Multipolar Decomposition for Far-field Engineering in Advanced Dielectric Nanostructures

Seung Hyeon Hong, Seokhyeon Hong, Young Soo Kim, Bo Kyung Kim, and Soon-Hong Kwon*
Department of Physics, Chung-Ang University, Korea
**E-mail:shkwon@cau.ac.kr*

Mie resonance phenomena occur when electromagnetic radiation interacts with structures whose dimensions are comparable to the wavelength of the incident light. Various multipolar contributions, namely the electric dipole (ED), magnetic dipole (MD), and higher-order modes, can be engineered to exhibit directional scattering through constructive and destructive interference under specific amplitude and phase conditions. The phase relationship between the ED and MD contributions determines whether the first or second Kerker conditions are satisfied, resulting in zero backward scattering or zero forward scattering, respectively. In contrast, complex scattering phenomena, such as transverse scattering and enhanced forward directivity, require additional higher-order multipolar contributions, including electric quadrupole (EQ) and magnetic quadrupole (MQ) modes[1].

Controlled scattering properties enable the creation of advanced metamaterials, high-efficiency reflectors, precision optical filters, and innovative metalenses[2]. Nevertheless, achieving optimal directional scattering remains challenging because the design of simple structures with precisely controlled multipolar moments presents significant difficulties. Modifications to nanostructure geometry invariably affect all resonant modes simultaneously, thereby rendering the independent control of individual multipolar contributions virtually unattainable in conventional geometries.

To overcome this limitation, we devised a theoretical framework aimed at predicting far-field scattering patterns based on vectorial and tensorial representations of electric and magnetic multipole moments, incorporating both amplitude and phase information even for complex structural geometries. Our methodology enables the decomposition and independent examination of the far-field intensity contributions from distinct multipolar components. Using this methodology, we can systematically engineer structures that satisfy the specified scattering criteria, including various Kerker conditions and complex directional scattering patterns. This approach presents potential advantages for the development of optical functionalities through innovative design strategies, thereby potentially broadening the opportunities for applications in optical filtering, directional scattering, and photonic devices.

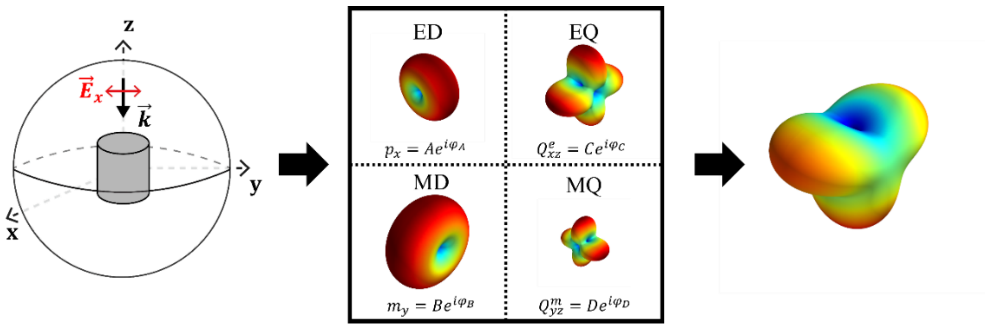

Figure. 1. Multipolar decomposition showing how electromagnetic scattering from a nanostructure can be represented through individual ED, MD, EQ, and MQ contributions (with their corresponding amplitude and phase parameters), which superpose to form the complete far-field scattering pattern.

References

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2. L. Wenwei et. al., "Dielectric Resonance-Based Optical Metasurfaces: From Fundamentals to Applications", iScience., 23(12), Nov 2020