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TIIVISTELMÄRAPORTTI (SUMMARY REPORT)

Use of nonlinear materials to control radar cross section: modelling scattering from a nonlinear sphere

Keijo Nikoskinen, Luis R. J. Costa and Jari Hänninen
Aalto University, Department of Radio Science and Technology
keijo.nikoskinen@aalto.fi

Abstract The scattering of a sinusoidal plane wave from a sphere made of nonlinear material is simulated using a finite-difference-time-domain-based computation. The sphere material is modelled as a string of diodes aligned in the direction of the polarisation of the incident sinusoidal plane wave. Simulation results reveal that the scattered electric field in the back-scattered direction contains harmonics and a very strong DC component relative to the harmonics in its spectrum when the dielectric constant is the same at that of the surrounding medium-one in this case. The overall level of these harmonics, however, is very small, and these effects due to nonlinearity are no longer evident when the value of the dielectric constant of the region within the nonlinear sphere is set to that of silicon; the scattering due to the dielectric swamps the weak harmonics. The configuration of diodes within the sphere in this study is not ammenable to stealth technology, but further study is necessary to better understand whether nonlinearity is applicable longside target geometry and material loss to enhance stealth.

1. Introduction

Since the invention of the radar, various approaches have been used to avoid or reduce the target’s chance of detection. Such stealth technology includes the use of suitable geometry in the target to deflect and reduce the electromagnetic energy scattered from it back to the radar combined with the use of lossy materials that absorb the incident radar radiation thus further reducing scattering in the direction of the radar. This reduction of the so-called radar cross section (RCS) of the target is one factor that makes it less susceptible to detection. However, the absorption achieved using lossy materials is limited, and so traditionally stealth technology has concentrated on optimising the target geometry in order to reduce back scattering. With increasingly more complex systems such optimisation is ever more difficult. Also, the spectral signature of the scattered signal received by the radar even makes identifying the target possible.

A third potential technique to exploit in stealth technology is nonlinearity, which generates harmonics. Since energy must be conserved, the energy propagating in the incident radar signal at the carrier frequency must be transferred to the generated harmonic frequencies, thus reducing the back-scattered energy in the direction of the radar at the carrier frequency. This transfer of energy will also confound the frequency signature of the target so at least making identifying the target far more difficult. Studying the feasibility of using nonlinearity to manipulate the RCS is the primary objective, but by no means the only one, of this study.

Accounting for nonlinearity in an electromagnetic field simulation is a demanding computational task, and few papers (for example, F. Auzanneau and R. W. Ziolkowski, “Microwave signal rectification using artificial composite materials composed of diode-loaded electrically small dipole antennas,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 11, pp. 1628–1637, Nov. 1998) discuss the use of nonlinear media in electromagnetic simulations. Hence, our knowledge of the detailed effects of the interaction of a plane-wave and a nonlinear material is wanting, and thus another goal of this study is to supplement the existing knowledge in this area.

2. Research objectives and accomplishment plan

The primary goal of this study is to study the scattering of an incident plane wave from a sphere made of nonlinear material, with the objective to discover whether effects due to nonlinearity can be exploited in stealth technology. Understanding the mechanisms behind the nonlinear effects is of paramount importance and a prerequisite if these effects are to be properly taken advantage of. Does the spectrum of the scattered field of a scatterer made of nonlinear material illuminated by a sinusoidal plane wave contain harmonics? And if it does, how strong are these harmonics? In other words, how much energy is transferred from the fundamental frequency to the higher harmonics? Can these effects, if they exist, be utilized in stealth technology alongside the existing technologies? These are some of the questions that this study hopes to answer.

Since the finite-difference time-domain (FDTD) method is the only approach that lends itself to simulating nonlinearity in electromagnetics, it is the method used to compute the field scattered by a sphere made of nonlinear material. The simulation setup, shown in figure 1, comprises the sphere made of nonlinear material at the centre of the computational space, where it is illuminated by a sinusoidal plane wave by enclosing it within a total-field-scattered-field TFSF) region. The TFSF region is in turn enclosed by a Huygens surface so as to determine the scattered far field and so also the RCS. The computational space is terminated in a convolutional perfectly-matched layer (CPML) in order to model continuous free space in the truncated computational space. These are all standard FDTD techniques that are well documented in the literature, and they are to be implemented in a program written in the C programming language. Rendering of the simulated data is to be done using Matlab.

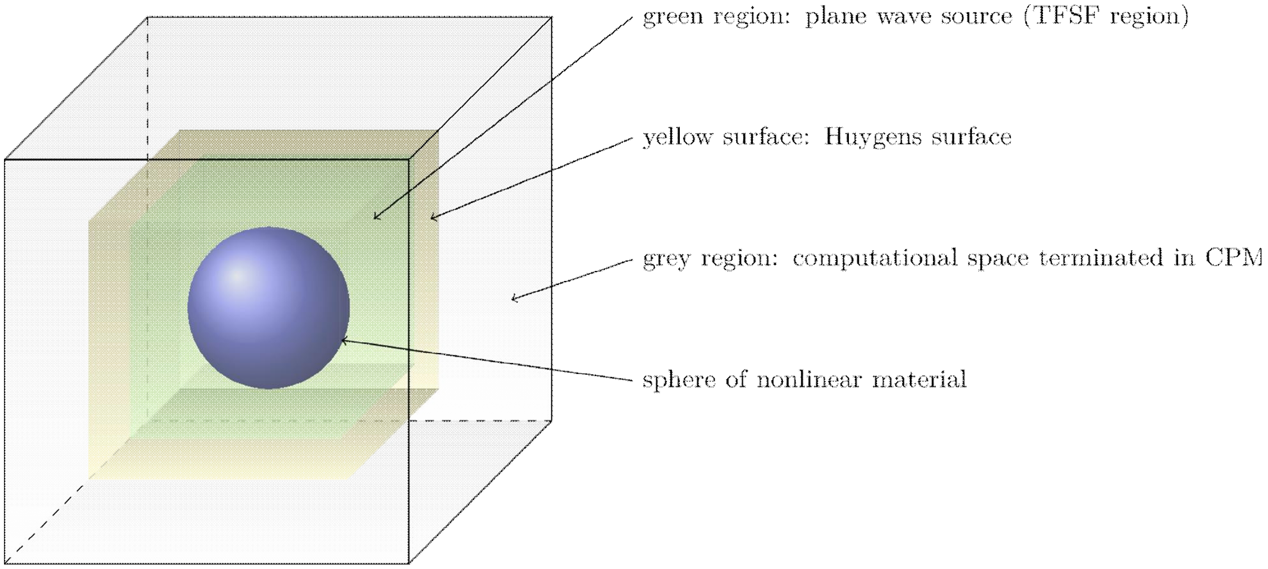


Figure 1: The general simulation setup of the study.

The nonlinear medium is modelled in the FDTD computational space using the approach developed by the authors to embed lumped elements in FDTD, an approach known as LE-FDTD. The nonlinearity used is the current-voltage dependency of a diode since the nonlinear behaviour of diodes in circuits is well known; its application as a rectifier is ubiquitous and the spectrum of the rectified waveform is more than familiar. Being exponential by nature, the diode current nonlinearity will also put the analysis method to the test; should the method successfully simulate the fields with this very strongly nonlinear medium, it should manage to simulate the fields with any other nonlinear medium. The nonlinear material was chosen to consist of pn-junctions (diodes) connected within the space occupied by the sphere. As such, the scattered field is expected to display characteristics of a rectified current or voltage. However, the strongly nonlinear behaviour of the numerous, closely packed diodes (see figure 2 below) is expected to be a challenge numerically. The implementation of such a geometrical object having a nonlinear medium in an electromagnetic simulation is novel and of great interest from a scientific point of view.

The scattering caused by a sphere—and thus the resulting RCS—known as Mie scattering, is well known and serves as a canonical benchmark to which the results can be compared. Also, using a spherical scatterer makes smaller demands on the implementation of the TFSF region since the direction of illumination is irrelevant.

3. Materials and methods

The basis of this study is the FDTD method, wherein the electric and magnetic field components in the computational space are arranged such that every electric field component is adjacent to a magnetic field component and every magnetic field component is adjacent to an electric field component in the primary directions, x, y, and z. Additionally, the electric and magnetic fields are solved, respectively, at alternate time steps. This leap-frog arrangement of the electric and magnetic fields components both in space and time enables the field updating equations to be explicit thus eliminating the need to solve a large matrix equation. Being a time-domain analysis, it allows including nonlinearity into the computation.

The CPML termination is the current state-of-the-art to model continuous free space in a truncated FDTD computational space. It is able to absorb fields impinging at any angle far better than any other technique developed for the job. An additional bonus in the technique is that it is fairly simple to implement, far simpler than its contender.

The TFSF region serves as the source of a plane wave. Within the region, the fields existing are those of the propagating plane wave as well as those resulting from the scattering that results when an object is place in—the total field. The fields outside this region are those of the scattered field only, since the fields of the incident wave are subtracted from the fields leaving the TFSF region.

The nonlinear material of the sphere is modelled by embedding a nonlinear lumped element—a diode in this case—that introduces a nonlinear current into the FDTD grid in the region of the sphere, using the method by the authors described in L. R. J. Costa, K. Nikoskinen and M. Valtonen, “A robust technique for modelling nonlinear lumped elements spanning multiple cells in FDTD,” in *Scientific Computing in Electrical Engineering SCEE 2008*, Eds. J. Roos and L. R. J. Costa, pp. 53–59, Mathematics in Industry (14), Springer, 2010. The diode current, as is well known, depends exponentially on its voltage and thus is very strongly nonlinear. Earlier work during the development of this diode model has indicated that this model very stable and works well even at very high diode voltages. This novel and versatile approach lends itself well to modelling nonlinear materials.

The sphere simulated in this study is made up of diodes aligned in the z direction, as shown in figure 2. The incident plane wave is polarised in the z direction as well. This arrangement of the diodes with respect to the polarisation of the incident wave should cause the sphere to behave like a rectifier when illuminated. The voltage is the greatest across the poles of the sphere, and the largest current is expected to flow during the positive half-cycle of the incident wave through the diode string from pole to pole.

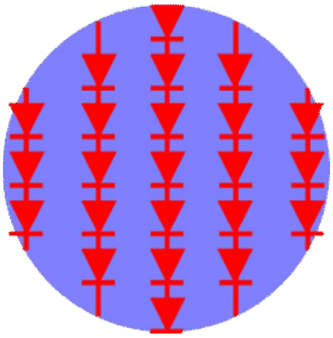


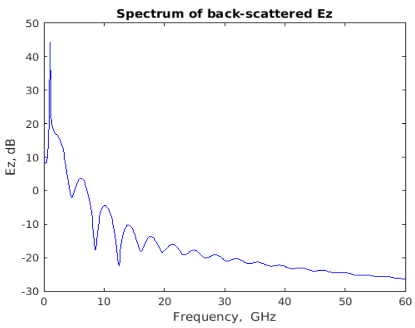
Figure 2: The alignment of diodes modelling the nonlinear material of the sphere.

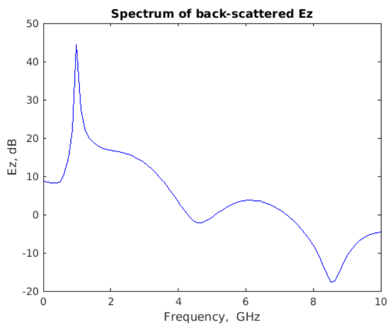
As was to be expected, the strong nonlinearity and the numerous diodes in close proximity pose a numerical challenge to the computation. The time step used had to be dropped to half or less of the maximum possible time step allowed by the Courant-Friedrichs-Lewy condition, and the amplitude of the incident plane wave could not be arbitrarily large. The large amplitude in the electric field created a large voltage across the diodes causing them to conduct relatively large currents, and even small changes in the large voltage resulted in relatively large changes in the diode currents.

4. Results and discussion

The simulation space used in all simulations of this study was a 120x120x120 grid, each cell measuring 0.5 mm, in which a 32 mm (64 cells) was placed. The computational space was truncated in a ten-cell-thick CPML. The Huygens surface was separated from the inner surface of the CPML by ten cells and the separation between the Huygens surface and the TFSF face was five cells. The frequencies used for the illuminating sinusoidal plane wave were 1 GHz and 10 GHz, implying that the wavelength of the plane wave was either large compared to the diameter of the sphere (the small scatterer case) or it was the about the same dimension as the sphere.

Three spheres were used in the simulation. The first was a sphere made of a perfect electric conductor (PEC); the second a sphere with z-aligned diodes, but in a medium having a dielectric constant 1; and the last a diode sphere in a medium with dielectric constant 11.68, which is the value for the dielectric constant of silicon. The spectra for the simulated cases are presented in the figures below, for which the number of time steps *n* in the simulations was 16,384 in all the cases.





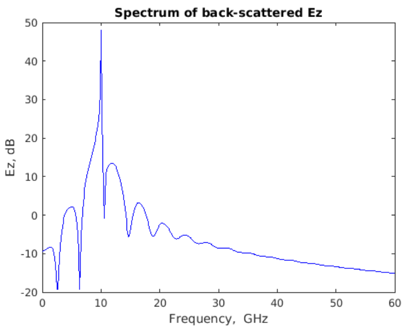


Figure 3: The spectrum of the back-scattered electric field z component scattered from a PEC sphere illuminated by a plane wave of 1 GHz (left) and a close-up of this spectrum (right) indicate that the fundamental frequency is that of the incident wave. Similarly, for a plane wave propagating at a frequency of 10 GHz, the spectrum of the back-scattered field has a prominent peak at 10 GHz.

Figure 3 shows the spectra of the electric field in decibels scattered from the PEC sphere in the back-scattered direction from which the frequency of the incident wave is clearly evident, as is to be expected. The error of the model due to the Fourier transform for a simulation of 16,384 time steps is also apparent, but this error can be increasingly reduced by increasing the number of time steps, but not completely eliminated.

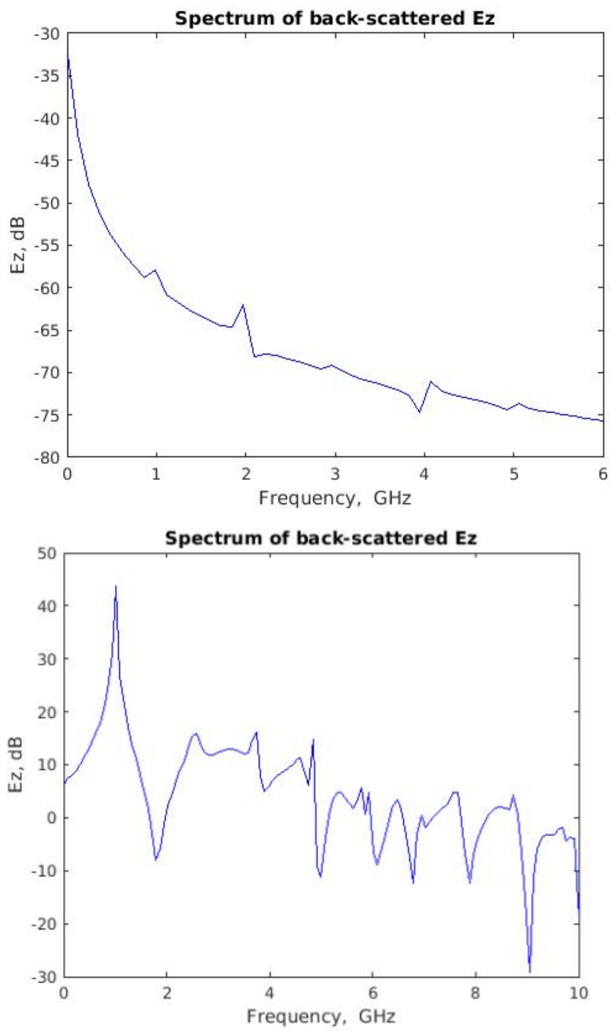


Figure 4: The spectrum of the back-scattered electric field z component of the nonlinear sphere with die-

lectric constant 1 (left) and dielectric constant 11.68 (right) when illuminated at 1 GHz.

The spectra of the back-scattered electric field for the two nonlinear spheres are shown in figure 4. The left panel is the spectrum of the sphere with dielectric constant 1. The fundamental frequency and harmonics are evident, but the overall level of the amplitudes is very small. What is interesting in this spectrum, however, is the strong DC component. Observing the near field E_z field component indicated that the electric field was indeed rectified, as was to be expected, but the positive field grew and then levelled off, staying positive for the entire duration of the simulation, which explains the strong DC component. But what made the positive scattered near field grow? Since the sphere material is lossless, during the negative half-cycle of the incident wave when the diodes were not conducting, electric charge within the sphere was trapped at the nodes of the FDTD grid, unable to move anywhere thus creating a positive field. During each new negative half-cycle, more charge got trapped within the sphere until a maximum was attained.

The right panel in figure 4 shows the spectrum of the E_z component scattered from the nonlinear sphere having a dielectric constant 11.68. Now, a strong peak is visible at the incident plane wave frequency of 1 GHz, and the scattering due to the dielectric medium is so strong as to swamp the nonlinear effects that were visible in the case for the sphere with dielectric constant 1.

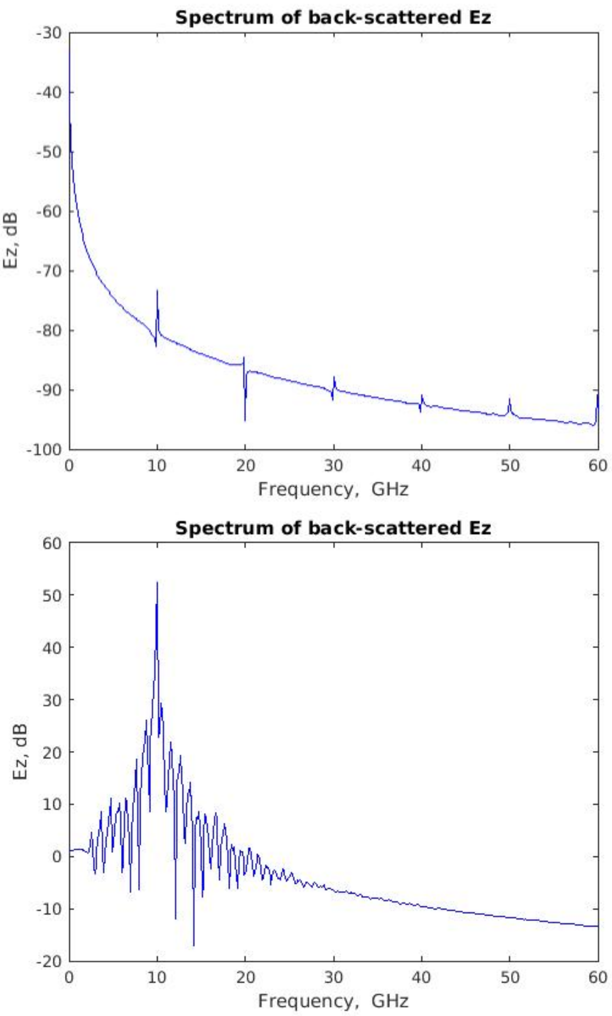


Figure 5: The spectrum of the back-scattered electric field z component of the nonlinear sphere with dielectric constant 1 (left) and dielectric constant 11.68 (right) when illuminated at 10 GHz.

Just as when illuminated at 1 GHz, now too the harmonics that are generated are weak, but the DC component is overpowering when the dielectric constant is 1. Again, when the dielectric constant is 11.68, as before, only the incident frequency is clearly visible, and all the harmonics are buried under the effects of the dielectric.

What these results seem to indicate is that the diode-like material does indeed rectify the scattered field, but in order that the expected harmonics are observable there should be no scattering due to the dielectric, since their overall amplitudes are extremely small. Further studies are necessary to find out whether arranging the diodes differently within the sphere would create strong enough harmonics for dielectric constants great than one. A real sphere made of a great number of z-aligned silicon diodes does not transfer much energy away from the incident frequency, based on this study, but the case is not closed on the potential use of nonlinearity in stealth technology.

5. Conclusions

An FDTD program that computes the field scattered from a sphere made of nonlinear material has been successfully implemented. The numerical challenges arising from the strongly nonlinear material modelled were overcome without having to resort to elaborate control mechanisms; just suitable choice of values in parameters like simulation time step, plane-wave amplitude, and iteration errors both absolute and relative for the nonlinear region was sufficient. The modelling technique used to model the nonlinear medium is novel, and scattering from a sphere of nonlinear material has been computed for the first time, to best knowledge of the authors.

The simulation results show that the diode sphere does indeed act like a rectifier and generates harmonics in the back-scattered electric field, just as expected. However, the amplitudes of these harmonics are very small, but interestingly the DC component is extremely large compared to the harmonics. Curiously, these effects due to nonlinearity can be observed only when the dielectric constant is set to be the same as the surrounding medium, 1 in this case. Including the dielectric constant of silicon in the sphere region in the simulation resulted in the nonlinearities (harmonics) being completely drowned by the scattering due to the dielectric sphere. Thus the application of nonlinearity to stealth in the studied case is not feasible. However, more studies with different diode alignments might reveal applicable configurations.

Future lines of investigation, in addition to studying different diode configuration, lie in studying the interaction of different waveforms-modulated pulses-with the nonlinear material.

6. Scientific publishing and other reports produced by the research project

No scientific papers have been published yet, but a paper on the work described in this report is in preparation. This paper will be part of the doctoral thesis of one of the authors, Luis R. J. Costa.