Analytic Overlap Integral Computation for Enhanced Multi-waveguide Fourier Coupled-mode Theory

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Coupled mode theory (CMT) [1] computes modal coupling between optical structures as complex networks of optically coupled blocks that are spatially divided. In CMT, the numerical overlap integral method, which is, performed in the process of calculating the mode coupling operator representing the interaction between eigen-modes of each local regions, is expressed as follows.

$$M_{\mu,\nu}^{q,p,\pm} = \int u_z \left[\tilde{E}_\nu^{(p)\pm}(x) \times \tilde{H}_\mu^{*(q)\pm}(x) + \tilde{E}_\mu^{*(q)\pm}(x) \times \tilde{H}_\nu^{(p)\pm}(x) \right] dx , \tag{1}$$

$$H_{\mu,\nu}^{q,p,\pm} = j\omega\varepsilon_0 \int \left(\varepsilon - \varepsilon^{(p)} \right) \tilde{E}_\nu^{(p)\pm}(x) \cdot \tilde{E}_\mu^{*(q)\pm}(x) dx , \tag{2}$$

where M and H denote the excitation efficiency and the mode coupling coefficient between νth mode of pth waveguide and μth mode of the qth waveguide. If the sampling interval of a spatial domain is not small enough, the overlapped accuracy of the integration is greatly reduced. To improve the accuracy of calculations, one approach is to set the x-y sampling intervals very small. However, this leads to geometrically increasing computational costs for the M and H matrices of the mode coupling operator. So, we aim to enhance the accuracy of overlap integrals by analytically solving all process of calculating overlap integrals.

In this research, to analytically compute the overlap integral for Fourier coefficients of eigen-modes in the frequency domain, first, we represent eigen-modes of electric (E) and magnetic (H) fields using Fourier modal analysis [2]. Second, we separated each mode profile for specific regions and set criteria for the integration domain. In the 3D structural analysis, a mode profile for a single local structure within the global domain can be represented by separating it into the internal E and H fields represented by Fourier modal analysis and the four external E and H fields interpreted by free-space propagation model. The process of computing the M and H matrices involves considering scenarios where the modes for the pth and qth local structures are either at the same position or at different positions. In 2D optical structure analysis, we compare the high-order mode coupling operator values obtained through both the analytic and the numerical overlap integral method while gradually reducing the x-axis sampling interval. We confirmed these results indicate that the analytic overlap integral method proposed in this study enhances simulation accuracy.

In conclusion, this research verifies that the analytic overlap integrals method of obtaining the M and H matrices contribute to the enhancement of accuracy in CMT represented Fourier modal analysis. And we present the results of computational accuracy improvement and field variations for 2D and 3D structural analysis simulations by applying the proposed method.

References

1. W. -P. Huang, J. Opt. Soc. Am. A 11, 963-983 **(1994)**.
2. H. Kim, J. Park, and B. Lee, CRC Press **(2012)**.