Proposal for new method to design all-dielectric photonic metamaterials using an analytical approach

Eric Cassan, Khanh-Van Do, Xavier Le Roux, Charles Caer, Delphine Marris-Morini, Nicolas Izard, and Laurent Vivien

Institut d'Electronique Fondamentale, Université Paris-Sud, CNRS UMR 8622
Bât. 220, 91450 Orsay Cedex, France
Email: eric.cassan@u-psud.fr

Abstract

We propose a new analytical approach to the study of all-dielectric metamaterials allowing the prediction of the optical index maps and the required hole drilling distributions making light follow prescribed paths. The method will be applied to proof-of-concept structures based on the silicon-on-insulator technology. Light propagation will be studied using FDTD simulation to verify light trajectories, study the influence of extended light beams, and evaluate the robustness of the semi-classical approach based on equations of Hamiltonian optics. The presented results will show that the proposed method can be used for the straightforward design of new optical functionalities within the photonic metamaterial regime.

1. Introduction

Metamaterials have received a growing interest in the recent period due to their ability for electromagnetic field manipulation through artificially engineered media. The main approach for this is to properly design the material unit cell by controlling the values of permeability μ and permittivity ε [1]. This method has been applied to various situations, including the realization of negative-index materials or for cloaking purposes [2], and most of previous experimental demonstrations have been achieved in the microwave frequency regime [3]. More recently, efforts have been done to transpose these concepts at optical frequencies. On a practical point of view, drilling of holes in semiconductor silicon on insulator (SOI) membrane was achieved in most of recent works [4, 5]. Controlling either the spatial distribution of holes or the hole filling factor indeed makes possible to choose the local average refractive index. This approach is valid in the so-called homogenization regime or metamaterial regime, in which light wavelength λ in vacuum is fairly large with respect to the unit cell size a, i.e. $a/\lambda<<1$.

Contrary to previous approaches relying on numerical methods, we propose here a new flexible method to design photonic metamaterials using analytical relationships.

Using this approach, index distributions suited to make light follow prescribed light paths will be derived in several cases, and light propagation will then be verified using numerical electromagnetic full-vectorial simulations. Doing so, it will be shown that the proposed method is useful for the straightforward study of new optical functions based on photonic metamaterials.

2. Analytical calculation of required refraction index distribution and study approach

Light propagation in graded all-dielectric metamaterials (GADMs) can be described using a semi-classical approach based on Hamiltonian optics [6], i.e. by using the local photonic bandstructure or dispersion diagram $\omega(k)$ [7,8]. The problem is simplified in case of long wavelength hypothesis (sub-λ corrugation), which makes the material behave as a spatially modulated index medium with refractive index $n(x,y)$ over the considered (x,y) propagation plane. Light path can then be described by the propagation of a ray, or a set of rays, in an inhomogeneous optical medium, i.e. by following both the position $\mathbf{r}$ and the wavevector $\mathbf{k}$ of the ray, i.e. managing the set of $(\mathbf{r},k)$ in space and time [6].

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Using this approach, we will show that the required bi-dimensional refraction index distribution that makes light follow a prescribed trajectory is given by:

$$\frac{\partial \ln(n(x,y))}{\partial x} = \frac{\frac{d^2x(\sigma)}{d\sigma^2}}{\left(\frac{dx(\sigma)}{d\sigma}\right)^2 + \left(\frac{dy(\sigma)}{d\sigma}\right)^2}$$

$$\frac{\partial \ln(n(x,y))}{\partial y} = \frac{\frac{d^2y(\sigma)}{d\sigma^2}}{\left(\frac{dx(\sigma)}{d\sigma}\right)^2 + \left(\frac{dy(\sigma)}{d\sigma}\right)^2} \quad (1)$$

where $\{x(\sigma),y(\sigma)\}$ represents the parametric curve for light path.

3. Device implementation and light propagation

Typical device design implementations will be considered using SOI photonic crystals working in the metamaterial regime. Equation (1) will be used to predict the required n(x,y) index maps in several proof-of-concepts cases. Then, propagation of light will be verified using FDTD simulation with PML boundary conditions.

As a typical example, we give just hereafter the result obtained in one case: a logarithmic spiral curve is chosen as the required light path, i.e. $x(\sigma)=a.\exp(b\sigma).\sin(\sigma)$ and $y(\sigma)=a.\exp(b\sigma).\cos(\sigma)$ are considered in Cartesian coordinates.

Using equation (1), the following relationship can then be deduced using equation (1):

$$n(x,y) = \frac{D}{\rho^{\frac{b^2-1}{b^2+1}}}, \text{ with } \rho = \sqrt{x^2+y^2} \quad (2)$$

, with D and b two introduced parameters.

Figure 1 shows the obtained field obtained by considering an optical gaussian source located at 60 lattice periods (60a) from the structure center after 2000 optical periods. The parameter b was fixed to 0.02, and the considered normalized wavelength was fixed to 0.13 ($a/\lambda=0.13$). As shown here, light path follows the prescribed spiral light curve.

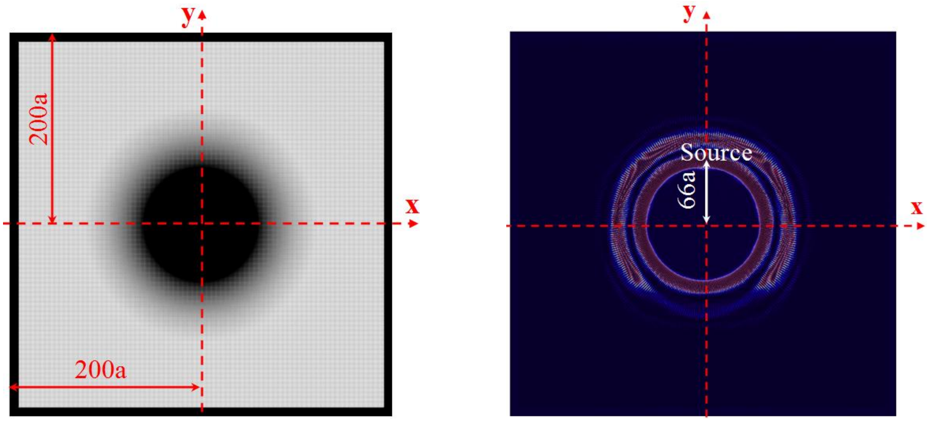

Fig. 1: FDTD simulation of the considered spiral light path: (a) Structure permittivity overview deduced from equation (1) and considered into the numerical simulation, (b) Field state at normalized frequency $a/\lambda=0.13$ after 2000 optical periods.

Other cases will be considered, showing the flexibility of the proposed method to explore electromagnetic phenomena and propose new optical functions within the photonic metamaterial regime.

4. Conclusion

We propose a new analytical approach for the study of photonic metamaterials based on relationships giving the bi-dimensional in-plane index map n(x,y) to shape optical beams according to a prescribed path in the photonic metamaterial regime.

The main advantage with respect to transformation optics methods relies on the direct analytical prediction of hole drilling two-dimensional in-plane r/a(x,y) profile. The method will be applied to given proof-of-concept configurations, bends and logarithmic spirals, for which light paths will be verified using FDTD simulation.

The presented results aim at serving for the design of new optical functions within the photonic metamaterial regime.

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