Light Propagation in Time-Varying Environments using a Multipolar Multiple Scattering Method

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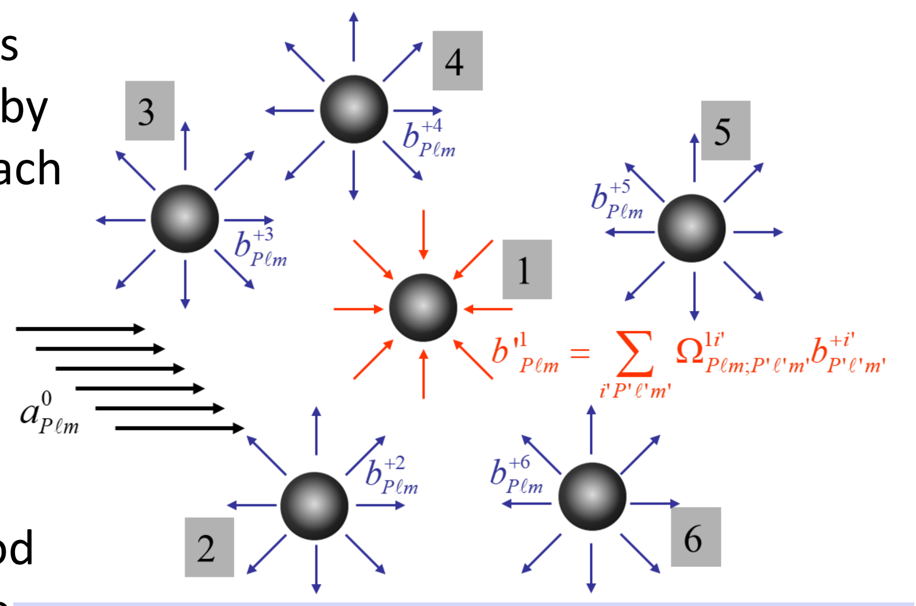
Introduction

Understanding light propagation in time-varying environments can lead to new ways to manipulate light. Using time-varying photonic structures it is possible to achieve optical responses like frequency conversion, optical isolation, parametric amplification, temporal cloaking, breaking of Lorentz reciprocity, and many others. We recently developed a dynamical multiple scattering method for the solution of Maxwell’s equations in time-varying environments and, specifically, in layered structures that consist of two-dimensional periodic arrays of scatterers. Moreover we have considered the scattering from a single dielectric sphere with time-varying permittivity[1] or radius[2]. The generalization of multiple scattering theory offers very interesting possibilities to study novel optical phenomena in metasurfaces and photonic crystals. The method is very efficient and enables physical insight, since the scattering properties can be easily assigned to the optical response of the individual particles.

[1] I Stefanou, P.A. Pantazopoulos, N. Stefanou, Light scattering by a spherical particle with a time-periodic refractive index. JOSA B 38 (2), 407-414, (2021).
[2] E. Panagiotidis, E. Almpanis, N. Papanikolaou, N. Stefanou Inelastic light scattering from a dielectric sphere with a time-varying radius Phys. Rev. A 106 (1), 013524, (2022).

Layer Multiple Scattering (LMS) Method

The method solves the Maxwell’s equations for arrays of particles by describing the scattering from each particle and then connecting all scattering events through the multiple scattering equations.



For time varying scatterers in a fixed lattice, the LMS method is generalized by introducing the dynamic T-matrix that mixes the frequency channels.

$$b^{+i}_{P\ell m} = T^{i}_{P\ell}\left(a^{0i}_{P\ell m} + b'^{i}_{P\ell m}\right)$$

$$\sum_{i'P'\ell'm'}\left[\delta_{ii'}\delta_{PP'}\delta_{\ell\ell'}\delta_{mm'} - T^{i}_{P\ell}\Omega^{ii'}_{P\ell m;P'\ell'm'}\right]b^{+i'}_{P'\ell'm'} = T^{i}_{P\ell}a^{0i}_{P\ell m}$$

The Dynamic LMS is semianalytical and fast, (few seconds on a laptop), and allows the efficient design of dynamic metasurfaces

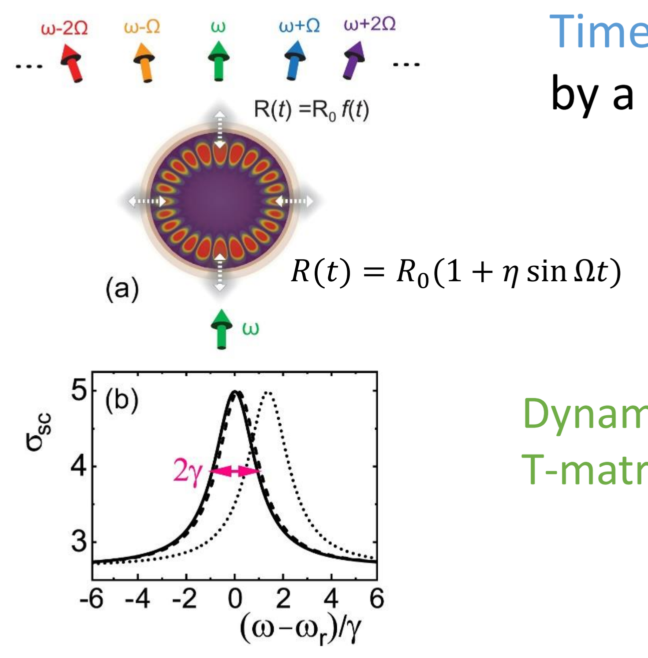
Spherical expansion of the EM field, Mie theory

$$\boldsymbol{E}^{0}(\boldsymbol{r}) = \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell}\frac{i}{k}a^{0}_{E\ell m}\nabla\times j_\ell(kr)\boldsymbol{X}_{\ell m}(\hat{\boldsymbol{r}}) + \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell}\frac{i}{k}a^{0}_{H\ell m}\,j_\ell(kr)\boldsymbol{X}_{\ell m}(\hat{\boldsymbol{r}})$$

$$\boldsymbol{E}^{sc}(\boldsymbol{r}) = \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell}\frac{i}{k}a^{+}_{E\ell m}\nabla\times h_\ell(kr)\boldsymbol{X}_{\ell m}(\hat{\boldsymbol{r}}) + \sum_{\ell=1}^{\infty}\sum_{m=-\ell}^{\ell}\frac{i}{k}a^{+}_{H\ell m}\,h_\ell(kr)\boldsymbol{X}_{\ell m}(\hat{\boldsymbol{r}})$$

Scattering T-matrix: $a^{+}_{P\ell m} = T_{P\ell}a^{0}_{P\ell m}$

Light scattering by a single time varying sphere



Time-Floquet analysis of the scattering by a particle with time varying radius

$$E(r,t) = \sum_{n=-\infty}^{\infty}\mathrm{Re}[E^{(n)}(\mathrm{r})\exp(-\mathrm{i}\omega_n \mathrm{t})]$$

$$\omega_n = \omega - n\Omega, n = 0, \pm1, \pm2 \ldots$$

Dynamic scattering T-matrix

$$a^{+(n)}_{P\ell m} = \sum_{n'} T^{nn'}_{P\ell}\, a^{0(n')}_{P\ell m}$$

Scattering and Absorption cross sections

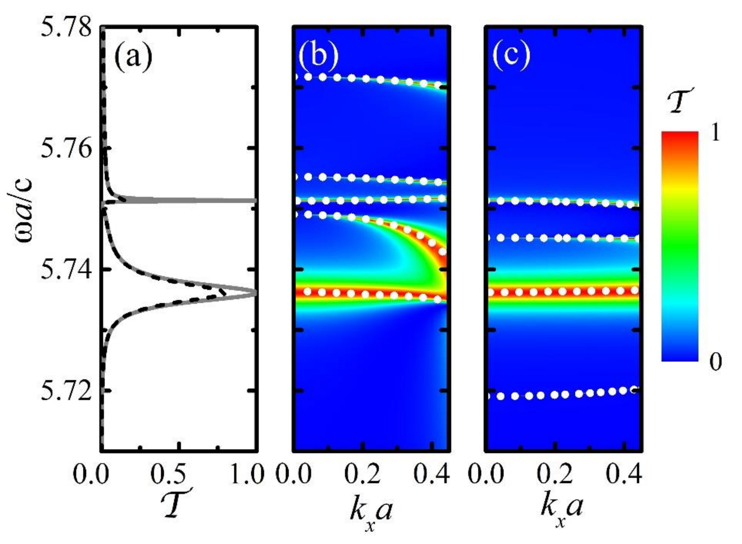
$$\sigma_{sc} = \sum_{n=-N}^{N}\frac{2}{(k_nR_0)^2}\sum_{P\ell}(2\ell+1)\left|T^{n0}_{P\ell}\right|^2$$

$$\sigma_{abs} = -\sum_{n=-N}^{N}\frac{2}{(k_nR_0)^2}\sum_{P\ell}(2\ell+1)\{\left|T^{n0}_{P\ell}\right|^2 + Re(T^{n0}_{P\ell})\,\delta_{n0}\}$$

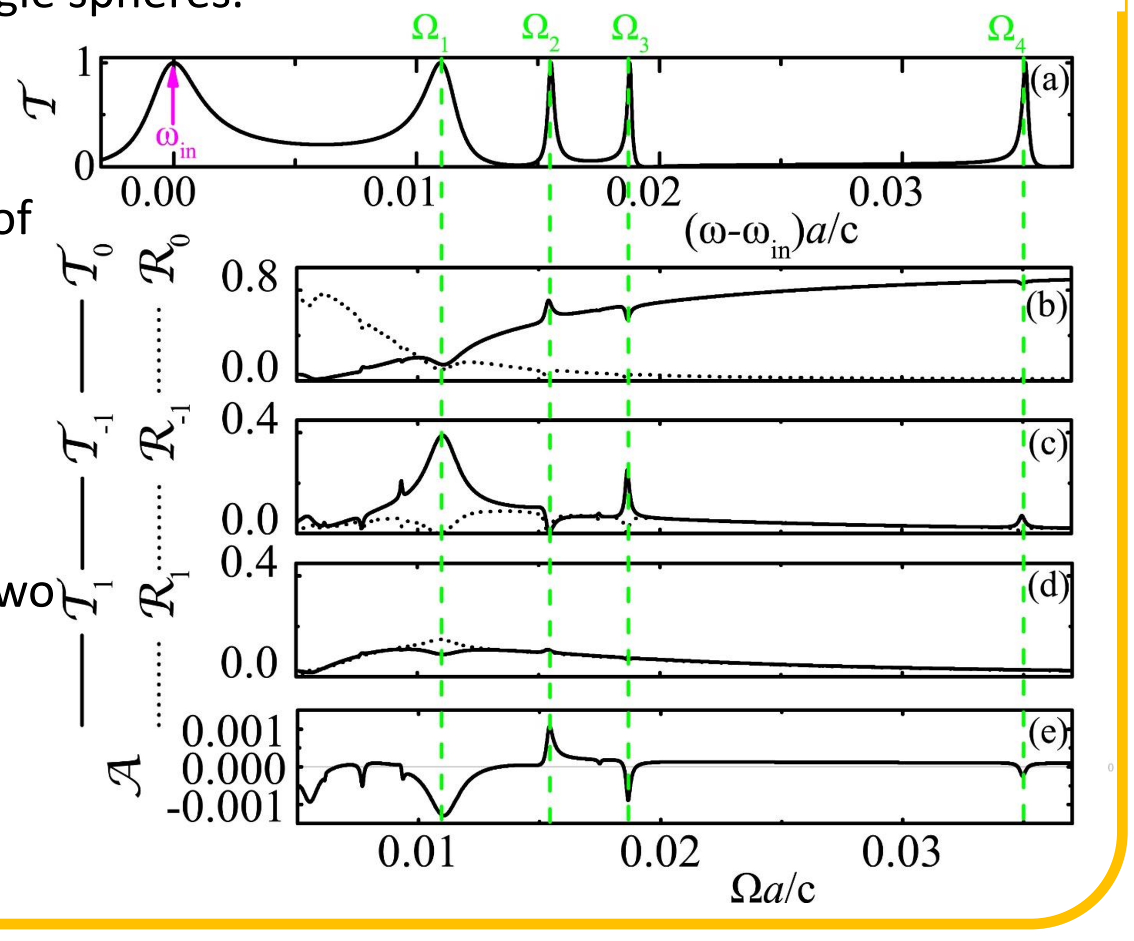
For slow temporal variations $\Omega \rightarrow 0$ the quasistatic adiabatic approximation that considers snapshots as the particle varies, is valid, but overestimates the phenomena

Monolayer of dynamic dielectric spheres

Square lattice with lattice constant a of spheres with radius, $R=0.4a$ with varying permittivity: $\varepsilon(t) = \varepsilon_0[1+\sin(\Omega t)], \varepsilon_0 = 12$



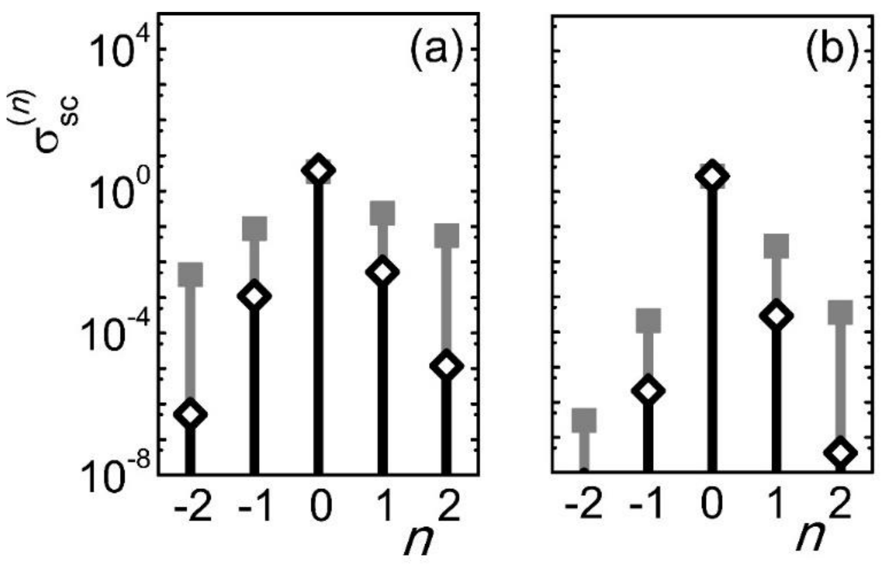
The transmission spectrum shows many resonances and bound states in the continuum due to the Mie resonances of the single spheres.



Fourier components of transmission and reflection.

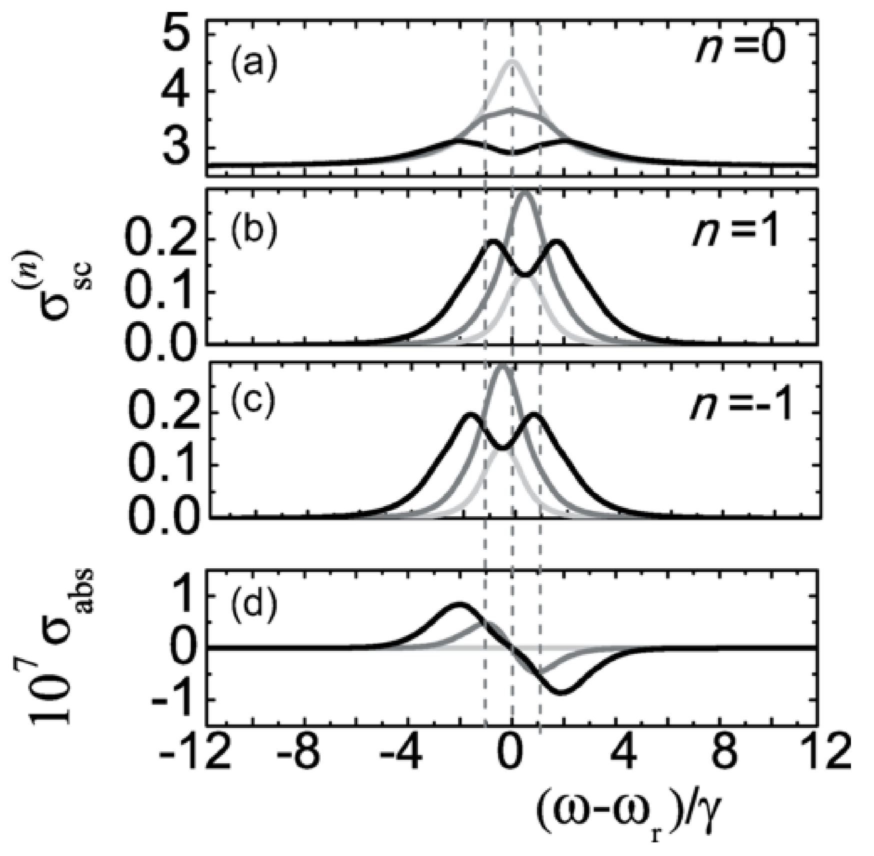
Resonances appear when Ω matches the difference between two resonances.

Scattering cross section of a Si sphere with time varying radius $R(t) = R_0[1+\eta\cos(\Omega t)]$



Fourier components
(a) Incoming light frequency $\omega = \omega_r + \gamma$ and $\Omega = \gamma$.
(b) $\omega = \omega_r + 6\gamma$ and $\Omega = 6\gamma$.

open symbols $\eta = 10^{-10}$
filled squares $\eta = 10^{-9}$.



Fourier components of the optical scattering and absorption cross section, for the first-order TE$_{\ell=12}$ Mie resonance

$\Omega = \gamma$

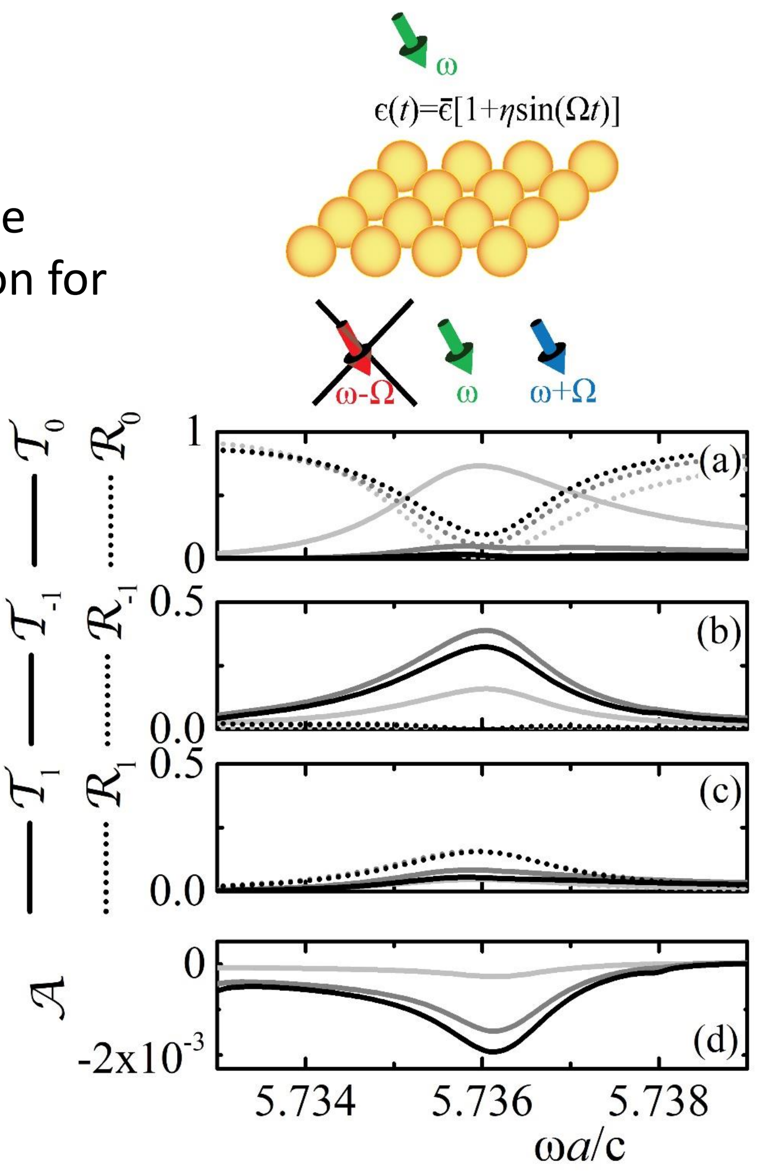
For vibration amplitudes:
$\eta = 5\times10^{-10}$ (light gray line)
$\eta = 10^{-9}$ (gray line)
$\eta = 2\times10^{-9}$ (black line).

The problem of the optical response of the dielectric sphere with a periodically time-varying radius, is equivalent to that of an oscillator with a time-varying eigenfrequency.

E. P. was supported for this research, which is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme “Human Resources Development, Education and Lifelong Learning” in the context of the project “Strengthening Human Resources Research Potential via Doctorate Research” (MIS- 5000432), implemented by the State Scholarships Foundation (IKY).

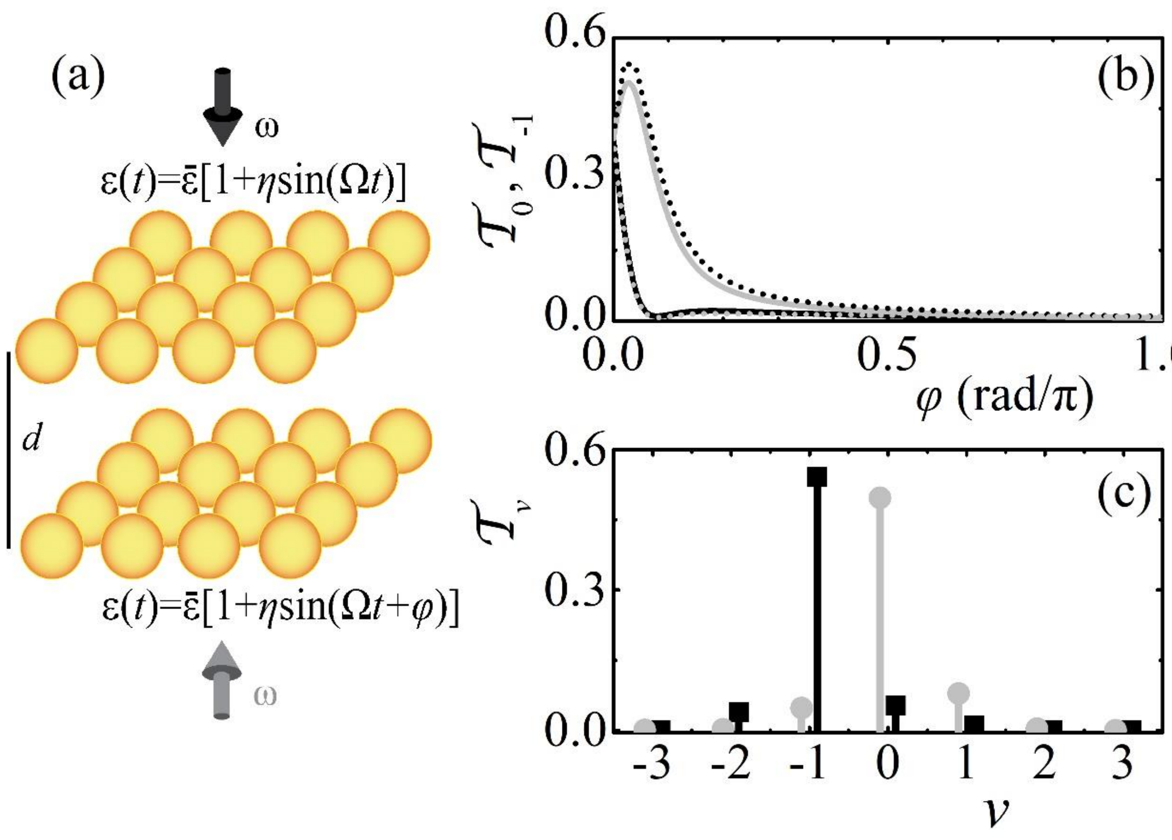
Non reciprocal metasurfaces

Frequency up conversion.
Triple resonance transitions.
Dependence on the strength of the oscillation η. Requires optimization for optimum upconversion efficiency.



Transmission and reflection components for fixed incoming light frequency ω, vs Ω.

When Ω is equal to the difference between two resonances, strong frequency conversion occurs, while the Stokes component is suppressed



Non reciprocal transmission is achieved with two layers where the $\varepsilon(t)$ oscillates with a phase shift between them.