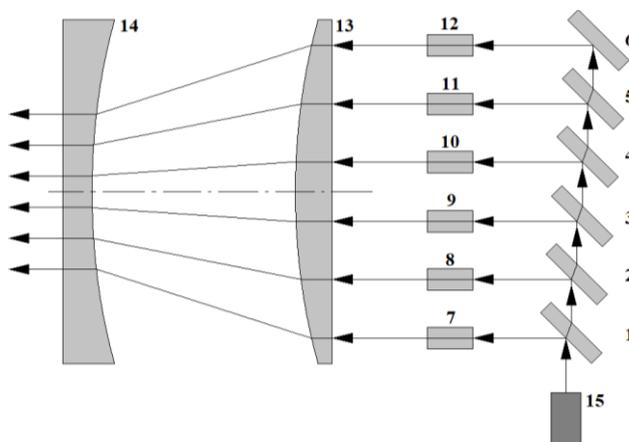
One of the most important problem in optical antenna region is so call smart materials that allows us to control an antenna pattern. Such materials have been described for example in [11,12].

In this work we present smart optical antenna array that can be projected by using well-known optical materials without nanostructure. The structure and operation principle are described in Section 2. The antenna components and the expressions for parameter calculation are presented in Section 3. The very important point in the antenna creating is the choice of smart material to control the pattern. This problem is discussed in detail in the paper too.

## 2. Operating principle

The structure of the presented here optical antenna array is presented in figure 1. The one consists of the translucent mirrors 1,2,3,4,5; absolutely reflective mirror 6; phase shifters 7,8,9,10,11,12; collecting lens 13; diffusing lens 14; laser 15.

The light beam from the laser 15 enters the power divider (the mirror system 1-6). This system divides power into six equal parts. The rays reflected from the mirrors enter the phase shifters 7-12 which compensate for the phase shift due to difference in the paths of the rays and provide an additional phase shift to control the radiation pattern of the optical antenna array. Next, the rays arrive at the converging lens 13 which serves to focus the rays at the antenna output. Indeed, for efficient forming of a beam, the distance between the beams should be commensurate with a wavelength, but previous devices have much larger size for the effective signal processing. The diverging lens 14 serves to form a parallel beam of rays at the antenna output. Moreover, the outer surface of the diverging lens can be a two-dimensional diffraction grating of transparent holes, which allows to form the desired radiation pattern.



**Figure 1.** The structure of the smart antenna array of the optical domain: 1,2,3,4,5 are the semi-transparent mirrors; 6 is the fully reflective mirror; 7,8,9,10,11,12 is the phase shifters; 13 is the converging lens; 14 is diverging lens, 15 is the laser.

In the considered antenna array, the laser beam can be divided into even and odd number of beams. Early it has been shown that the use of more than 7 rays is impractical since further increase in the emitters practically does not lead to a narrowing of the radiation pattern. In the next sections the components of the antenna will be presented in detail.

## 3. The antenna components

### 3.1. The mirror system

The radiation of the laser source 15 incident on the semi-transparent mirror 1 with the power reflectance  $R_1 = \frac{1}{N}$ , where  $N$  is the number of output of antenna array (in this case,  $R_1 = \frac{1}{6} = 0.167$ ). A part of power that is equal to  $T_2 = \frac{N-1}{N}$  passes to the semi-transparent mirror 2, and a part that equal to  $R_1 = \frac{1}{N}$  (in this case  $1/6 = 0.167$ ) passes to the phase shifter 7. The reflection coefficient of the mirror 2 is  $R_2 = \frac{1}{N-1}$  (in this case,  $1/5=0.2$ ). A beam with this fraction of power ( $T_1 R_2 = \frac{1}{N}$ ) goes to the phase shifter 8. That is same power signals is incident on the phase shifters 6 and 7. The part of power  $\frac{N-2}{N}$  (in this case,  $4/6=2/3=0.6(6)$ ) of the total power passes to the mirror 3, etc. The mirror 3 has a reflection coefficient  $R_3 = \frac{1}{N-2}$  (in this case,  $R_3 = \frac{1}{4}=0.25$ ). Analogously,  $R_4 = \frac{1}{N-3}$ ,  $R_5 = \frac{1}{N-4}$ ,  $R_6 = \frac{1}{N-5}$ , etc. The reflection coefficient of the last mirror is equal to unit (in this case,  $R_6 = \frac{1}{N-5} =$

$\frac{1}{6-5} = 1$ ). It can be seen from this description that in the general case the reflection coefficient of the  $i$ -th mirror is

$$R_i = \frac{1}{N-i+1} \quad (1)$$

and the transmission coefficient is

$$T_i = 1 - \frac{1}{N-i+1} = \frac{N-i}{N-i+1} \quad (2)$$

Thus the radiation power within the mirror system is divided equally. Then the beams incident to the corresponding phase shifters 8-13. The mirrors must have small losses and small frequency dispersion in the operating wavelength domain  $1550 \pm 50$  nm. Such a property can be obtained by using inhomogeneous dielectric structures. For practical applications usual quartz glass can be used to manufacture such the mirrors.

### 3.2. The phase shifter

The phase shifters should compensate the phase shifts due to difference in the paths of the beams along different  $N$  paths and introduce an additional phase shift to control the direction of the main lobe of the antenna pattern.

The difference in travel due to propagate through each uniform mirror

$$a = d \cos \alpha \sqrt{\frac{k_0^2 \sin^2 \alpha}{k^2 - k_0^2 \sin^2 \alpha}} \quad (3)$$

where

$$\begin{aligned} k_0 &= \omega \sqrt{\varepsilon_0 \mu_0} \\ k &= \omega \sqrt{\varepsilon \varepsilon_0 \mu \mu_0} \end{aligned} \quad (4)$$

Here  $\omega = 2\pi f$  is the angular frequency,  $d$  is the thickness of the previous mirror,  $\alpha$  is the angle of incidence of the beam on the mirror,  $\varepsilon_0$  is the dielectric permittivity of vacuum,  $\mu_0$  is the magnetic permeability of vacuum,  $\varepsilon$  is the relative dielectric permittivity of the mirror,  $\mu$  is the relative magnetic permeability of the mirror. Thus for the  $i$ -th mirror we have

$$a_{i \text{ mirror}} = (i-1) \frac{dk_0 \cos \alpha \sin \alpha}{\sqrt{k^2 - k_0^2 \sin^2 \alpha}} \quad (5)$$

Thus the phase shift for  $i$ -th mirror is

$$\Delta_{i \text{ mirror}} = (i-1) \frac{dk_0^2 \cos \alpha \sin \alpha}{\sqrt{k^2 - k_0^2 \sin^2 \alpha}} \quad (6)$$

The path difference due to the convergence of the rays between the converging and diverging lenses with an even number of rays

$$a_{n \text{ lens}} = \frac{1}{2} \left[ \sqrt{(2n-1)^2 (b_1 - b_2)^2 + 4b_n^2} - \sqrt{(b_1 - b_2)^2 + 4b_1^2} \right] \quad (7)$$

Here  $b_1$  is the distance between the rays at the exit of the converging lens,  $b_2$  is the distance between the rays at the input of the diverging lens,  $b_n$  is the distance between the lenses taking into account the curvature of their surfaces and the displacement of the beam. Here the number of the beam is counted from the axis of the lens in both directions. Then the phase shift for the  $n$ -th ray is

$$\Delta_{n \text{ lens}} = \frac{k_0}{2} \left[ \sqrt{(2n-1)^2 (b_1 - b_2)^2 + 4b_n^2} - \sqrt{(b_1 - b_2)^2 + 4b_1^2} \right] \quad (8)$$

The path difference due to the convergence of the rays between the converging and the diverging lenses and the corresponding phase shift with an odd number of rays are following

$$a_{n \text{ lens}} = \sqrt{(n-1)^2 (b_1 - b_2)^2 + b_n^2} - b_1 \quad (9)$$

$$\Delta_{n \text{ lens}} = k_0 \left[ \sqrt{(n-1)^2 (b_1 - b_2)^2 + b_n^2} - b_1 \right] \quad (10)$$

The additional phase shift exists also in the lenses and depends on the thickness of the lens at the point of passage of the beam and the material parameters of the lens

$$\Delta_{n \text{ conv}} = k_{\text{conv}} (y_{n \text{ conv}} - y_{1 \text{ conv}}) \quad (11)$$

$$\Delta_{n \text{ div}} = k_{\text{div}} (y_{n \text{ div}} - y_{1 \text{ div}}) \quad (12)$$

Here

$$k_{conv} = \omega \sqrt{\epsilon_{conv} \epsilon_0 \mu_{conv} \mu_0} \tag{13}$$

$$k_{div} = \omega \sqrt{\epsilon_{div} \epsilon_0 \mu_{div} \mu_0} \tag{14}$$

are the wave propagation constants in the converging and diverging lenses,  $y_{n\ conv}$ ,  $y_{n\ div}$  are the thickness of the lenses at the points of passage of the  $n$ -th ray determined by the curvature of the lens surface.

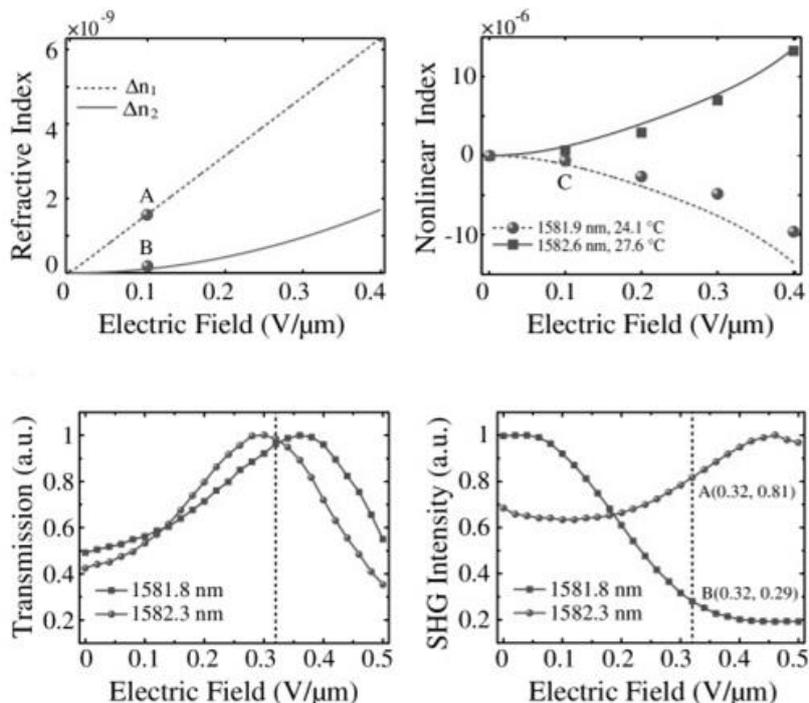


Figure 2. The dependences of LiNbO<sub>3</sub> on electric field [11].

As for the additional phase shift to control the antenna pattern, we need to use smart materials for this aim. The parameters of such materials depend on the value of the external control signal. Today only few such materials are known in optics. For example it is lithium niobate, the refractive index of which depends on the value of the external applied voltage, and garnet ferrites whose parameters are determined by the value of the external magnetic field. In particular, the dependence of the refractive indices for lithium niobate at a wavelength of 1581.9nm is represented in [11] (figure 2).

As we can see, the dependence of the refractive index on the value of the external magnetic field is very weak.

The garnet is another smart material in the optical domain. The dependence of optical power on the magnetic field value (figure 3) has been studied in [12], for example.

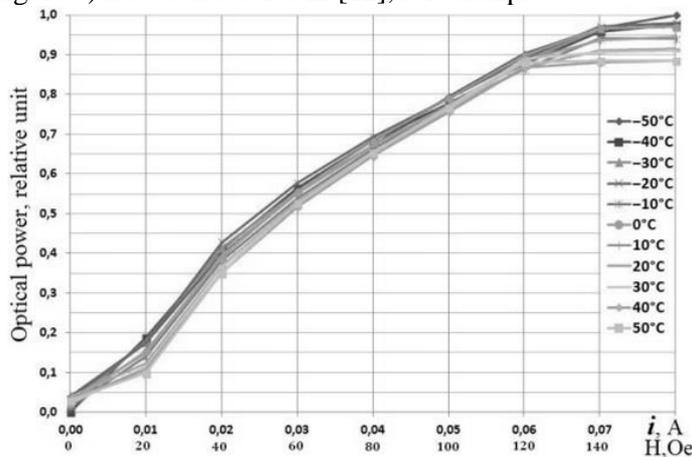


Figure 3. The dependence of yttrium-iron garnet on magnetic field [12].

### 3.3. The lens system

The lens system must transform the beams from the phase shifter so that the distance between the outgoing rays is half the wavelength. Additionally the output beams must be parallel one to other. The example of such a system is presented in figure 4. This system for wavelength 1550nm is obtained by using paraxial lenses in ZEMAX. We can see the usual multistage scheme. Each stage reduces a distance between the rays by approximately 5 times. Obviously, it is possible to obtain any spacing between output beams using multistage scheme.

The characteristics of presented system are presented in figure 5. The cross-aberration graphics is given in figure 5a, optical path difference is shown in figure 5b. The results are found in the program ZEMAX.

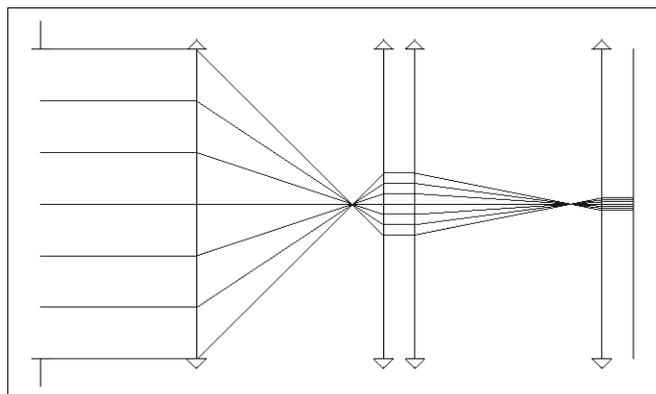


Figure 4. A scheme of the lens system.

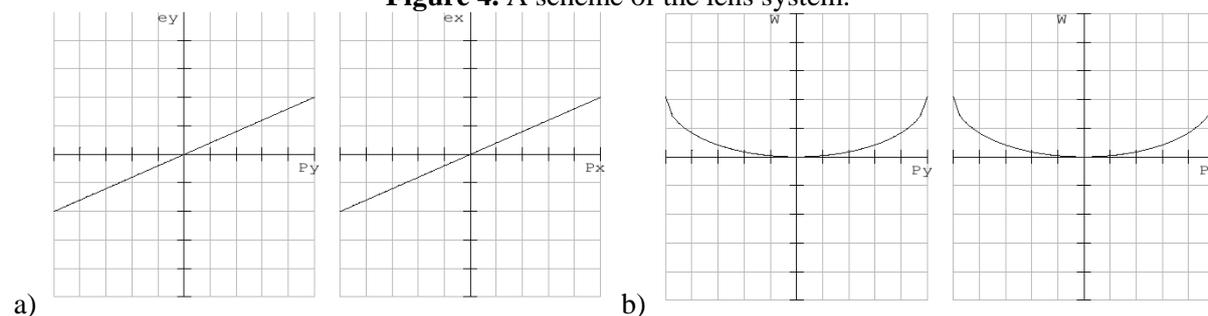


Figure 5. The characteristic of the lens system.

## 4. Conclusions

In this work we present the main physical foundations of optical antenna array. This antenna array is based on the mirror system and lens system. To provide the necessary phase shift we propose two kinds of structures: based on lithium neobate and based on ferrite-garnet. The main analytical expressions describing system behaviour are found for the first time. The results of calculation of the lens system parameters in the program ZEMAX are presented also.

## 5. References

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