

$$\begin{aligned}\hat{\varepsilon}_x &= \varepsilon_x (1 - \Delta_x)^{-1} \\ \hat{\varepsilon}_y &= \varepsilon_y (1 - \Delta_y)^{-1},\end{aligned}\tag{10}$$

which account for non-local effects including angular dependence. In Eq. (10),

$$\begin{aligned}\Delta_x &= \frac{1}{12} \delta^2 r^2 (1-r)^2 (\varepsilon_1 - \varepsilon_2)^2 / \varepsilon_x \\ \Delta_y &= \Delta_x \left(\frac{\varepsilon_y^2 \varepsilon_x^2}{\varepsilon_1^2 \varepsilon_2^2} - \alpha^2 (\varepsilon_1^{-1} + \varepsilon_2^{-1})^2 \varepsilon_y^2 / \varepsilon_x \right).\end{aligned}\tag{11}$$

The rest of the analysis closely follows that of the EMT₁ method and is not repeated here.

5.4 Spatial harmonic analysis (SHA) method

The spatial harmonic analysis (SHA) method, also known as the Fourier modal method (FMM) or rigorous coupled wave analysis (RCWA), is one of the most widely used methods based on differential equations for studying the diffraction characteristics of electromagnetic waves in periodic structures. The advantages of SHA are that it is a non-iterative and mesh-free technique for obtaining the exact solution to Maxwell's equations using the Bloch-Floquet formalism. Recent publications show that the SHA method has been successfully used to simulate plasmonic structures and metamaterials [26, 27, 39]. We modeled the multilayer structure with a two-dimensional SHA in a single layer (each layer in the structure is a segment in the model) with arbitrary thickness, and we extracted the dominant eigenmode obtained by SHA. We get the effective dielectric permittivity from the wavevector of the eigenmode. Note that the two-dimensional version of SHA is staged online and is free for public access [40].

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