Physica B 426 (2013) 150–154

Contents lists available at SciVerse ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Design of electromagnetic refractor and waveguide bends using complementary medium

Jin-Shuo Mei [a,b], Qun Wu [a,*], Kuang Zhang [a,*]

[a] School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, PR China
[b] School of Applied Science, Harbin University of Science and Technology, Harbin 150080, PR China

ARTICLE INFO

Article history:
Received 21 August 2012
Received in revised form
6 May 2013
Accepted 10 June 2013
Available online 20 June 2013

Keywords:
Transformation optics
Homogeneous metamaterials
Refractor
Wave splitter
Waveguide bends

ABSTRACT

Based on the theory of transformation optics and concept of complementary medium, a kind of electromagnetic refractor and wave splitter using homogeneous metamaterials with negative refraction index is proposed. The operating mechanisms are described and constitutive tensors of the complementary medium are derived. Full wave simulations are performed to confirm the functionality of the proposed devices. Simulation and calculation results verified that this approach can be further utilized to design novel waveguide bends structure with different cross section width and angle using homogeneous metamaterials with negative refraction index, in addition, the simulations results show that nearly all the energies are transmitted and there is no wave fronts distortion when wave transmits through the bend.

1. Introduction

Since the theory of transformation optics was proposed by Pendry et al. [1], great efforts have been devoted to design various electromagnetic devices based on the transformation optics, such as invisibility cloaks [2–9], EM field rotators [10], concentrators [11,12], complementary cloak [13–15], and so on. Recently, optical transformation theory has been applied to refractor [16] and waveguide. Rahm et al. first proposed the waveguide bends using finite embedded transformation for the design of beam shifters and splitters [17]. Inspired by the above work, this finite embedded TO approach is further utilized in the design of various waveguide devices, and many theoretical studies, numerical simulations and parameter designs have been devoted to the waveguide devices [18–24]. Most of these designs of refractor and waveguide bends can be realized with positive refraction index metamterials based on the coordinate transformation from free space to an arbitrarily compressed or stretched region. In order to make the involved metameterials simpler, great effort has been made to realize the waveguide bends proposed [25,26]. Qiu et al. proposed a kind of adaptive waveguide bends which could be realized with homogeneous, nonmagnetic, and isotropic materials [27]. However, it can be nonmagnetic only when connecting two waveguides are of equal width. Based on the former work, another kind of all-dielectric tapered waveguide bender with homogeneous loading, arbitrary bending and simplified geometry was proposed [28]. Recently, Ding et al. proposed the arbitrary waveguide bends with negative refraction index [29]. Other waveguide devices with homogeneous complementary medium were also proposed, such as connector and shifter [30]. It is known that complementary media can optically "cancel" a certain volume of space at a certain frequency, and has important implications and motivated various applications, such as "perfect lens" and "superscatterer". With the development of the metamaterials, various negative-index materials were proposed [31,32], the realization of the above waveguide devices is becoming possible. However, the bends proposed in Ref. [29] can only connect two waveguides of equal width. Inspired by the idea of cloak and waveguide devices with complementary medium, a kind of refractor using homogeneous materials with negative-index was proposed in this paper. Based on the same principle, the wave splitter was proposed by using the combination of two complementary medium. Moreover, this approach is further utilized to design the waveguide bends using homogeneous materials with negative refraction index, which is more general than waveguide bend proposed in Ref. [29]. With the coming forth of more and more negative index metamaterials, the fabrications of the homogeneous NIM have become convenient. Different from the proposed waveguide bends with positive refraction index metamterials based on the transformation optics, there is no phase change at the ends of waveguide bend with negative refraction index metamaterials, that is, there is no information loss. It is expected that our approach provides a general recipe to design refractor, wave splitter and waveguide bends with complementary medium.

* Corresponding authors at: School of Electronics and Information Engineering, Harbin Institute of Technology, Harbin 150001, PR China. Tel.: +86 451 86403028.
E-mail addresses: meijinshuo@126.com (J.-S. Mei), qwu@hit.edu.cn (Q. Wu), zhangkuang@hit.edu.cn (K. Zhang).

0921-4526/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physb.2013.06.021

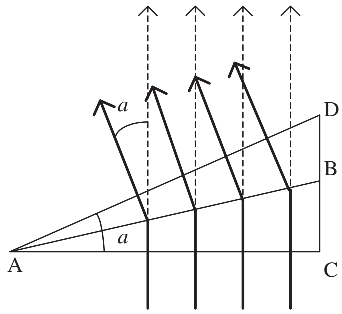

Fig. 1. Schematic diagram of the space transformation for the refractor using complementary medium (the deflection angle a is defined as the refraction angle under normal incidence).

2. Principle description

In order to control the propagation of the electromagnetic wave, a space transformation for realizing a refractor is shown in Fig. 1. The region ADB is folding back onto ACB, and this folding transformation results in transformed region ADB with negative refraction index. In free space of ACB, the incident wave is normal to AC, and it experiences a distance s as an effective distance (called an optical path length). While the transformation that folds ADB back on ACB gives rise to a negative optical path length. Therefore, the region from AC to AD has zero optical length, and the phase difference is canceled by complementary materials of region ADB. As light moves from interface AC to AB, the negative index material "undoes" the propagation from interface AB to AD so that the wave front ends up exactly as it was at interface AC. That is, the wave is deflected with an angle a, as shown in Fig. 1.

It should be noted that the coordinates of points A, B, C and D are constants and can be expressed as (x_A, y_A), (x_B, y_B), (x_C, y_C) and (x_D, y_D), respectively. We can freely choose the deflected angle between interface AD and AC where $0 < a < 90$. The transformation equations can be expressed as follows.

$$x' = a_1 x + b_1 y + c_1$$
$$y' = a_2 x + b_2 y + c_2$$
$$z' = z \tag{1}$$

where

$$\begin{bmatrix} a_1 \\ b_1 \\ c_1 \end{bmatrix} = \begin{bmatrix} x_A & y_B & 1 \\ x_B & y_B & 1 \\ x_C & y_C & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_A \\ x_B \\ x_D \end{bmatrix} \text{ and } \begin{bmatrix} a_2 \\ b_2 \\ c_2 \end{bmatrix} = \begin{bmatrix} x_A & y_A & 1 \\ x_B & y_B & 1 \\ x_C & y_C & 1 \end{bmatrix}^{-1} \begin{bmatrix} y_A \\ y_B \\ y_D \end{bmatrix}.$$

According to the coordinate transformation method, the permittivity and the permeability in the transformed space are given as follows [1].

$$\varepsilon' = \frac{A\varepsilon A^T}{\det A}$$
$$\mu' = \frac{A\mu A^T}{\det A} \tag{2}$$

where ε and μ are the permittivity and permeability of the original space. A is the Jacobian transformation matrix, A^T denotes the transpose of matrix A, and det A is the determinant of the matrix. In this paper, the space ABC is assumed to be free space. So the parameters of transformed space ADB can be easily obtained as follows.

$$\bar{\bar{\varepsilon}}' = \bar{\bar{\mu}}' = \frac{\begin{bmatrix} a_1 & b_1 & 0 \\ a_2 & b_2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_1 & b_1 & 0 \\ a_2 & b_2 & 0 \\ 0 & 0 & 1 \end{bmatrix}^T}{\begin{vmatrix} a_1 & b_1 & 0 \\ a_2 & b_2 & 0 \\ 0 & 0 & 1 \end{vmatrix}} \tag{3}$$

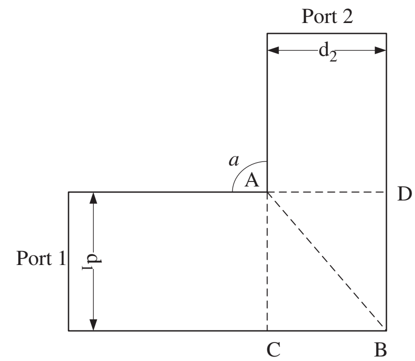

Fig. 2. Schematic illustration of coordination transformation in the design of waveguide bends using complementary medium.

It is noted that the constitutive parameters are spatially invariant in Eq. (3). Based on the above approach, wave splitter can be realized by combination of two refractors. Moreover, this approach can be used to design the waveguide bend also. Fig. 2 shows the scheme to design waveguide bend with complementary medium by folding triangle ADB into ACB. Because of phase cancellation, there is no wave front distortion when guiding modes transmit through the bending structure.

Similarly, the constitutive parameters for wave splitter and waveguide bends can be obtained. Different from Ref. [29], these approach exhibit a general way for the waveguide bend connecting two waveguides with different width aperture. To demonstrate our idea above, the full wave simulations using the commercial finite element solver COMSOL Multiphysics are performed to validate the functionality of the proposed refractor, wave splitter, and waveguide bend using the complementary medium in the next section.

3. Simulations and discussions

To validate our design, the finite element method has been used to simulate the functionality of the proposed devices. Firstly, 2D field mapping of the functionality of the proposed refractor is calculated with the four boundaries defined as perfectly matched layers. The incident wave is taken as a Gaussian beam with a frequency of 1.5 GHz, which is incident from the bottom to the top. Fig. 3 shows the electric field distribution of the refractor using complementary medium with different deflection angles. In Fig. 3 (a), the complementary medium is placed in the region EFHG which is folding back to region ACHG. It is obvious that the wave fronts at the interface EF are almost the same as that at the interface AC. In such case, the wave is deflected with an angel of $a = 0°$. In Fig. 3(b), the complementary medium is placed in the region ABD which is folding back to region ABC. It can clearly be seen that the wave fronts at the interface AC are almost the same as that at the interface AD. In such a case, the wave is deflected with an angle $a = \angle$DAC.

Since the propagation direction of electromagnetic wave can be controlled by complementary medium, splitting can be realized by combinations of two refractors. In Fig. 4, two refractors are assembled together to realize the functionality of the wave splitter. In Fig. 4, the constitutive parameters of the left triangular region are: $\varepsilon = \mu = (-0.866, -0.5, 0; -0.5, -1.444, 0; 0, 0 -0.866)$, and the constitutive parameters of the right triangular region are: $\varepsilon = \mu = (-0.866, 0.5, 0; 0.5, -1.444, 0; 0, 0 -0.866)$. In the simulation, the wave is incident from the bottom to the top. The distributions of electric field and time-average power outflow are shown in Fig. 4(a) and (b), respectively. From Fig. 4, we can see that the incident wave and the incident energies are equally