Shaping Light with an Inclusion: Contribution of Multipoles in Scattering Effect on Waveguide

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Abstract

Spectral multipole resonances of cylindrical inclusion embedded in a waveguide core and excited by guided optical mode are numerically explored. Here, we show that the scattered light can be shaped by means of the cylindrical inclusion filled with air in optical waveguide. A numerical FDTD method is applied for the calculations of the scattering cross sections. The contribution of multipole moments to the scattering effect is analyzed using our reformulation of the semi-analytical multipole decomposition approach.

1. Introduction

The phenomenon of light scattering by small particles is ubiquitous and central to many science and engineering disciplines [1]. Scattering depends largely on the size, shape [2, 3], and refractive index of the particles [4]. Therefore, understanding the electromagnetic scattering is important for characterizing the optical properties of the particle in numerous fields, including terrestrial and planetary remote sensing, biomedicine, engineering, and astrophysics [5]. Despite the fact that scattering effect is widely explored when a particle is illuminated by a plane wave in vacuum, the scattering from the particle when it is illuminated by the guided mode in a waveguide is somehow overlooked. Here, we explore the scattering from the inclusion (particle, index of 1) of cylindrical shape in waveguide core. Figure 1 shows the schematics of the explored system.

2. Light scattered by a particle or inclusion on waveguide

When the particle is illuminated by electromagnetic wave it can be decomposed to mutlipoles and the contribution of multipoles to scattering cross-section can be explored. However, when the particle is replaced by inclusion filled with air and placed on optical waveguide, the currents are not enclosed in the physical boundary of the inclusion anymore. Such a problem can be solved by the Babinet's principle, however here, we followed the classical multipole decomposition formalism and propose the amendments to multi-
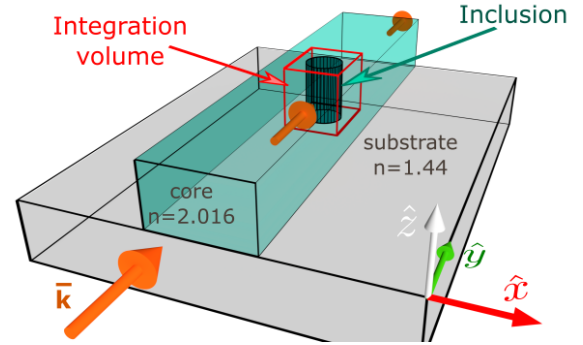

Figure 1: Schematics of the ridge waveguide structure with inclusion of cylindrical shape as deep as the guiding layer and the integration volume of parallelepiped-like shape. Waveguide core index is 2.016 and the substrate index is 1.44.

pole decomposition which allow us to reformulate the scattering cross-section. Any electric and magnetic fields are represented by six quantities. However, only four of them are independent. For this reason, we can describe electric and magnetic fields using four quantities: the scalar and vector potentials. After the derivations we obtain the relation for scattered light intensity (I):

$$
\begin{aligned}
I = {} & \frac{k^4}{12\pi\, v\, \mu\mu_0\, \varepsilon^2\varepsilon_0^2}|\boldsymbol{d}|^2 + \frac{k^2}{12\pi\, v\, \varepsilon^2\varepsilon_0^2}|\boldsymbol{U}|^2 \\
& + \frac{k^6}{32\pi\, v\, \mu\mu_0\, \varepsilon^2\varepsilon_0^2}\left(\frac{1}{5}Q_{ij}Q_{ij}^* - \frac{1}{15}Q_{ii}Q_{jj}^*\right) + \\
& + \frac{k^4}{12\pi\, v\, \varepsilon\varepsilon_0}|\boldsymbol{m}|^2 + \frac{k^4}{32\pi\, v\, \varepsilon\varepsilon_0}\left(\frac{1}{5}U'_{ij}U'^*_{ij} - \frac{1}{15}U'_{ii}U'^*_{jj}\right) + \\
& + \frac{k^8}{288\pi\, v\, \mu\mu_0\, \varepsilon^2\varepsilon_0^2}\left(\frac{8}{105}O_{ijk}O_{ijk}^* - \frac{2}{105}O_{ijj}O_{ikk}^*\right) + \\
& + \frac{k^6}{32\pi\, v\, \varepsilon\varepsilon_0}\left(\frac{1}{5}M_{ij}M_{ij}^* - \frac{1}{15}M_{ii}M_{jj}^*\right) + \\
& + \frac{k^6}{288\pi\, v\, \varepsilon\varepsilon_0}\left(\frac{8}{105}U''_{ijk}U''^*_{ijk} - \frac{2}{105}U''_{ijj}U''^*_{ikk}\right) \quad (1)
\end{aligned}
$$

k is the wave vector in medium ϵ, v is the speed of light in vacuum, μ and μ_0 are magnetic permeabilities in medium and vacuum respectively, ϵ and ϵ_0 are electric permittivities in medium and vacuum respectively, $\boldsymbol{d}$ is the electric dipole, $\boldsymbol{m}$ is the magnetic dipole, U is the first amendment, U' is the second amendment and U'' is the third amendment. Q is the electric quadrupole and O is electric octupole. M is magnetic quadrupole.

3. Results and discussion

Figure 2a shows the inclusion of cylindrical shape embedded in waveguide core and enclosed in Integration volume (red box), extracted from the FDTD model. Figure 2b shows the contribution of multipoles to the scattering cross-section. It appears that the first amendment U' and magnetic dipole $\boldsymbol{m}$ have major contributions to the scattering cross-section. However, the electric dipole, electric quadrupole, electric octupole, second amendment, and third amendment have negligible contribution to the scattering cross-section. In addition, we analyzed the scattering diagrams shown in Figure 3. We observed that for the wavelength of $\lambda = 2\mu m$ the light is predominantly scattered in the forward direction, suppressed in backward direction and also scattered toward the substrate and the superstrate three times stronger compared to the scattering effect at wavelength of of $\lambda = 2.4\mu m$. At wavelength of $\lambda = 3\mu m$ the scattered light is suppressed order of magnitude in direction of the substrate and superstrate, and in direction of the waveguide width.
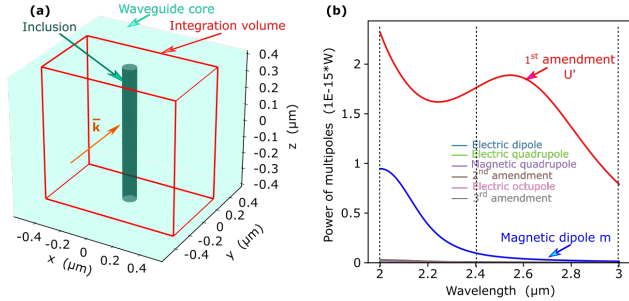

Figure 2: (a) Integration volume (red box) in the waveguide core with the inclusion of cylindrical shape, direction of illumination is indicated by k vector; (b) Contribution of multipoles to the scattering cross-section. Wavelength of $\lambda = 2\mu m, \lambda = 2.4\mu m$ and $\lambda = 3\mu m$ are indicated by the dashed lines.

4. Conclusions

We reformulated the scattering corss-section by introducing amendments. We showed that the scattered light can be shaped by means of the cylindrical inclusion made of air on optical waveguide. Scattering diagrams show that for the wavelength of $\lambda = 2\mu m$ the light is predominantly scattered in the forward direction, suppressed in the backward direction. At wavelength of $\lambda = 2.4\mu m$, the light
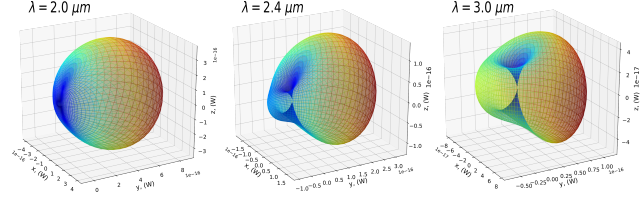

Figure 3: Calculated scattering diagrams for the wavelengths of $\lambda =2$ μm, $\lambda =2.4$ μm, and $\lambda =3\mu$m from the inclusion in the waveguide core as shown in Figure 1.

is scattered toward the substrate and the superstrate thrice stronger compared to the scattering effect at wavelength of $\lambda = 2\mu m$. At wavelength of $\lambda = 3\mu m$ the scattered light is order of magnitude suppressed in direction of the substrate, superstrate and in waveguide width.

Acknowledgment

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