Electromagnetic Field Simulation for Large-scale Waveguide Combiner for Augmented Reality

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Abstract: To analyse a meta-grating embedded AR waveguide, a large-scale electromagnetic field solver is required. We propose the Fourier coupled modal method, which combines the Fourier modal method and the coupled mode theory. © 2024 The Author(s)
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1. Introduction

Meta-grating is a promising optical element in augmented reality (AR) display for its ability to diffract more energy at higher angles and facilitate a compact form-factor. Conventional optical elements such as diffractive optical elements (DOEs) and a holographic optical elements (HOEs) face physical limitations in terms of energy efficiency, diffraction angle, and bulky size. A simulation of optical fields in meta-grating-attached waveguide combiner necessitates electromagnetic field solver. Given that the waveguide combiner dimensions are in the millimeter scale, the current electromagnetic field solver faces limitations in terms of computational costs. We proposed the Fourier coupled modal method (FCMM), which calculates the optical interconnection of individual layers along the optical axis using the Fourier modal method (FMM) [1], and the coupling between individual sections in the vertical direction along the optical axis using the coupled mode theory (CMT) [2]. A parallelization of algorithm and mode selection, which focuses on the guided-modes reduce computational costs. In addition to numerical analysis, it would be important to design a meta-grating capable of generating optical modulation characteristics for AR combiners. The FMM has potential for an inverse design of the metasurface that can improve the light extraction efficiency of the μLED [3]. Several optimization and simplification approaches have been applied to FEM-based three-dimensional electromagnetic field simulations, yielding successful results [4]. FCMM also has potential in design of meta-grating through Adjoint method and gradient-based optimization [5] techniques.

2. Fourier Coupled Modal method

While it is common to directly solve the Maxwell equations to analyse the structure of appropriate size, in the analysis of large-scale structures, approximation methods become necessary to reduce computational costs. The electromagentic field propagation is composed of two distinct processes. One involves propagation across layers along the optical axis, which can be solved using the scattering matrix and multiblock interconnection. The other involves propagation across the waveguide in a direction perpendicular to the optical axis, and this can be solved using the CMT. Based on the CMT, the entire electromagnetic field distribution would be described as a weighted sum of eigenmodes defined by the separated local waveguide. These weights $C_\nu^{(p)\pm}$ represent coupling coefficients along the optical axis. P denotes the total number of waveguides, with p serving as the index for each waveguide ranging from 1 to P. N denotes the number of eigenmodes of a single waveguide, with ν serving as index of eigenmodes for each waveguide, ranging from 1 to N.

$$\begin{aligned}\begin{pmatrix}\tilde{E}^{\pm}\\ \tilde{H}^{\pm}\end{pmatrix} &= \sum_{p=1}^{P}\left[\sum_{\nu=1}^{N} A_\nu^{(p)\pm}(z)\, e^{\alpha_\nu^{(p)\pm}(z-z_\mp)}\begin{pmatrix}E_\nu^{(p)\pm}(x)\\ H_\nu^{(p)\pm}(x)\end{pmatrix} e^{j\beta_\nu^{(p)\pm}(z-z_\mp)}\right]\\ &= \sum_{p=1}^{P}\left[\sum_{\nu=1}^{N} e^{\alpha_\nu^{(p)\pm}(z-z_\mp)} A_\nu^{(p)\pm}(z)\begin{pmatrix}\tilde{E}_\nu^{(p)\pm}(x)\\ \tilde{H}_\nu^{(p)\pm}(x)\end{pmatrix}\right] = \sum_{p=1}^{P}\left[\sum_{\nu=1}^{N} C_\nu^{(p)\pm}\begin{pmatrix}\tilde{E}_\nu^{(p)\pm}(x)\\ \tilde{H}_\nu^{(p)\pm}(x)\end{pmatrix}\right]\end{aligned} \tag{1}$$

It is unnecessary to calculate eigenmodes of a single waveguide in global domain, because most regions are free-space. When calculating eigenmodes of a single waveguide, the eigenmode inside the waveguide is numerically calculated by FMM, while the eigenmodes outside the waveguide is analytically represented using the free-space propagation model. This approximation approach enhances the computation efficiency of solving eigenmode for a local single waveguide. In FMM, a single waveguide consists of a structure where a material with a refractive index higher than 1 is surrounded by free-space with a refractive index of 1. The guided-mode of the waveguide can be numerically calculated. However, there is a problem when expressing the electromagnetic field distribution within a waveguide with a refractive index of 1 or less, as the eigenmode must be in the form of guided-mode. The refractive index of the surrounding material was reduced to 0.1 to calculate the guided mode of the waveguide composed of a material with a refractive index of 1 or less. In addition, more guided-modes would be obtained from high refractive index waveguides. As shown in Fig. 1, it would be presented that when a gaussian beam of an angle that does not satisfy the total internal reflection (TIR) condition between the material with a refractive index 1.5 and the free-space is incident, some of it reflected and goes inside the waveguide, but some of it is refracted.

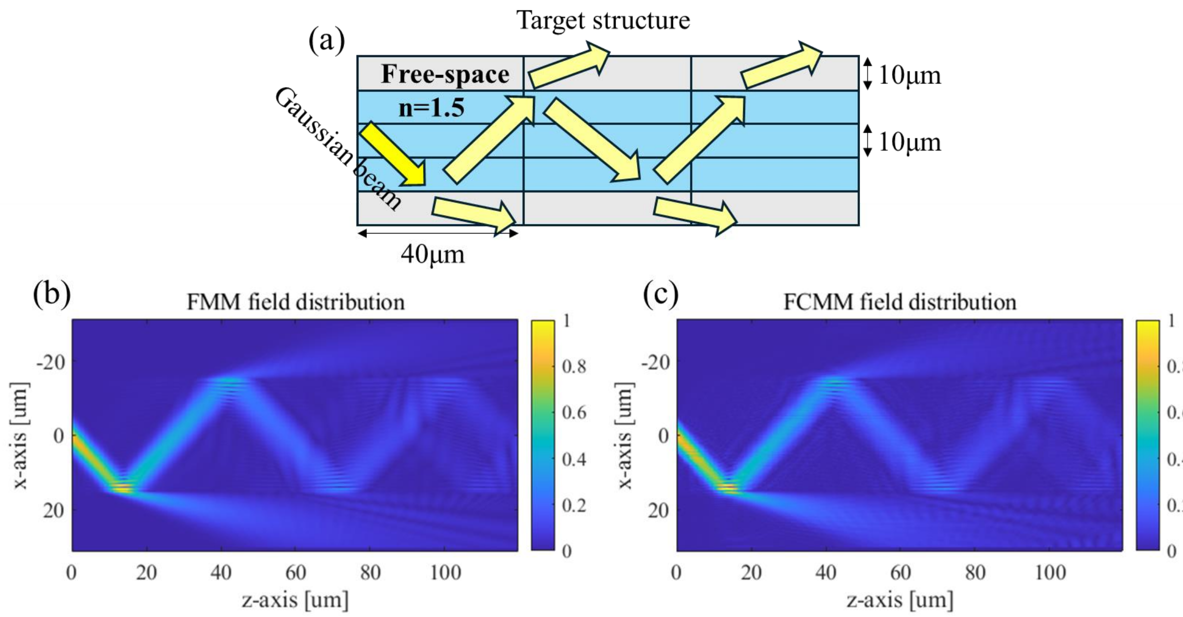

Fig. 1. FCMM simulation of simple waveguide for tilted gaussian beam. The structure was divided into five local regions along the x-axis, each with a width of 10μm, and consisted of three layers, with a thickness of 40μm, along the optical axis. (a) Structure schematic. (b) Field visualization results (FMM). (C) Field visualization results (FCMM).

3. Conclusion

In this paper, we introduce the FCMM, a large-scale electromagnetic field solver combining FMM, which calculates the coupling of each layer and interconnects the coupling of all layers using a scattering matrix and CMT which calculates the coupling of separated local regions. We demonstrate the accuracy of FCMM through simulations of simple waveguide structure. We expect that FCMM, with Adjoint method and gradient-based optimization, enables to design large-scale meta-grating for AR waveguide combiners.

4. Acknowledgements

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5. References

[1] W.-P. Huang, “Coupled-mode theory for optical waveguides: an overview”, J. Opt. Soc. Am. A 11, 963-983 (1994).

[2] H. Kim, J. Park, and B. Lee, “Fourier Modal Method and its Applications in Computational Nanophotonics, (CRC, 2012).

[3] M. F. Schubert, and A. M. Hammond, “Fourier modal method for inverse design of metasurface-enhanced micro-LEDs,” Opt. Express 31, 42945-42960 (2023).

[4] C-C. Lee, P-H. Liao, C-W. Huang, S-W. Wen, C-J. Chang, W-k. Lee, Y-T. Chen, C-C. Chen, W-Y. Lin, B. L. Kwak, R. J. Visser, and C-C. Wu, “Fully electromagnetic wave optic simulation and analyses of the cross-scale reflective 3D OLED pixel configuration,” Org. Electron. 95 (2021), 106213.

[5] C. Kim, and B. Lee, "TORCWA: GPU-accelerated Fourier modal method and gradient-based optimization for metasurface design," Comput. Phys. Commun. 282, 108552 (2023).