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Guidance Condition Correction into the Design of Two Dimensional Nanophotonic Devices

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Abstract—We quantify the importance of including finite thickness effects into the design of two dimensional nanophotonic metamaterial devices. Direct band diagram method and analytical guidance condition method are introduced and verified with nanostructured Lüneburg lens.

Keywords—two dimensional photonic device, guidance condition, band diagram

I. INTRODUCTION

With the development of optoelectronics and nanophotonics, nanophotonic metamaterial devices are becoming increasingly important. Many three dimensional (3D) design and fabrication methods have been proposed [1], [2]. However, 2D design still prevails due to its consistency with existing planar nanofabrication techniques. Currently most 2D photonic metamaterial device designs are based on the assumption of infinite height along the third dimension. However, this is unachievable in actual fabrication so finite height structures are generally implemented instead [3]. This results in index guiding along the third dimension and deviates the actual performance of the devices from the original expectation. This point has been discussed in terms of photonic crystal slabs [1]; however, it is seldom considered in non-periodic nanophotonic metamaterial devices, where the actual local effective refractive indices differ significantly from those under 2D assumption. In this paper, we analyze in detail the importance of guidance condition correction in 2D nanophotonic device design, and introduce two corresponding design methods, one based directly on the band diagram and the other using analytical electromagnetic (EM) wave guidance condition. As an example, nanostructured subwavelength Lüneburg lenses are designed and compared with and without including the waveguide effects, and a significant difference between their photonic performance is observed.

II. METHODS

In this paper, without loss of generality, we consider a subwavelength structure on a glass substrate, composed of square unit cells of size $a \times a$ with silicon rods of height $h = 1.24a$ (Fig. 1(b)). It is operated under transverse electric (TE, electric field perpendicular to the 2D plane) illumination of free space wavelength $\lambda = 6a$.

Our first method is based directly on the band diagram calculated numerically. Here a 3D supercell of height $H = 20a$ is used instead of the square unit cell while assuming 2D

Fig. 1: Structures of infinite height rods under 2D assumption (a), finite height rods (b) and the corresponding effective uniform waveguide (c). (d) Band diagram comparison between these three cases for rod radius $r = 0.5a$.

(Fig. 1(a)(b)). The height of the supercell is made sufficiently large for the fields to decay to negligible values at the boundary. This method is computationally inefficient since it requires band solving in 3D. We refer to it as direct band diagram (DBD) method.

Instead, the second proposed method avoids this computation problem and provides analytical results through the EM wave guidance condition (WGC). Firstly the rod slab is treated as a waveguide of uniform effective refractive index (Fig. 1(c)), where the effective index is calculated from the local dispersion diagram of the infinite structures assumed to be adiabatically variant. The dispersion relation of the waveguide slab is then governed by the EM guidance condition, e.g. for TE wave [4]

$$\arctan\left(\frac{\epsilon_2 \alpha_1}{\epsilon_1 k_{2z}}\right) + \arctan\left(\frac{\epsilon_2 \alpha_3}{\epsilon_3 k_{2z}}\right) = k_{2z} h + m_{TE} \pi, \quad (1)$$

where $k_{2z} = (\epsilon_2 \omega^2 / c^2 - k_{//}^2)^{1/2}$ is k_z in medium 2, $\alpha_1 = (k_{//}^2 - \epsilon_1 \omega^2 / c^2)^{1/2}$ and $\alpha_3 = (k_{//}^2 - \epsilon_3 \omega^2 / c^2)^{1/2}$ are the attenuation constants along z in medium 1 and 3, $k_{//}$ is the phase-matched wave vector along the interfaces, c is the free

space light velocity, and m_{TE} is an integer. Analytical solution for the band diagram is possible by graphically solving Eq. 1.

Band diagrams and the relationships between rod radius and local effective refractive index of the unit cell are shown in Fig. 1(d) and Fig. 2. Results from both proposed methods agree well with each other, but they are significantly different from the results without guidance correction. This shows that the wave guidance plays an important role since a large portion of the fields are located in air and the substrate.

Fig. 2: Relationship between the rod radius and local effective refractive index calculated from both methods: DBD and WGC, and the comparison to the results under 2D assumption.

III. EXAMPLE

As an example, subwavelength dielectric nanostructured Lüneburg lenses are designed and compared with the FDTD simulation under TE illumination. The Lüneburg lens is a gradient-index lens with a refractive index distribution $n(r) = n_0 \sqrt{2 - (r/R)^2}$, where n_0 is the ambient index outside the lens, R is the radius of the lens and r is the distance to the lens center for certain point [5]–[7]. It is able to focus an incoming plane wave into a geometrical perfect point at the opposite edge of the lens. Here the same subwavelength structure discussed in the previous section is used to achieve the required index distribution. The ambient indices n_0 are chosen as 1.53 and 2.10 for designs with and without guidance correction. We assume planar implementation on glass substrate for both designs, with the same radius $R = 15a$ and finite rod height $h = 1.24a$ (Fig. 3(a)). The FDTD simulation is used to test their performance and the results are illustrated in Fig. 3(b)(c). It can be observed that by including the guidance correction, a good focus is formed at the right edge of the lens, while no significant focus exists for the case without correction.

IV. CONCLUSION

We have verified that the effective refractive indices for a certain unit cell in nanophotonic metamaterial devices are significantly different with and without guidance correction, using two methods: DBD and WGC. The Lüneburg lens design verified the importance of 3D correction. It is likely that other metamaterial and transformation optics devices will require similar correction to work properly.

Fig. 3: (a) Top and side views of the finite height sub-wavelength Lüneburg lens. (b) The FDTD results of the Lüneburg lens with wave guidance correction. Blue lines are the Hamiltonian ray tracing [8] results based on the dispersion relation. (c) The FDTD results of the lens designed under 2D assumption but implemented with finite height rods.

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