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Rays inserting method (RIM) to design dielectric optical devices

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A B S T R A C T

In this article, a novel approach, called Rays Inserted Method (RIM), is introduced to design dielectric optical devices. In this approach, some rays are inserted between two ends of desired device and then the refractive index of the points along the route of rays are obtained. The validity of the introduced approach is verified by designing three types of optical devices, i.e. power splitter, bend, and flat lens. The results are confirmed with numerical simulations by the means of FDTD scheme at the frequency of 100 GHz.

1. Introduction

Optical devices are vastly used in microwave and optical circuits. Some of these devices are bends [1–3], power splitters [4], cloaks [5], concentrator [6], lenses [7,8] etc. By now, some approaches have been introduced to design the likes of these devices, such as Transformation Optics [9–11], Geometric optics [12–16], Conformal Mapping [5,17,18] and Optimization [19]. The Transformation Optics approach applies coordinate transformation to Maxwell's equations. This approach yields unusual materials with complex and anisotropic permeability and permittivity. This drawback is mitigated to some extent by using other approaches such as Conformal Mapping and Optimization methods. In this paper, a novel as well as simple idea is proposed to design optical devices by available inhomogeneous dielectric material. In this approach, called Rays Inserted Method (RIM), some rays are inserted between two ends of the desired device and then the refractive index of the points along the route of rays are obtained by the well-known Eikonal equation [20]. The refractive index of the desired optical device is matched to input and output surfaces. Consequently this results in an acceptable voltage standing wave ratio (VSWR). It is main improvement of this method with respect to other works using transformation optics and conformal mapping methods. It is worthy to mention that as we insert more rays between two surfaces, the resulted refractive index will be smoother and more continuous. The validity and performance of the introduced RIM approach was verified by designing three types of optical devices, i.e. power splitter, bend, and flat lens. The results are confirmed with numerical simulations by the means of FDTD scheme at the frequency of 100 GHz.

2. Rays inserting method (RIM)

Fig. 1 depicts a typical optical device which contain two input and output surfaces. The aim is to find the refractive index between two surfaces of the desired optical device. For this purpose, we propose the RIM (Rays Inserting Method). In this method, we insert some arbitrary rays between the input and output surfaces of the device.

The trajectory of a ray could be written as follows as a function of independent variable t (not time).

$$\vec{r}(t) = x(t)\hat{a}_x + y(t)\hat{a}_y + z(t)\hat{a}_z \tag{1}$$

where the variable t varies from 0 to t_f for input and output surfaces, respectively. The parameter t_f is the final value of the parameter t and may be different from ray to ray. The inserted rays must not cross each other and not pass a point more than once and should be monotonic. Also, the inserted rays must meet some conditions on the input and output surfaces. A typical ray starts from a point located at (x_0, y_0) and of refractive index n_0 with slope of α_0 and arrive at a point located at (x_f, y_f) and of refractive index n_f with slope of α_f, as shown in Fig. 1.

Each inserted ray specifies the refractive index, $n = \sqrt{\varepsilon_r}$, of those points it passes them. It is well known that the refractive index is related to the ray trajectory as given by Eikonal equation [20].

$$n^2(x, y, z) = \dot{x}^2(t) + \dot{y}^2(t) + \dot{z}^2(t) \tag{2}$$

in which dots denote differentiation with respect to the variable t.

Moreover, each inserted rays has an effective length which is independent of frequency, ω, and is defined as follows.

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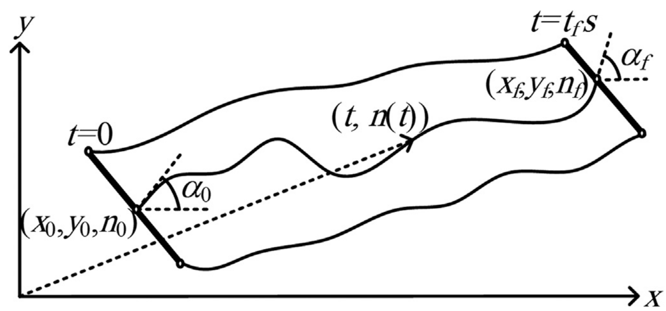

Fig. 1. A typical optical device with some rays inserted between its two input and output surfaces.

$$l_e = \frac{c\Delta\phi}{\omega} = \int nds = \int n\sqrt{\dot{x}^2 + \dot{y}^2 + \dot{z}^2}dt = \int_0^{t_f} n^2(t)dt \tag{3}$$

where c is the velocity of the light and $\Delta\phi$ is the electric phase between two ends of the ray. By Eq. (3), the parameter t_f determines the effective length, l_e, and vice versa. According to (3), the effective length of each ray, will be greater than its physical length, because $n \geq 1$.

3. Trajectory of the rays

The trajectories of the inserted rays are arbitrary and thereby are not unique. Here, we introduce comprehensive functions $x(t)$ and $y(t)$ to produce a set of two-dimensional trajectories. The proposed functions for trajectories are written as follows.

$$\begin{cases} x(t) = x_0 + \dfrac{n_0 t_f \cos(\alpha_0)}{p}\sin\left(p\dfrac{t}{t_f}\right) \\ + \dfrac{A}{p}\left[cos\left(p\dfrac{t}{t_f}\right) - 1\right] \\ y(t) = y_0 + \dfrac{n_0 t_f sin(\alpha_0)}{q}\sin\left(q\dfrac{t}{t_f}\right) \\ + \dfrac{B}{q}\left[cos\left(q\dfrac{t}{t_f}\right) - 1\right] \end{cases} \tag{4}$$

where coefficients A and B are given by

$$\begin{cases} A = \dfrac{p(x_f - x_0) - n_0 t_f \cos(\alpha_0)\sin(p)}{1 - \cos(p)} \\ B = \dfrac{q(y_f - y_0) - n_0 t_f \sin(\alpha_0)\sin(q)}{1 - \cos(q)} \end{cases} \tag{5}$$

Also, the parameters p and q in (4)–(5), after some mathematical manipulations, could be separately found from the following nonlinear relations.

$$\begin{cases} \tan\left(\dfrac{p}{2}\right) = \dfrac{x_f - x_0}{n_0 t_f \cos(\alpha_0) + n_f t_f \cos(\alpha_f)}p \\ \tan\left(\dfrac{q}{2}\right) = \dfrac{y_f - y_0}{n_0 t_f sin(\alpha_0) + n_f t_f sin(\alpha_f)}q \end{cases} \tag{6}$$

Substituting (4) in (2), gives us the refractive index along the inserted trajectory $\vec{r}(t)$.

$$n^2(t) = \left[n_0\cos(\alpha_0)cos\left(p\frac{t}{t_f}\right) + \frac{A}{t_f}sin\left(p\frac{t}{t_f}\right)\right]^2 + \left[n_0 sin(\alpha_0)cos\left(q\frac{t}{t_f}\right) + \frac{B}{t_f}sin\left(q\frac{t}{t_f}\right)\right]^2 \tag{7}$$

Also, substituting (7) in (3), yields the effective length of the inserted trajectory $\vec{r}(t)$.

$$l_e = \frac{1}{4}n_0^2 t_f\left(2 + \cos^2(\alpha_0)\frac{\sin(2p)}{p} + \sin^2(\alpha_0)\frac{\sin(2q)}{q}\right) + \frac{A^2 + B^2}{2t_f} - \frac{A^2}{4t_f}\frac{\sin(2p)}{p} - \frac{B^2}{4t_f}\frac{\sin(2q)}{q} + An_0\cos(\alpha_0)\frac{\sin^2(p)}{p} + Bn_0\sin(\alpha_0)\frac{\sin^2(q)}{q} \tag{8}$$

4. Examples and results

To validate the aforementioned approach and design formulas, three examples are given. These devices are matched to input and output surfaces. The designed devices are simulated at the frequency of 100 GHz.

4.1. Bend

A bend of angle θ_0 and radii a and b is desired whose typical configuration is depicted in Fig. 2(a). The slopes α_0 and α_f must be zero and $-\theta_0$, respectively. To have matched ends, their refractive index must be one, i.e. $n_0 = n_f = 1$. In bends, the effective length of all rays must be the same. Here, we chose all $l_e s$ equal to $b\theta_0$ to obtain the values of the refractive index as low as possible and also greater than 1.

A TM—polarized Gaussian beam with a free space wavelength of $\lambda_0 = 3$ mm impinges on the bend from the left-hand side. Figs. 2(b), 2(c) and 2(d) show the inserted rays, the profile of refractive index and the magnetic field distribution for a designed bend, assuming $\theta_0 = 90°$, $a = 10$ mm and $b = 20$ mm. Also, Fig. 3 shows the profile of refractive index and the magnetic field distribution for two designed bend with $\theta_0 = 45°$ and $\theta_0 = 135°$ assuming $a = 10$ mm and $b = 20$ mm. It is seen that index profile of designed bends are equal to one on input and output surfaces. Figs. 2 and 3 indicate the good performance of the bends designed by RIM method.

4.2. Lens of flat walls

A flat lens of thickness d, focal length of f and wall diameters D_1 and D_2 is desired whose typical configuration is depicted in Fig. 4(a). The slopes α_0 and α_f must be $\tan^{-1}(y_0/f)$ and zero, respectively. To have matched walls, their refractive index must be one, i.e. $n_0 = n_f = 1$. To have the same phase for all rays on the right wall, the term $l_e + f/\cos(\alpha_0)$ must be a constant value in all rays.

The Flat lens is illuminated by a Gaussian beam which propagates in the fixed point shown in Fig. 4. Fig. 4(b)–(d) show the inserted rays, the profile of refractive index and the magnetic field distribution for a designed flat lens, assuming $d = 10$ mm, $f = 5$ mm, $D_2 = 37$ mm and $D_1 = 28$ mm. Here, we chose the constant $l_e + f/\cos(\alpha_0)$ equal to 40.3 mm. Fig. 4 shows the good performance of the flat lens designed by RIM method.

4.3. Power splitter

A two-way power splitter of parameters w, d and L is desired whose typical configuration is depicted in Fig. 5(a). The slopes α_0 and α_f must be zero. To have matched ends, their refractive index must be one, i.e. $n_0 = n_f = 1$. In power splitters, the effective length of all rays must be the same.

A TM—polarized Gaussian beam with a free space wavelength of $\lambda_0 = 3$ mm impinges on the power splitter from the left-hand side. Figs. 5(b)–(d) show the inserted rays, the profile of refractive index and the magnetic field distribution for a designed power splitter, assuming $w = 10$ mm, $d = 5$ mm and $L = 50$ mm. This figure sounds the good performance of the splitter designed by RIM method. Here, we chose all $l_e s$ equal to 116 mm to obtain the values of the refractive index as low as possible and also greater than 1.