

Light focusing by the unique dielectric nano-waveguide array

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Abstract: The light focusing by using dielectric nano-waveguides array with its length in micron is investigated *via* the finite-difference time domain (FDTD) method. Simulated results show that the focal length depends on the length and the total width of the arrays and can be altered from tens of micron to wavelength order. Both TM and TE mode incident light can be focused by the array. The wavelength-order focal length is achieved by employing the dielectric nano-waveguide array with variant separations. The unique focusing behavior is contributed to the radiation mode with longer decay length and the large evanescent field which appears in the nano-waveguide array. We believe this simulation results can be a promising guidance for the experiments.

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OCIS codes: (230.7390) Waveguides, planar; (230.3990) Micro-optical devices; (220.3630) Lenses.

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1. Introduction

Nowadays, the miniaturization of the traditional optical components has been essential and significant with the development of the integrated optics. As the most ubiquitous optical components, lenses are extensively used in applications that range from imaging to concentrating light and focusing especially. However, it becomes one of the limiting factors that the capability of conventional dielectric lenses deteriorates in scaling down those to a wavelength or sub-wavelength range. In order to overcome this problem, array is used as a perfect substitute for the traditional lenses. In 2004, Sun and Kim introduced the refractive transmission of light and beam shaping with metallic nano-optic lenses [1]. Later, numerical simulation works on metallic nano-slits with variant widths [2], nanoscale metal waveguides arrays as plasmon lenses [3], and metallic nano-slit array containing nonlinear media [4] were achieved. Very recently, Verslegers et al. experimentally demonstrate the excellent planar lenses based on the nanoscale slit arrays in a metallic film [5]. The focusing of the metallic array lens is explained by the Surface Plasmons (SPs) excitation and Fabry-Perot (F-P) resonance in the nano-slit.

Alternatively, the array may consist of dielectric optical waveguides, either planar ones formed by selective ion implantation [6] or fibers placed side by side [7,8]. Previous work lays out the theoretical investigation on the light focusing by using the bundle of micron scale fibers [9]. There was also array consisting of waveguides based on the nonlinear material for focusing the light [10]. However, little attention has been put on the nano scale dielectric array composing of nano-waveguides or nano-fibers [11] for focusing the light. Waveguide of nano scale plays as one of the key roles in the design and fabrication of intergraded micro-photonics devices. The energy transmission in the nano waveguide is different from the case in those for the communication [12]. The strong evanescent field outside the core is the most notable property of the nano-waveguides. It offers great flexibility in designing new devices without being restricted by the constraints of conventional optics, such as sensor [13], coupler [14], and slot waveguide for particle transporting [15].

Motivated by the previous work, herein we investigate the focusing action of the linear dielectric nano-waveguide array by numerical simulation. It should be noted that the wire spacing and the diameter in this design is smaller than the wavelength of light. Therefore, no grating diffraction effect is involved in the optical transmission through the nano-optic structure, unlike the diffractive optics case. It is also worthy to note that, different from the traditional long waveguide array, in our design, the length of the nano-waveguides is in the order of micrometer hence the influence of the radiation mode [16] is introduced into the beam propagation. Synthesizing the influence of the radiation mode and the strong evanescent field, as expected, the focusing action of the short-length dielectric nano-waveguide arrays is achieved in this work. With the adjustment of individual wires properties, it becomes possible to alter the focal length of the array. This study focuses on the focal length of the array. We conduct five factors studied, waveguide length, width, the separation between waveguides, the amount of the waveguides and the full width at half-maximum (*FWHM*) of the incident light. Their influence on the focal length is investigated orderly after the demonstration of the typical focal behavior of the array.

2. Simulation model

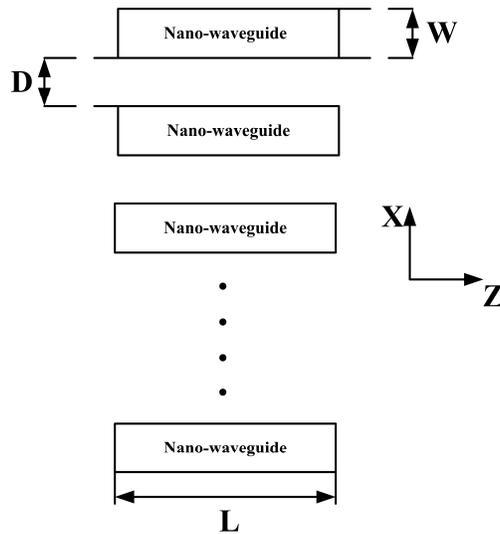


Fig. 1. The schematic of the nano-waveguide arrays. W is the width of the single nano-waveguide, D the wire separation and L the wire length.

Figure 1 shows the schematic of the nano-waveguides array and the coordinates. The nano-waveguides extend along the Z -axis, which is also the propagating direction of the incident light. W denotes the width of the single nano-waveguide, D is the separation between adjacent nano-waveguides, L is the length of the equilateral nano-waveguides and N is the amount of the waveguides in the following. In this work, the focusing action of the dielectric nano-waveguide arrays is investigated *via* the finite-difference time domain (FDTD) method [17]. To avoid reflection from the output end of the arrays, the perfectly matched layer (PML) absorbing boundary condition [18] is employed. The number of the PML was taken as 15, which can reduce the numerical reflection effectively. For the FDTD cell size, it is found that the sizes, $dx = dz = 20\text{nm}$, are small enough to yield satisfactory simulation accuracy with an acceptable computation time. For the simplification, the numerical simulation is performed in 2-dimensional. The nano-waveguide only includes the high refractive index core and is surrounded by infinite air cladding with refractive index of 1.0. Recent works show that the surface roughness of the nano-waveguide can introduce energy decay [19]. Therefore we also assume that the wire is uniform in width and smooth in sidewall. The nano-waveguide with assumption above has been shown achievable experimentally and is also of the typical outlook [11]. The material of the nano-waveguide is taken as fused silica. The refractive index of the fused silica is calculated by the Sellmeier-type dispersion formula at room temperature [20]. In this work, λ is taken as $0.67\mu\text{m}$ and therefore the refractive index of the core holds 1.456. A plane wave with the intensity of Gaussian profile in transverse direction is incident onto the array in the geometry that the beam axis coincides with the symmetric axis of the array. The maximum amplitude of the electric field of the incident light is taken as 1V/m . Without emphasis, the full width at half-maximum (*FWHM*) of the incident light is set to be equal to the array width (array width = $N \cdot W + (N-1)D$, N , W and D is defined as we mentioned above), which ensures that all the nano-waveguides are illuminated by the incident light source. In the following, without special emphasis, the polarization of the incident beam is of TM mode.

3. Results and discussions

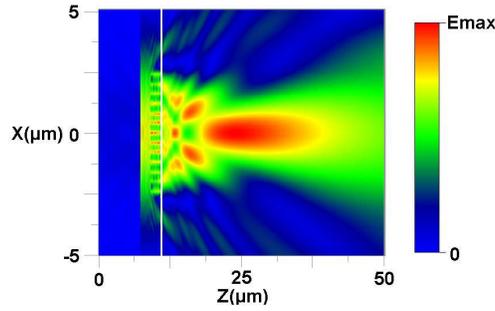


Fig. 2. The electric field distribution of the nano-waveguide array with $N = 13$, $W = D = 300\text{nm}$, $L = 2.0\mu\text{m}$. The $FWHM$ of the incident light is $7.5\mu\text{m}$. The white vertical line presents the end of the array.

Firstly, the array consists of 13 nano-waveguides ($N = 13$, $FWHM = 7.5\mu\text{m}$) with $W = D = 300\text{nm}$ and $L = 1.0\mu\text{m}$ is considered. Figure 2 shows the FDTD simulation result. One can see clearly the light focusing. Herein the focal point is defined as the point where transmitted intensity reaches the maximum. The focal length, denoted by f in the following, is the distance from the exit of the array to the focal point. In Fig. 2, the focal length $f = 28.67\mu\text{m}$ and the $FWHM$ at the focal point is $4.12\mu\text{m}$. The amplitude of the electric field E at the focal point reaches 1.3V/m . It is worthy to note that besides the central focus there are several equidistant higher order foci with smaller intensity. The higher order foci come from the periodic arrangement of light emitting from different wires as single sources.

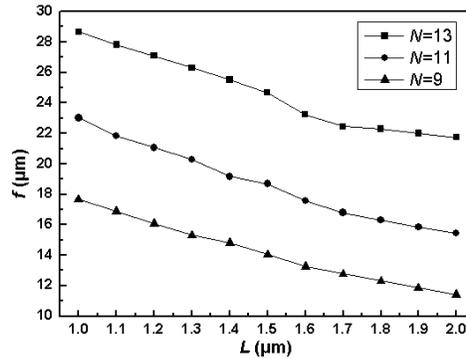


Fig. 3. The focal length f versus array length L with $W = D = 300\text{nm}$. The solid squares represent f for $N = 13$ ($FWHM = 7.5\mu\text{m}$), the solid circles for $N = 11$ ($FWHM = 6.3\mu\text{m}$) and the solid triangles for $N = 9$ ($FWHM = 5.1\mu\text{m}$). The solid line is just the guiding link between the values.

Figure 3 shows the dependence of the focal length f on the array length L with $N = 9$, 11 and 13, while the $FWHM$ of the incident light is $5.1\mu\text{m}$, $6.3\mu\text{m}$, and $7.5\mu\text{m}$, respectively. The calculation results show that the f of the dielectric nano-waveguide array decreases with the increase in L . For examples, when $N = 13$, f change from $24.17\mu\text{m}$ to $21.73\mu\text{m}$ when L increase from $1.5\mu\text{m}$ to $2.0\mu\text{m}$. This is very different from situation of the metallic slit lenses, in which lenses with short slits cannot achieve light focusing far from the array [5]. One might expect a shorter focusing length by longer L . However, if the array length keeps increasing, for example, to be $2.5\mu\text{m}$ or $3.0\mu\text{m}$, the energy density at the focal point is lower than the incident light. For example, when $L = 3.0\mu\text{m}$, the maximum transmitted beam amplitude is 0.9V/m . It is lack of significance for the practical applications. The FDTD results in Fig. 3 also prove that the focal length of the dielectric nano-waveguide array decreases with the

increase in the amount of wires N . Concerning the array with $L = 2.0\mu\text{m}$ and $W = D = 300\text{nm}$, $f = 27.43\mu\text{m}$ for $N = 11$ and $f = 23.42\mu\text{m}$ when $N = 9$. It comes partially from that the actual focal length is to a large degree determined by the lens size [21]. When N increases, the width of array also increases.

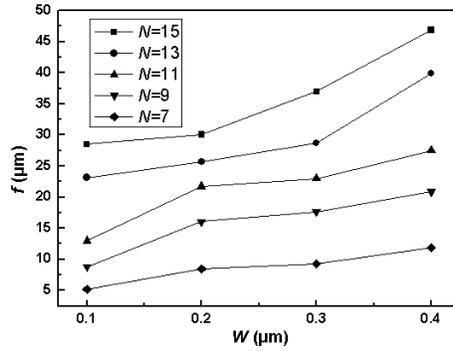


Fig. 4. The focal length f versus the wire width W with $D = 300\text{nm}$ and $L = 1.0\mu\text{m}$. The solid squares represent the values that $N = 15$; the solid circles, $N = 13$; the solid triangles, $N = 11$; the solid nablas, $N = 9$; the solid diamonds, $N = 7$. The solid line is just the guiding link between the values.

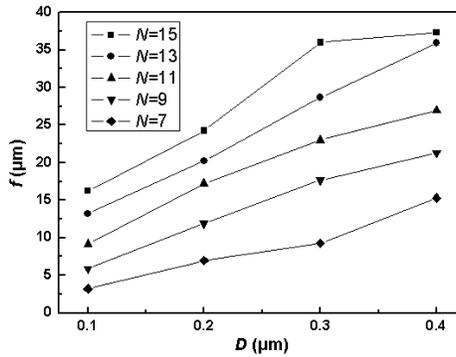


Fig. 5. The focal length f versus the wire separation D with $W = 300\text{nm}$, $L = 1.0\mu\text{m}$. The solid squares represent the values that $N = 15$; the solid circles, $N = 13$; the solid triangles, $N = 11$; the solid nablas, $N = 9$; the solid diamonds, $N = 7$. The solid line is just the guiding link between the values.

The electric field distribution in nano-waveguide array is determined by the refractive index and the width of a single nano-waveguide [22], and also by the separation between the waveguides. Therefore, if we alter the width or the separation of the nano-waveguides, the electric field distribution in the array changes and the focal length is expected to be adjusted. The FDTD results match our expectation. Figure 4 shows the focal length variety versus the width W . In Fig. 4, D and L keep 300nm and $1.0\mu\text{m}$ respectively and N changes from 7 to 15. The focal length decreases when the waveguide width becomes smaller. Figure 5 shows the dependence of f on D with constant W and L ($W = 300\text{nm}$ and $L = 1.0\mu\text{m}$, respectively). The results in Fig. 5 point out that f decreases with the decrease in D . Decrease in W or D means the total width of the array becomes smaller. Hence the focal length decreases when the aperture of the array reduces.

The focusing properties of the nano-waveguide array also depend on the $FWHM$ of the incident light. In the simulation above, $FWHM$ keeps equal to the array width. When $FWHM$ is smaller than the array width, the decrease of the $FWHM$ will cause a decrease in focal length and the energy at the focus. For instance, in the array with $N = 13$, $W = D = 300\text{nm}$ and

$L = 2\mu\text{m}$, when $FWHM$ decreases from $7.5\mu\text{m}$ (13 nano-waveguides illuminated) to $6.3\mu\text{m}$ (11 nano-waveguides illuminated), the focal length changes from $21.73\mu\text{m}$ to $21.41\mu\text{m}$, and the amplitude of the electric field E at the focus attenuates from 1.3V/m to 1.1V/m .

The properties of the focusing effect in dielectric nano-waveguides array are quite different from the cases in the micro-meter fiber array. We attribute the unique focusing behavior in nano-waveguide array to the radiation mode with longer decay length and the large evanescent field which appears in the nano-waveguide array. In micrometer-fiber-array, according to the coupled mode theory, the beam power is blocked from returning to the source guide due to the phase reversal [23]. Therefore, the energy in the center of the array reaches the peak. The guiding mode in the fiber array is the source of focusing. Therefore the focusing has little relationship with the length of the fiber and is also not sensitive to the width and the separation of the fibers.

Unfortunately, by now there is no analytic formula describing the electromagnetic field in a dielectric nano-waveguide array. So we cannot get the exact details of light propagation in the nano-waveguide arrays such as the decaying length of the radiation mode and the coupling coefficient between the radiation and the guiding modes. However, it is reasonable that when the length of the wire increases, the amplitude of the radiation mode become weaker. In a single nano-waveguide, the decay length of the radiation mode is decided by [16]:

$$L_{ra} = \frac{\rho}{2\theta_c} \text{Exp}\left[\frac{V}{2}\right] \quad (1)$$

where $\rho = W/2$ is the radius of the wire, θ_c the critical incident angle and λ the wavelength. $v = \frac{2\pi\rho}{\lambda} \sqrt{n_w^2 - n_o^2}$ is the waveguide constant, where n_w and n_o represent the refractive index of the nano-waveguide and the cladding, respectively. In our model, $n_w = 1.456$ and $n_o = 1.0$, for a nano-waveguide with width of $W = 300\text{nm}$, the decay length of the radiation mode L_{ra} is $0.19\mu\text{m}$. When $W = 300\text{nm}$, the evanescent field outside the nano-waveguide is quite strong. The small separation between the adjacent waveguides makes the overlap of the evanescent field, i.e. the coupling between nano-waveguides far stronger than the coupling in micro fiber. It makes the decay length of the radiation mode in the nano-waveguide array larger than the value described in Eq. (1). So when L reaches $1.0\mu\text{m}$ or $2.0\mu\text{m}$, radiation mode still exists. The radiation mode introduces additional phase shift onto the transmitted light and plays a key role in the focusing effect in dielectric nano-waveguide array. When L is large enough, such as $4.0\mu\text{m}$, the radiation mode is too weak to produce significant phase change and therefore no focusing is observed. In our work, it is found that $2.0\mu\text{m}$ is the appropriate length for the nano-waveguides to achieve practical focusing through the wire array.

It is well known that the evanescent field of a single nano-waveguide depends strongly on the wire diameter [22]. If the width of the nano-waveguides in our design changes, the radiation and the guiding mode change due to the variation in the evanescent field. Smaller W is, larger the evanescent field there is and larger the phase modulation introduced onto the beam by the radiation mode. So the focal length decreases with the decrease in W . Similarly, the overlap of the evanescent field from different wires increases if the separation D becomes smaller. As a result, f also decreases with the decrease in D .

It is worthy to note that the nano-waveguide array can be regards as the discrete version of the gradient-index (GRIN) lens structure. In a GRIN lens of which the optical thickness is described as $N_{ot}(r) = N_0(1 - \alpha^2 r^2 / 2)$, the focal length is given by $f = \frac{1}{N_0 \alpha \text{Sin}(\alpha d)}$ [24], where N_0 is the optical thickness at the lens center, d is the physical thickness of the lens, and α is the index constant. In order to achieve the same focal length, the GRIN lens needs far larger thickness than the nano-waveguide array. For example, in the array with $N = 13$, $W = D = 300\text{nm}$ and $L = 1\mu\text{m}$, the focal length f is $28.67\mu\text{m}$. To achieve the same focal length, the thickness of the GRIN lens should be 8.02mm . Here the index constant α is taken as 0.61mm^{-1} . The focal length of the GRIN lens with the same thickness as the array is very

longer than the one of array. Due to the contribution of the radiation mode and the evanescent field, the array can achieve a short focal length with a smaller size. This might also prove the key role of the radiation mode and the evanescent field in the focusing of the array.

Interestingly, in nano-waveguide array, the focal length can be modulated as lower as the order of incident wavelength. Similarly with previous work on metal slits arrays [2,5], the dielectric nano-waveguide array with variant separation D is also investigated. The modulation of the separation introduces further phase shift. Due to this, a short focal length is achieved. Here, a linear increase in D from the center to the boundary of the array is used. D in the center is $0.05\mu\text{m}$ and increases with a step of $0.05\mu\text{m}$ to the boundary of the array and $FWHM$ of the incident light is $1.6\mu\text{m}$. In our work, the shortest focal length $0.88\mu\text{m}$ is achieved when the array composing of 7 nano-waveguides with $W = 0.1\mu\text{m}$, $L = 2.0\mu\text{m}$, as the Fig. 6 shows. In this structure, the maximum amplitude at the focal point reaches 1.44 V/m .

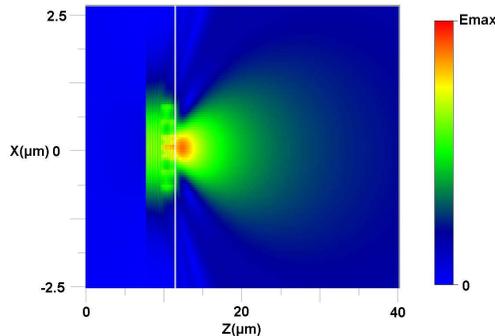


Fig. 6. The electric field distribution of the nano-waveguide array with variant separation and $N = 7$, $W = 100\text{nm}$, $L = 2\mu\text{m}$. D in the center is $0.05\mu\text{m}$ and increases linearly with a step of $0.05\mu\text{m}$ to the boundary of the array. The $FWHM$ of the incident light is $1.6\mu\text{m}$. The white vertical line presents the end of the array. The red color shows the energy peak as the focus.

The discussion above is all under the condition that the incident beam is TM mode. Alternatively, the TE mode can also be focused by the dielectric nano-waveguides arrays. The arrays with the same parameters as mentioned above are investigated. Results are shown in Fig. 7. It indicates that the focal length for the TE mode is slightly shorter than the one for the TM mode. For example, the arrays with $N = 13$, $W = D = 300\text{nm}$, $L = 1.0\mu\text{m}$, the $FWHM$ of the incident light is $7.5\mu\text{m}$, the focal length f is $24.33\mu\text{m}$ for the TE mode while the value is $28.67\mu\text{m}$ for the TM mode. Same as the case of TM mode, the focal length decreases with the increase of the array length L . It is similar as the TM mode that the long-length of the array destroys the focusing of the light. However, it shows that it is more difficult for the focusing action of the TE mode, even the length of the array is less than $2\mu\text{m}$. Interestingly, for the array with $N = 13$, $L = 1.9\mu\text{m}$, the focusing action is not observed in the FDTD simulation. From Fig. 7, it also can be found that the focal length of the TE mode and TM mode has the same trend when N changes.

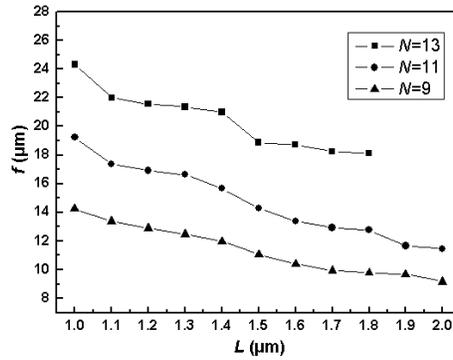


Fig. 7. The focal length for light of TE mode in the array with $W = D = 300\text{nm}$. The solid squares represent the value that $N = 13$ ($FWHM = 7.5\mu\text{m}$); the solid circles, $N = 11$ ($FWHM = 6.3\mu\text{m}$); the solid triangles, $N = 9$ ($FWHM = 5.1\mu\text{m}$). The solid line is just the guiding link between the values.

4. Conclusion

In conclusion, we have shown the simulated evidence of light focusing by using short dielectric nano-waveguide array. Simulation results show that the focal length of the nano-waveguide array can be simply altered from tens of micron to wavelength order by adjusting the length, the width of the waveguides, the separation between adjacent waveguides, the amount of them and the $FWHM$ of the incident light. It should be noted that changing the width of the wires or the separation is to change the total size of the array actually. It confirms that the focal length is to a large degree determined by the lens size. The unique focusing behavior is attributed to the radiation mode with longer decay length and the large evanescent field which appears in the nano-waveguide array. The wavelength order focal length is achieved by using array with variant separation, in which the separation increases linearly from the center to the boundary of the array. Both of TM and TE mode beams can be focused. Results also indicate that focal length for the TE mode is slightly shorter than the one for the TM mode. It is worthy mentioning that the phase of each array element can also be altered by adjusting other structural and/or materials parameters of waveguides or the gaps between them, such as changing array profile or adding material with nonlinearity in the gaps. These features are useful for individual and independent control of phase at each array element, and offer great flexibility in designing the nano-optic lenses without being restricted by the constraints of conventional optics in further researches. We believe our simulation results can be a promising guidance for designing planar dielectric lens.

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