Multipole engineering for enhanced backscattering modulation

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An efficient modulation of backscattered energy is one of the key requirements for enabling efficient wireless communication channels. Typical architectures, based on either electronically or mechanically modulated reflectors, cannot be downscaled to subwavelength dimensions by design. Here we show that integrating high-index dielectric materials with tunable subwavelength resonators allows one to achieve an efficient backscattering modulation, keeping a footprint of an entire structure small. An interference between high-order Mie resonances leads to either enhancement or suppression of the backscattering, depending on a control parameter. In particular, a ceramic core shell, driven by an electronically tunable split-ring resonator, was shown to provide a backscattering modulation depth as high as tens of the geometrical cross section of the structure. The design was optimized toward maximizing the reading range of radio-frequency identification tags and shown to outperform existing commercial solutions by orders of magnitude in terms of the modulation efficiency. The proposed concept of multipole engineering allows one to design miniature beacons and modulators for wireless communication needs and other relevant applications.

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I. INTRODUCTION

The modulation of electromagnetic signals is a cornerstone for enabling a vast majority of modern communication systems. Information is typically encoded by imposing amplitude and phase temporal changes on a carrier wave. Specific application requirements dictate critical parameters, such as the carrier frequency and the bandwidth, essential to ensure a sufficient level of transmitted energy and information capacity of a channel. Carrier frequencies can be as small as several hertz (e.g., for submarine communications [1,2]) and grow up to hundreds of terahertz in optical communications [3] and even further toward x rays to serve frontier space missions [4]. While numerous modulator architectures have been developed to serve the above-mentioned needs, they all share the same property—a relatively bulky footprint with respect to the central operational wavelength [5]. The physical reason here relies on the essence of electromagnetic field interactions with matter. To impose a significant phase shift on a propagating wave, an interaction length should prevail a distance over a wavelength. For example, typical telecommunication optoelectronic modulators, based on Mach-Zehnder interferometer architecture, are as big as several millimeters [6].

To achieve a significant interaction between waves and matter in a small volume, resonant phenomena should be employed. Theoretically, a π shift can be achieved via an interaction with a high-quality factor resonator by tuning its resonant frequency around the carrier one. This single resonance approach has an immediate drawback, tightly related to the well-known Chu-Harrington limit [7], which predicts a significant drop in an operational bandwidth with a device footprint reduction. An overview of the previously mentioned constraints indicates that obtaining a significant phase and amplitude modulation within a small interaction volume without a significant bandwidth degradation is a challenging task, which requires development of alternative theoretical and experimental approaches. A possible solution to the problem is to employ multiple resonances in a small structure, as we will show hereinafter.

To obtain a resonant response in a subwavelength structure, the latter should be made of a material with high permittivity (we will put localized plasmon resonance phenomena aside) [8,9]. The concept of dielectric resonant antennas (DRAs) has been developed in the radio physics community and was found to be beneficial in cases, where, e.g., size reduction without a significant bandwidth degradation or sustainability to high radiated power are needed [10,11]. Typically, high-quality ceramics are used in those applications [12,13]. Ceramic composites can have electric permittivity as high as hundreds and thousands without exhibiting significant Ohmic losses. Recently, the concept of resonance engineering in high-index dielectric materials has been pursued. For example, all-dielectric nanoantennas and metasurfaces have contributed to the tailoring of light-matter interaction on a nanoscale [14]. A vast majority of designs are based on controlling electric and magnetic Mie resonances in spheres, cylinders, and other shapes, which can be accurately fabricated from semiconductor wafers using different lithographic techniques.
or workshop postprocessing in the case of centimeter-scale devices [15–18].

While quite a few different applications of all-dielectric electromagnetism (i.e., DRAs and nanophotonics) have been discussed [13,19], here we will concentrate on a relatively new aspect, which has both fundamental and applied sides. The well-known examples here include friend or foe transponders, marine radar reflectors, radio-frequency identification (RFID), and many others. The design of beacons with a small footprint is the challenge, which will be addressed here. To make the report less abstract and more applied, we will focus on RFID applications.

II. MAXIMIZATION OF BACKSCATTERING MODULATION FOR RFID APPLICATIONS

Since different terminologies might be in use while discussing scattering cross sections, hereinafter we will align with classical electromagnetic definitions. The differential cross section is defined as the ratio of the scattered power in a given direction to the incident wave energy flux. Further, in the paper, backward cross section would mean the differential scattering cross section in the backward direction. The backscattering modulation, on the other hand, is the difference between differential cross sections in the backward direction, obtained for two different states of a system. It is worth noting that backscattering modulation is a key parameter in applications, where beaconlike devices are in use.

RFID is a widely used form of wireless communication that is based on a time-modulated scattered electromagnetic wave (or electrostatic coupling), which uniquely identifies an object [20]. A typical RFID system consists of passive tags and an active reader, which trigger tags using an interrogating electromagnetic pulse. The readout of digital data is performed by analyzing time-modulated backscattered signals. High-frequency RFID systems operate at 860–960 MHz bands, making free-space propagation mechanisms to govern the physics of the communication channel. This far-field approximation is even better justified in cases when long-range readout is required. Typical distances, considered as a long range, are several meters and can reach 20–30 m and higher if state-of-the-art equipment and antenna design are employed. [21,22] The key parameters, capable of extending the readout range of a tag, are a load factor and modulation efficiency [23]. The first one is related to energy harvesting of the tag’s electronics, while the second is capable of establishing an efficient communication channel—the previously discussed beacon application. In a monostatic regime, where a single interrogating antenna is used, the power modulation of the backscattered signal is given by a radar equation as follows [23]:

\[ \Delta p_{\text{RCS}} = \frac{P_r \lambda^2 G_t^2 \Delta \sigma_{\text{back}}}{(4\pi)^2 r^4}, \]  

where \( P_r \) is the power transmitted by a reader, \( G_t \) is the gain of the reader’s antenna, \( r \) is the distance from the reader to the tag, \( \lambda \) is the carrier’s wavelength, and \( \Delta \sigma_{\text{back}} \) is the backscattering modulation. Two states of the system, in this case, correspond to the internal impedance of an integrated circuit (IC), which is plugged within a tag. While two states of real RFID chip have their own complex-valued impedances, typically provided by a vendor, we will use a commonly used notation on an open and short circuit. This approach allows one to make an analysis which is not IC specific. Now, since the value of \( (P_r + G_t) \) in dBm cannot exceed 36 dBm (4 W of equivalent isotropically radiated power) according to international regulations, \( \Delta \sigma_{\text{back}} \) becomes the key parameter for optimization. Typically, RFID communication protocols are based on amplitude-shift keying (ASK) and, hence, both minimal and maximal values of backward cross section are important to maintain a robust continuous communication [24].

Furthermore, an additional valuable property is anisotropy of a readout scenario. Standard RFID systems, based on dipolelike antenna tags, suffer from a polarization mismatch—a misalignment of the tag’s orientation with respect to the reader’s antenna, which results in the readout distance drop. Creating isotropic beacons is an additional important task, which allows addressing this issue. Having in mind those general requirements, we will develop an approach based on multimode interference within small high-index resonators.

To maximize the backscattering modulation, we will explore interference between multipoles (Mie resonances) [25], providing the efficient directive scattering. The most noticeable example of the scattering manipulation via multipole interference is the Kerker effect, which is based on an interplay between electric and magnetic dipoles. Initially, it was proposed to suppress the backscattering [26]. Today this effect has been realized in many different geometries and was generalized to include interference between higher-order multipoles [27]. Here, we will explore a core-shell geometry, optimizing it towards providing a maximized backscattering modulation.

Figure 1 demonstrates the conceptual design of the resonator—a spherical ceramic core and a shell, separated by a transparent (e.g., air) layer. The spherical shape allows each resonance of the structure (Mie resonance) to be associated with a single multipole (dipole, quadrupole, etc.). It is worth...
noting that multipole mixing in structures, which do not obey spherical symmetry, complicates the analysis [28]. Here, the magnetic dipole and magnetic quadrupole were designed to resonate at nearly the same frequency [Fig. 1(b)].

Consideration of the spherical particle allows one to take advantage of analytical Mie solutions and perform a computationally efficient parametric study over quite large search space. In order to demonstrate tuning capability, we first change the core’s permittivity, which leads to shifting of its magnetic dipole resonance and allows one to control the scattering direction. Obviously, this theoretical model does not reflect the reality. Nevertheless, it will underline the principle of maximization of the backscattering modulation. An alternative and practical way to shift resonant frequency is to introduce an electronic switch. Our implementation here will employ a split-ring resonator (SRR), switched between open or short circuit states [see Figs. 1(b) and 1(c)]. In commercial RFID applications, the switch is replaced with an IC, which has a vendor-defined internal impedance, subject to a protocol-based modulation scheme.

III. MULTIPOLe ENGINEERING OF BACKSCATTERING MODULATION WITH MIE THEORY

Relatively high values of the core’s permittivity allow the resonances of the core and shell to be manipulated independently, as a first approximation. Exact Mie solutions exist for spherically symmetric structures [29]. Figure 2 shows color maps of the scattering cross-section efficiency as a function of the system’s parameters. The permittivities of the core and the shell are subject to the optimization. The operational frequency was chosen to be 900 MHz, consistent with RFID standards (EPCGEN2 UHF RFID band is 860–960 MHz) [24]. Other parameters are as follows: the core’s radius \( r_{\text{core}} = 5.5 \text{ mm} \) and inner and outer radii of the shell, \( r_{\text{inner}} = 13.5 \text{ mm} \) and \( r_{\text{outer}} = 39.5 \text{ mm} \) (there is an 8-mm-wide air layer between the core and the shell). Those numbers were chosen to provide magnetic dipole (MD), magnetic quadrupole (MQ), and electric dipole (ED) resonances of the standalone structures (the shell and the core) in the range of achievable parameters. Mixing powders of high-quality ceramics allows one to obtain moderately high values of relative permittivity. The ranges considered in the analysis are \( \varepsilon_{\text{shell}} = 33 - 49 \) and \( \varepsilon_{\text{core}} = 900 - 930 \). The loss tangent of the materials was taken to be \( \tan \delta = 5 \times 10^{-4} \), consistent with reported experimental data [30].

The total and backward scattering cross-section efficiencies for both lossless and lossy cases appear in Figs. 2(a)–2(d), where the evolution of resonant branches can be clearly seen. These quantities, normalized to the geometrical cross section of the structure, are given by [31]

\[
Q_{\text{sca}} = \frac{\lambda^2}{2\pi r^2} \sum_{n=1}^{\infty} (2n + 1)(|a_n|^2 + |b_n|^2), \quad (2)
\]

\[
Q_{\text{back}} = \frac{\lambda^2}{2\pi r^2} \left| \sum_{n=1}^{\infty} (2n + 1)(-1)^n(a_n - b_n) \right|^2, \quad (3)
\]

where \( Q_{\text{sca}} \) and \( Q_{\text{back}} \) are total and backward scattering efficiencies, \( \lambda \) is the wavelength, \( r \) is the particle’s radius, \( n \) is an order of the corresponding Mie resonance, and \( a_n \) and \( b_n \) are scattering Mie coefficients. The semianalytical calculations are performed with PYTHON, where Mie coefficients are found with the scattering-matrix approach [31].

The most interesting points correspond to the intersection of modes, e.g., ED-MD and MQ-MD. The values on the color
FIG. 3. Backward cross-section efficiency spectra depending on refractive index of core sphere. The refractive index of the shell is constant. Inset: Radiation pattern of core-shell structure in the points of maximal and minimal values of backward cross-section efficiency.

maps are normalized to the geometrical cross section [i.e., \( \pi (r_{\text{outer}}^2) \)] of the structure and, hence, represent the scattering efficiencies. It is worth noting that the backward scattering efficiency can be as high as 62 (45) in lossless (lossy) cases, which is beneficial for establishing an efficient communication channel with miniature (\( \sim \lambda /10 \)) backscatterers.

The most interesting region of parameters for an efficient backscattering modulation is highlighted with a white dashed rectangle in Fig. 2(c). The destructive interference between \( MQ \) and \( MD \) leads to the suppression of the backscattering. However, a minor change in the core’s permittivity results in a jump of the backscattered signal—this is the key point for an efficient backscattering modulation, which will be analyzed in detail next. It is also worth noting that losses do not cause significant degradation of the effect. \( \Delta \sigma_{\text{back}} \) reaches values of 41 (26) geometrical cross sections for lossless (lossy) cases.

To highlight the tuning capability, Fig. 2(d) is sliced along the \( MQ \) branch. The shell’s permittivity in this case is \( \varepsilon_{\text{shell}} = 36.61 + 0.01i \). The backscattering efficiency is then plotted as the function of the core’s permittivity (Fig. 3). The insets in the figure indicate the far-field scattering diagrams, demonstrating that only 0.5% permittivity tuning leads to \( \Delta \sigma_{\text{back}} \) of about 26 geometrical cross sections. It is worth noting that the backscattering does not vanish and remains relatively high, which might be beneficial for the ASK communication protocol.

IV. BACKSCATTERING MODULATION WITH AN INTEGRATED CIRCUIT

While in the previously considered theoretical model the resonance frequency is controlled by changing the permittivity of the inner sphere, this approach is not practical from the implementation standpoint. To shift magnetic dipolar resonance of the core we will introduce a split-ring resonator (SRR), wrapped around the inner sphere. An IC is plugged within the SRR’s gap. Commercial RFID ICs typically have complex impedances in modulation states and may vary from vendor to vendor. To make the model general, we will assume the modulation between an open and short circuit. The layout of the device appears in Fig. 1—the SRR is inductively coupled to the inner sphere and, as a result, the backscattering strongly depends on the IC’s state.

To analyze and optimize the reperformance of the structure we made a full-wave numerical simulation in CST MICROWAVE STUDIO using the frequency-domain solver. The same

FIG. 4. (a) Backward cross-section efficiency spectra for an open circuit (blue curve), short circuit (red curve), and the difference between the states (orange curve). \( MD, MQ, \) and \( ED \) are the multipoles contributing to the peaks. (b) Magnetic near-field maps—normalized absolute values. Integrated circuit states and frequencies are indicated on the plot.
geometrical parameters as in the theoretical model have been used: \( r_{\text{core}} = 5.5 \text{ mm}; \) \( r_{\text{core}} = 898 \) \( (\tan \delta = 5 \times 10^{-4}) \). The SRR is made of a copper wire (with losses): \( r_{\text{ring}} = 6 \text{ mm} \); the wire’s diameter \( d_{\text{wire}} = 1 \text{ mm} \). The ring has two gaps: one of them is functionalized with the IC; the second one \( (w_{\text{gap}} = 0.02 \text{ mm}) \) remains open to tune the SRR’s impedance for the effective inductive coupling with the core sphere. The shell properties are \( r_{\text{shell}}^{\text{inner}} = 13.5 \text{ mm}, \) \( r_{\text{shell}}^{\text{outer}} = 39.5 \text{ mm}, \) and \( \varepsilon_{\text{shell}} = 35.7 \). The structure is excited by a plane wave [see Fig. 1(a) for the configuration].

The numerically calculated backward cross-section efficiency for the two states of the IC are shown in Fig. 4(a). The contribution of \( MD, MQ, \) and \( ED \) multipoles to the backscattering can be clearly identified. It can be seen that the combination of \( MD \) and \( MQ \) is most sensitive to the IC’s state. The theoretical model also predicted that small perturbations will mainly affect the intersection of the \( MQ \) and \( MD \) branches. The difference between the backward cross sections [orange curve in Fig. 4(a)] reaches the absolute value of 12. Also, the backscattering does not vanish in either state, similar to the theoretical case.

In order to link the far-field changes with the inductive near-field coupling at the inner volume of the structure, magnetic field amplitudes were calculated for both states of the IC and at two characteristic frequencies, namely, \( f = 901 \text{ MHz} \) and \( 896 \text{ MHz} \) [see Fig. 4(b)]. At the latter frequency, the backscattering modulation reaches maximal value. The switching mechanism can be clearly seen now. The state of the IC controls the field localization in the core—the higher field localization is, the less energy is scattered to the far field. This mechanism links the field localization strength with the sign of the backscattering modulation.

It can be seen that values of backward scattering cross-section efficiency in the considered case are less than in the theoretical model. This effect is explained by the fact that the presence of SRR decreases the quality factor of the core’s dipolar resonance.

Finally, the modulation efficiency degradation is assessed versus an introduction of all loss channels. Figure 5 demonstrates the far-field scattering diagrams (H plane) for both states of the IC in the case both ceramic elements and the SRR are made of lossless materials (the SRR is made of a perfect electric conductor). Dotted lines correspond to the lossy ceramics and copper as the SRR’s material. The backscattering modulation efficiency is 21 and 12 geometrical cross sections in lossless and lossy cases, correspondingly. It means that no significant degradation occurs, and the concept can be implemented in real-life scenarios. It is also worth noting that at \( f = 896 \text{ MHz} \) (the frequency for which Fig. 5 was plotted), the open circuit state corresponds to almost complete suppression of \( MD \) and \( MQ \) and the scattering is governed by \( ED \); as a result, the losses at a given frequency have minimal influence (the black and red curves overlap at the current scale).

FIG. 5. Normalized radiation patterns in linear scale, polar plots (H-field planes).

The scattering diagrams almost perfectly resemble the dipolar pattern, confirming the proposed analysis of the interaction dynamics.

V. CONCLUSION

The problem of backscattering modulation maximization was considered and applied to boost efficiencies of passive RFID communication channels. Multipole engineering, resembling a generalized Kerker approach for scattering management, have been developed and applied on a core-shell geometry. It was shown that the backscattering suppression, typically targeted in Kerker-related problems, is a less efficient approach to follow in order to achieve an enhanced backscattering modulation efficiency. On the other hand, controlling interference between higher-order multipoles is a preferable route. This concept was shown to provide a modulation efficiency of 21 geometrical cross sections in the absence of losses and 12, when they were taken into account. The approach of multipole interference allows one to design devices for wireless communication systems with a broad range of applications across different frequency bands.

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