Generalized Kerker effect in dielectric antennas for enhanced backscattering modulation

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Abstract. Enhancement of electromagnetic signal modulation is one of the key problems for modern contactless communication systems. Using resonance effects allows to achieve significant interaction between an electromagnetic wave and matter of an antenna, providing opportunity to control scattering. This work demonstrates efficiency of multipole engineering based on Mie theory for dielectric core-shell antennas, particularly we show that generalized Kerker effect is a useful tool for backscattering modulation magnification. Our approach allows to manipulate scattering properties of devices without increasing their size by using all-dielectric concept.

1. Introduction
The modulation of an electromagnetic signal determines the quality of wireless communication systems, which have a broad range of applications: submarine communications [1-2], optical communications [3], frontier space missions [4], etc. To narrow our problem, we focus on radio-frequency identification (RFID) applications, widely used in automated tracking, on-site inspection support systems, location of buried assets [5].

Resonance phenomena can be employed to enhance interaction between an electromagnetic wave and antenna. Single-resonant antennas have a significant drawback described by Chu-Harrington limit [6]: size reduction leads to the drop in operational bandwidth. A possible solution is to work with multi-resonant systems. To save the subwavelength scale of a structure, high permittivity dielectric materials should be used for device production. This method is linked to the concept of dielectric resonant antennas, which allows to decrease the size of a device without a significant bandwidth degradation [7-8].
2. Backscattering modulation enhancement in RFID applications

The quality of communication channel is determined by the power modulation of the signal scattered by an antenna in the direction of a reader [9]:

$$\Delta P_{RCS} = \frac{P_r \lambda^2 G_r^2 \Delta \sigma_{back}}{(4\pi)^3 r^4} \quad (1)$$

where $P_r$ is power of the signal transmitted by a reader, $\lambda$ is wavelength, $G_r$ is gain of a reader, $r$ is distance between antenna and reader, and $\Delta \sigma_{back}$ is backscattering modulation. All parameters are fixed for the certain application except $\Delta \sigma_{back}$, which becomes a key parameter for optimization. Backscattering modulation is given by the difference between backscattering cross-sections of an antenna in two states maintained by a system:

$$\Delta \sigma_{back} = \sigma_{back}^{max} - \sigma_{back}^{min} \quad (2)$$

To increase this difference we implement a multipole engineering approach by controlling interference between resonances supported by an antenna. Fig. 1 presents the conceptual model of the antenna, which consists of the dielectric core with a wrapped split-ring resonator (SRR) and the shell supporting magnetic dipole (MD) and magnetic quadrupole (MQ) resonances, respectively. Core-shell geometry is chosen to apply Mie theory that provides a rigorous analytical solution to scattering problem on the sphere.

![Figure 1](image)

**Figure 1.** (a) A core-shell structure. Radius of core is 5.5 mm and inner and outer radiuses of the shell are 13.5 mm and 39.5 mm. (b) Principle of operation - magnetic quadrupole resonance in a shell, magnetic dipole in a core. The dipolar resonance is controlled by an impedance of a split ring resonator, wrapped around the sphere. (c) Modulation of radiation pattern for two states.

3. Multipole engineering with Mie theory

At the first step we consider a dielectric spherical particle consisting of the core with radius of 5.5 mm and shell with radius of 39.5 mm separated by an air layer with thickness of 8 mm.
According to Mie theory scattering and backscattering efficiencies are given as the following [10]:

\[ Q_{sca} = \frac{2}{\chi_l^2} \sum_{n=1}^{\infty} (2n + 1)(|a_n|^2 + |b_n|^2) \]  

(3)

\[ Q_{bk} = \frac{1}{\chi_l^2} \sum_{n=1}^{\infty} (2n + 1)(-1)^n(a_n - b_n)^2 \]  

(4)

where \( Q_{sca} \) is scattering efficiency, \( Q_{bk} \) - backscattering efficiency, \( \chi_l = \frac{\pi d}{\lambda} \) is size parameter (\( d \) - diameter of the particle), \( n \) - multipole order, and \( a_n \) and \( b_n \) are scattering Mie coefficients. Implementation of these calculations is performed in PYTHON and results are shown in fig.2. There is a set of color maps, demonstrating the scattering efficiencies as functions of the system parameters. Permittivity of the core and shell are the subject for optimization. The operational frequency is chosen to be 900 MHz, consistently with RFID standards. Here we consider both lossless and lossy systems. The ranges of permittivity values are 33-49 and 900-930 for the shell and core, respectively. The loss tangent of the materials is taken to be \( \tan \delta = 5 \times 10^{-4} \), consistently with the experimental data reported [11]. The total and backscattering efficiencies are plotted on the maps, and the evolution of resonances is clearly seen. At the crossing of MD and MQ highlighted by a dashed rectangle in fig.2(c) one can observe the highest jump in the backscattering efficiency with a small change of the core permittivity. It corresponds to the different regimes of interference between MD and MQ in frame of generalized Kerker effect. This effect is valid for the lossy system in fig.2(d), which allows to take the MD-MQ intersection as a work point.

![Figure 2. Scattering cross-section colormaps. Total scattering cross-section efficiencies for (a) lossless case, (b) lossy case. Backward scattering cross-section efficiencies for (c) lossless case, (d) lossy case.](image)

4. Resonant antenna with an integrated circuit

The approach discussed is based on permittivity changing of the core, which is inapplicable to current devices. To make our model more practical, we introduce a metallic ring wrapped around the core as an integrated circuit (IC). This ring has a gap to maintain two states: open (state 1) and closed (short, state 2). Switching between these two states is equivalent to changing of the permittivity in the theoretical model.
Numerical calculations of backward cross-section efficiency are performed in CST Microwave Studio and presented in fig.3. The contribution of MD, MQ and ED is observed, and from the plotted difference between open and short states (yellow line) it is clearly seen, that the combination of MD and MQ is the most sensitive to switching between the states.

Figure 3. (a) Backscattering spectrum for open and short states and difference between states. (b) Magnetic near field maps - absolute values

Magnetic field amplitudes are calculated and shown in fig.3(b) to demonstrate the dependence of far-field changes on the inductive near-field coupling at the inner volume of the antenna. Two characteristic frequencies equal to 896 MHz and 901 MHz are chosen. At the first one the backscattering modulation achieves its maximal value. Now, it is obvious - the higher the field localization in the core is, the less energy is scattered in the far-field, and this localization is controlled by IC responsible for the switching mechanism.

Remarkable that the model with IC demonstrates less backscattering efficiency than the theoretical model. This effect is linked to the presence of SRR, which decreases the quality factor of MD resonance of the core.

5. Conclusion
We have applied the multipole engineering approach based on Mie theory to the enhancement backscattering modulation problem. Generalized Kerker effect is demonstrated on the dielectric core-shell antenna. We have shown that interference between higher-order resonances provides an increase of backscattering modulation efficiency, and this enhancement takes place for the lossy antenna model with SRR. The presented method allows to develop wireless communication system models, which demonstrate high efficiency without increasing the device size.

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