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Gaussian beam focusing in metamaterial with the second harmonic generation effect as a perfect lens using paraxial group transformation

Z. Roosta, A. Keshavarz*, G. Honarasa

Department of Physics, Shiraz University of Technology, Shiraz, Iran

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ABSTRACT

In this paper, propagation of the Gaussian beam in two structures of the perfect lens with the ability of the second harmonic generation is investigated by using paraxial group transformation method. For this purpose, at first the concept of perfect lens, the second harmonic generation, and paraxial group transformation method are introduced. Then, generation and propagation of the second harmonic beam in two structures of perfect lens are simulated. Results show that the image quality can be increased by these structures.

1. Introduction

Materials with negative electric permittivity and magnetic permeability that lead to a negative refractive index were introduced by Veselago in 1968 [1]. This kind of material is called metamaterial [2]. At first, metamaterials were made at subwavelength but nowadays negative refractive index is available at visible optical range [3,4]. In 2000, Pendry introduced the concept of perfect lens by using Veslago's results about a slab of metamaterial. He showed that a slab of metamaterial can focus the beam and compensate the phase [5]. In recent decades, studies on the nonlinear effects in metamaterial such as the second harmonic generation have attracted more attention. Agranovich et al. investigated the second harmonic generation in a negative refractive index media in 2003 [6]. Using this nonlinear phenomena in a perfect lens can produce a half-wavelength in addition to focusing the beam.

Today, different ways are available for investigating the propagation of the beam in optical media. An exact solution is analytical solution of the governed wave equation, but maybe it is complicated. Therefore, an approximate solution is convenient to be used instead of exact solution. One of the approximate solution methods is numerical solution. Furthermore, we can use Huygens–Fresnel integral to study how the beam diffracts in the medium. This integral is modified by Collins and rewritten with respect to ABCD matrix of the optical system [7]. Along with it, Bandres et al. presented the beam propagation method in the group of symmetries of the paraxial wave equation which is called paraxial group, and obtained closed form expressions for the propagation of any paraxial beam through misaligned ABCD optical systems [8,9].

In this paper, at first the concept of perfect lenses is introduced and the second harmonic generation in negative and positive index media are compared. Then, perfect lens with the ability of the second harmonic generation is investigated and propagation of Gaussian beam in two different structure of these kinds of lenses are simulated by paraxial group transformation method. The first structure contains one perfect lens which can produce a focusing second harmonic beam and the second structure includes two lenses

* Corresponding author.
E-mail address: Keshavarz@sutech.ac.ir (A. Keshavarz).

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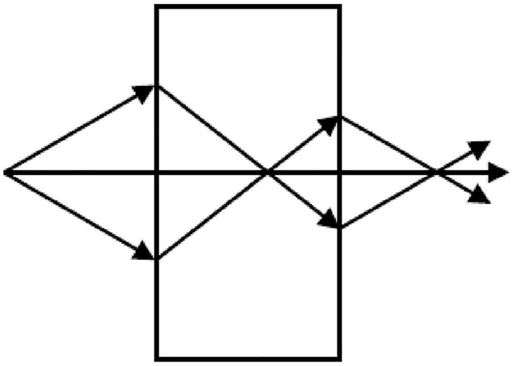

Fig. 1. A slab of metamaterial.

that guide the fundamental beam to the first lens which can generate a backward second harmonic beam that can be focused by second lens. At last, applications of these kinds of lenses are investigated.

2. Theory

This section contains three subsection. First, the theory of the perfect lens and second harmonic generation are presented in Sections 2.1 and 2.2, respectively. Then, in Section 2.3 the paraxial group transformation method has been introduced.

2.1. Perfect lens

Reform of Snell's refractive law in metamaterial and change of the direction of refracted beam in the boundary between positive and negative media are cause for focusing the beam in a slab of metamaterial and they form the concept of perfect lens. In Fig. 1 focusing the beam in a slab of metamaterial is shown. As it is seen in the figure, the beam in the boundary of two media is refracted and it is focused in two regions, in the slab and out of the slab [5,10].

If the refractive index of the lens and the positive media around the lens are the same, while the signs are different, the boundary between lens and positive media has no reflection [11]. So, this lens is perfect lens. In this paper, we consider $n_{Lens} = -1$ and $n_{Air} = 1$.

2.2. Second harmonic generation

One of the most important nonlinear optics phenomena is the second harmonic generation. When a medium has second order susceptibility tensor, $\chi^{(2)}$, the second harmonic beam can be generated. It means that the fundamental beam at frequency ω is converted to radiation at the second-harmonic frequency 2ω [12]. The second harmonic generation in negative and positive media are different because phase velocity vector and Poynting vector at ω frequency are in opposite direction. Negative refractive index can occur at a limited frequency range. So, a medium cannot be negative for fundamental beam at ω and the second harmonic beam at 2ω simultaneously. Also, phase matching condition and Manely–Rowe relations must be changed in nonlinear metamaterials [13–15]. Fig. 2 wave vectors and Poynting vectors direction in positive and negative media are compared. As it is represented in Fig. 2A, wave vector and Poynting vector of the fundamental beam (k_1, s_1) and these vectors of the second harmonic beam (k_2, s_2) are in the same direction. Fig. 2B shows the wave vector and Poynting vector when the medium is negative at ω and it is positive at 2ω.

In this case, because of phase matching condition, k_1 and k_2 must be in a same direction and as it was discussed in [13], s_2 is in the

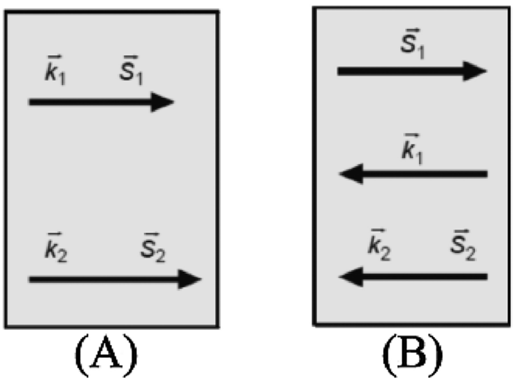

Fig. 2. Wave vectors and Poynting vectors direction for: (A) a medium with positive refractive index, (B) a medium with negative refractive index.