

# Enhancement of Air-ground Matching by Means of a Chirped Multilayer Structure: Electromagnetic Modeling with the Method of Single Expression

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**Abstract**—The enhancement of air-ground electromagnetic matching by means of a chirped multilayer structure is investigated. The modeling and simulation of the considered structure are performed by using the method of single expression (MSE), which is a convenient and accurate tool for wavelength-scale simulations of multilayers comprising lossy, amplifying or nonlinear (Kerr-type) materials. Numerical results show that a suitable chirped multilayer structure can reduce the reflection from the ground. Different values of the number of layers and of the layer thicknesses are considered. The distributions of the electric field components and the power flow density within the modelled structures are calculated.

**Keywords**—chirped multilayer structure, ground matching, method of single expression.

## 1. Introduction

Ground Penetrating Radar (GPR) is an electromagnetic technique currently in use for detection and imaging of buried objects, with resolution ranging from centimeters to few meters depending on the operation wavelength of the radar antenna [1]–[6]. The principles of GPR for detecting buried objects are well known, indeed GPR uses the same fundamental physical principles as conventional radars. GPR is a technique typically operating at frequencies included within the 10 MHz to 5 GHz range. The chosen frequency band depends on measurement purposes and properties of the investigated media. Target objects can be buried pipes, cables and reinforcing elements, caverns, flaws and cracks, as well as ground water and moisture, and more [6]–[11]. Nowadays, GPR is widely applied in archaeological investigations and for cultural heritage management, planetary exploration, forensics, civil, hydrogeological, geophysical and geotechnical engineering [6]–[11].

GPR detects the electromagnetic field backscattered by the targets and generates an image of it, which is interpreted

after proper signal processing. The GPR transmitter emits electromagnetic waves towards the ground or structure under test. When the waves encounter a buried object or a boundary between materials having different permittivity and conductivity values, they are reflected, refracted and scattered back to the radar. A receiving antenna catches the returned signal, which is analyzed and recorded. Depth and shape of the objects are calculated from the travel time and amplitude of the reflected signals, along an acquisition profile.

The signal attenuation and penetration depth at the desired operating frequency are the main factors influencing the functionality and resolution of a GPR device [2]–[6]. Resolution of GPR primarily is a function of the radar frequency and the permittivity of the detected medium. High resolution can be reached at the cost of penetration depth, because the attenuation of electromagnetic waves in common ground materials, as well as in materials utilized in manmade structures, is rather high and increases with frequency. At a lower frequency, GPR can sample deeper, but the resolution is lower. A higher frequency range gives a narrower pulse, yielding a higher time or depth resolution. On the other hand, attenuation increases with frequency. Therefore, a high frequency signal cannot propagate far and the depth of detection becomes shallower [12], [13]. To give a practical example, for applications requiring high resolution and a penetration depth down to approximately 60 cm, such as assessment of concrete structures, a frequency spectrum centered over 1 GHz is normally used. For applications requiring penetration from tens of centimeters to hundreds of meters, frequencies between 12.5 MHz to 500 MHz are used.

Antennas are essential components of GPR systems, which transmit and receive electromagnetic waves. Various types of antennas can be used: dipole, bowtie and horn antennas are the most common. Several systems use two separate antennas for transmitting and receiving, although they can

be packaged together. Some commercial systems employ shielded antennas to avoid reflections from objects in the air. The antenna gain is very important for efficiently emitting and receiving the electromagnetic energy. Antennas with a high gain improve the signal/noise ratio. A lower operating frequency requires larger antennas. Small antennas make the system compact, but they have a low gain at lower frequencies [12], [13].

Though the GPR technique is mature enough, some problems are still waiting for their solution [6]. One of them is to achieve a better matching of the electromagnetic waves emitted by the GPR with the ground, which would increase the signal penetration depth, minimize back reflections at the air-ground interface and enhance the signal/noise ratio at the receiving end. Different antenna configurations and antenna-medium interactions have been studied in the literature, mostly by using the finite-difference time-domain (FDTD) method or the method of moments [14]–[16].

In this paper, the possibility to enhance air-ground electromagnetic matching by means of a suitable chirped multilayer structure is studied. The wavelength-scale electromagnetic modeling and simulation of a chirped multilayer structure over a dielectric half-space, illuminated by a monochromatic plane wave, is performed by using the method of single expression (MSE) [17]–[22] (Section 2). The behavior of different structures is analyzed, to find advantageous configurations for matching enhancement (Section 3). Preliminary results were presented in [22]. Further studies are necessary, to consider more realistic sources and ultra-wideband radiation.

## 2. Electromagnetic-modeling Method

The method of single expression (MSE) allows to accurately analyze wavelength-scale multilayer structures comprising lossy, amplifying or nonlinear (Kerr-type) dielectric, semiconductor or metallic materials [17]–[22]. In this Section, the backbone of the MSE for normal wave incidence on a multilayer structure is resumed.

From Maxwell's equations in the one-dimensional case, the Helmholtz equation can be obtained, for the linearly polarized complex electric field component  $\dot{E}_x(z)$ :

$$\frac{d^2 \dot{E}_x(z)}{dz^2} + k_0^2 \hat{\epsilon}(z) \dot{E}_x(z) = 0, \quad (1)$$

where  $k_0 = \frac{\omega}{c}$  is the free space propagation constant and  $\hat{\epsilon}(z) = \epsilon'(z) + j\epsilon''(z)$  is the complex permittivity of a medium.

The essence of the MSE is the use of a general solution of the Helmholtz equation, having the following single expression:

$$\dot{E}_x(z) = U(z) \cdot e^{-jS(z)}, \quad (2)$$

instead of the traditional solution expressed as a sum of counter-propagating waves. In (2),  $U(z)$  and  $S(z)$  are real quantities describing the electric field amplitude and phase, respectively. Time dependence  $e^{j\omega t}$  is assumed, but suppressed in the formulas. The expression (2) can de-

scribe all the possible electric field amplitude distributions in a medium, corresponding to propagating, standing and evanescent waves. This gives advantages in the investigation of the interaction of electromagnetic waves with longitudinally non-uniform linear media and with intensity dependent non-linear media.

By introducing (2) in (1), the Helmholtz equation can be rewritten as a set of first-order differential equations:

$$\begin{cases} \frac{dU(z)}{d(k_0 z)} = Y(z) \\ \frac{dY(z)}{d(k_0 z)} = \frac{P^2(z)}{U^3(z)} - \epsilon'(z) \cdot U(z) \\ \frac{dP(z)}{d(k_0 z)} = \epsilon''(z) \cdot U^2(z) \end{cases}, \quad (3)$$

where  $Y(z)$  is the spatial derivative of  $U(z)$  and  $P(z)$  is a quantity that is proportional to the power flow density (Poynting vector) in a medium, i.e.  $P(z) = U^2(z) \frac{dS(z)}{d(k_0 z)}$ . The sign of  $\epsilon'(z)$  can assume either positive or negative values, describing relevant electromagnetic features of dielectric materials or plasma, respectively. The sign of  $\epsilon''(z)$  indicates loss or gain in a medium.

The set of equations in (3) can be integrated numerically starting from the non-illuminated side of a multilayer structure, where only one outgoing traveling wave is supposed to be present. The initial values for the integration can be obtained from the boundary conditions of electrodynamics at the non-illuminated side of the structure ( $z = L$ ), i.e.,  $U(L) = E_{tr}$ ,  $Y(L) = 0$ , and  $P(L) = \sqrt{\epsilon_r} E_{tr}^2$ , where  $E_{tr}$  and  $\epsilon_r$  are the amplitude of the transmitted wave and the permittivity of the medium beyond the multilayer structure at  $z > L$ , respectively. Numerical integration of (3) continues step by step towards the illuminated side of the structure, taking into account the actual value of the permittivity for the given coordinates at each step of integration. In the process of integration, any variable in (3) can be calculated and recorded, so that it is possible to obtain full information regarding the distribution of the electric field amplitude in the space, as well as the distribution of its derivative and power flow density.

At the interfaces between different material of the multilayer structure, the ordinary boundary conditions of electrodynamics bring to the continuity of  $U(z)$ ,  $Y(z)$  and  $P(z)$ . From the boundary conditions of electrodynamics at the illuminated side of the structure ( $z = 0$ ), the amplitude of the incident wave  $E_{inc}$ :

$$E_{inc} = \left| \frac{U^2(0) \cdot \sqrt{\epsilon_l} + P(0) + jU(0) \cdot Y(0)}{2U(0) \cdot \sqrt{\epsilon_l}} \right|, \quad (4)$$

and the power reflection coefficient  $R$ :

$$R = \left| \frac{E_{ref}}{E_{inc}} \right|^2 = \left| \frac{U^2(0) \cdot \sqrt{\epsilon_l} - P(0) - jU(0) \cdot Y(0)}{U^2(0) \cdot \sqrt{\epsilon_l} + P(0) + jU(0) \cdot Y(0)} \right|^2, \quad (5)$$

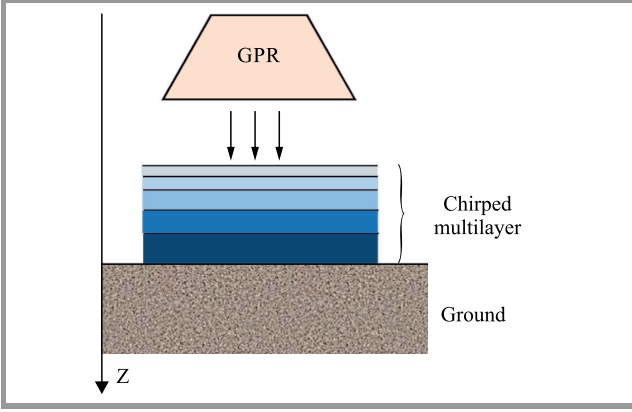
are restored at the end of the calculation. Here,  $U(0)$  is the amplitude of the electromagnetic wave,  $Y(0)$  is its derivative and  $P(0)$  the power flow density at the illuminated

interface of the structure  $z = 0$ ,  $E_{ref}$  is the amplitude of the reflected wave, and finally  $\epsilon_l$  is the permittivity of the medium in front of the structure, for  $z < 0$ .

The power transmission coefficient  $T = \frac{E_{tr}^2 \sqrt{\epsilon_r}}{E_{inc}^2 \sqrt{\epsilon_l}}$  is defined as the ratio of transmitted power to the incident one.

### 3. Numerical Results

The geometry of the modeled and simulated structure is represented in Fig. 1.



**Fig. 1.** Plane wave interaction with the ground through a chirped multilayer structure.

Normal incidence of a plane wave with wavelength  $\lambda_0 = 10$  cm on a ground of complex permittivity  $\hat{\epsilon}_{gr} = \epsilon'_{gr} + j\epsilon''_{gr} = 10 - j0.3$  [23] is considered. A chirped multilayer structure is positioned above the ground. It consists of two alternating dielectric slabs of low  $\epsilon'_{low} = 2.25$  and high  $\epsilon'_{high} = 6.0$  permittivity creating bilayers of increasing thickness towards the ground. A numerical analysis and optimization carried out by using the MSE revealed that bilayers should have the following normalized thicknesses (NT):  $NT_1 = 0.3471$ ;  $0.4471$ ;  $0.5471$ , where  $NT_i = \frac{L_i}{\lambda}$  ( $i = 1, 2, 3$  is a number of bilayers) starting from the illuminated side, being  $\lambda = \frac{\lambda_0}{\sqrt{\epsilon}}$  the wavelength in the slab with  $\epsilon = \epsilon'_{low}$  and  $\epsilon = \epsilon'_{high}$  permittivity, respectively.

Results for two particular structures are presented in the following. The permittivity profile of such structures is plotted in Fig. 2. For the first structure (Fig. 2a):

$$NT_1 = 0.3471 (\epsilon'_{high} \text{ and } \epsilon'_{low}),$$

$$NT_2 = 0.4471 (\epsilon'_{high} \text{ and } \epsilon'_{low}),$$

$$NT_3 = 0.5471 (\epsilon'_{high} \text{ and } \epsilon'_{low}).$$

The material with low permittivity  $\epsilon'_{low}$  is adjacent to the ground.

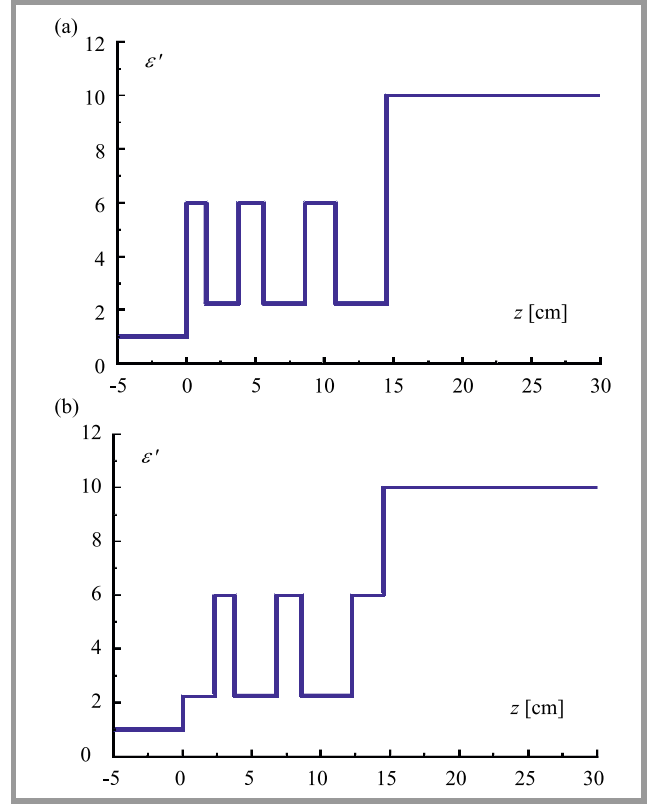
For the second structure (Fig. 2b):

$$NT_1 = 0.3471 (\epsilon'_{low} \text{ and } \epsilon'_{high}),$$

$$NT_2 = 0.4471 (\epsilon'_{low} \text{ and } \epsilon'_{high}),$$

$$NT_3 = 0.5471 (\epsilon'_{low} \text{ and } \epsilon'_{high}).$$

The material with high permittivity  $\epsilon'_{high}$  is adjacent to the ground.



**Fig. 2.** Permittivity profiles of two chirped multilayer structures positioned on the ground. Wave incidence from the left side of the graphs is considered.

The reflectance  $R$  from the structures air-multilayer-ground or air-ground interface is defined as  $R = \frac{P_{ref}}{P_{inc}}$  – see Eq. (5), where  $P_{inc}$  is a power flow density (Poynting vector) of the electromagnetic wave impinging on the multilayer structure, and  $P_{ref}$  is a power flow density (Poynting vector) of the electromagnetic wave reflected from the structure.

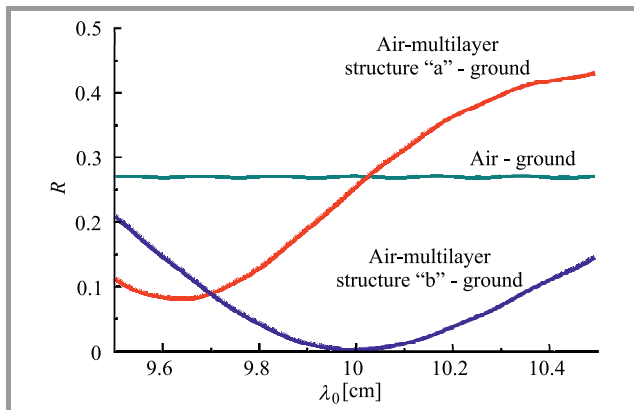
In the absence of a chirped multilayer structure the reflectance  $R_{gr}$  from the ground is defined as:

$$R = \left| \frac{\sqrt{\epsilon_l} - \sqrt{\hat{\epsilon}_{gr}}}{\sqrt{\epsilon_l} + \sqrt{\hat{\epsilon}_{gr}}} \right|^2, \quad (6)$$

which is a reflectance from the air-ground interface, the so-called Fresnel reflection coefficient. For the considered case, in the absence of the chirped multilayer structure, the reflectance  $R_{gr}$  from the air-ground interface equals to  $R_{gr} \approx 0.27$ . This value has been calculated by using the MSE and the formula in Eq. (6).

The structure in Fig. 2b, where the layer of high permittivity is contacted with the ground, permits to attain air-ground matching with overall reflectance of  $R \approx 0.0019$  while the structure in Fig. 2a indicated reflectance  $R \approx 0.25$  that is close to relevant value of reflectance  $R_{gr} \approx 0.27$  for the air-ground interface (without multilayer structure). Thus, an enhancement of air-ground matching is obtained for the structure where the slab of  $\epsilon'_{high}$  is contacted with the ground (Fig. 2b).

In Fig. 3 the reflectance spectra of the air-ground and air-multilayer-ground for the two types of chirped multilayer structures are presented for the wavelength range of  $\lambda_0 = (9.5 \div 10.5)$  cm.

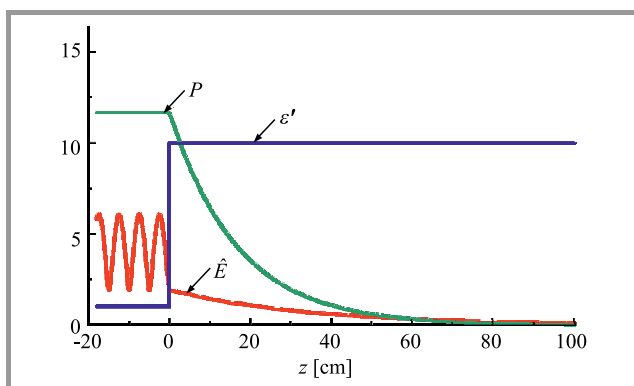


**Fig. 3.** Reflectance spectra of the air-ground and air-multilayer-ground for two types of chirped multilayer structures. (See color pictures online at [www.nit.eu/publications/journal-jtit](http://www.nit.eu/publications/journal-jtit))

The chirped multilayer structure with a layer of high permittivity contacted with the ground, i.e. the structure “b” in Fig. 2 has the lowest reflectance in the whole wavelength range as compared with the structure “a” in Fig. 2 and air-ground case. The lowest value of the reflectance  $R \approx 0.0019$  of the structure “b” is observed at the wavelength  $\lambda_0 = 10$  cm.

Thus, for better air-ground matching a chirped multilayer structure with a layer of high permittivity contacted with the ground (with reflectance of  $R \approx 0.0019$ ) at the wavelength of 10 cm should be chosen (structure “b”, Fig. 2b). Low reflectance permits deeper penetration of electromagnetic waves in the ground as it will be seen from the physics of difference of operation of two chirped multilayer structures, as well as of the air-ground interface in the absence of the multilayer structure.

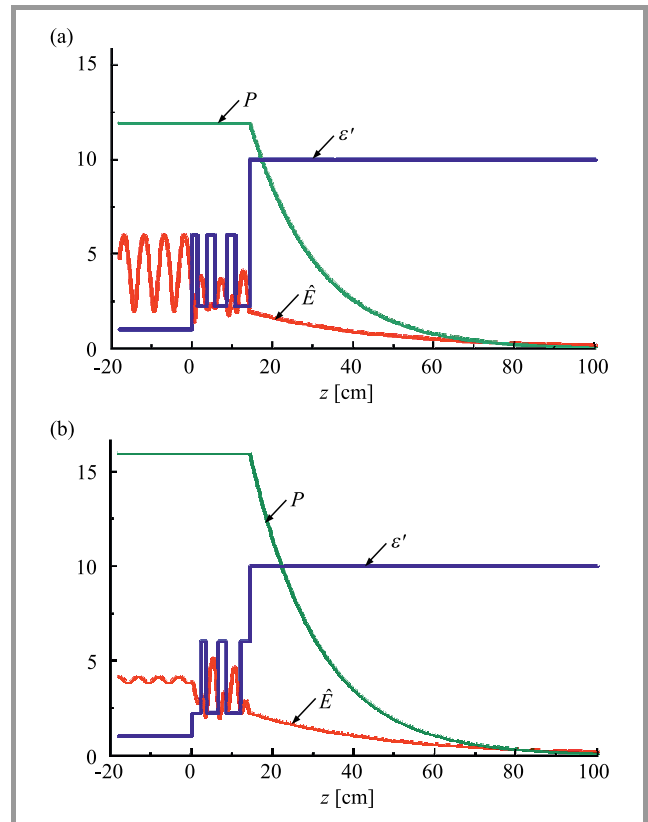
In the absence of the multilayer structure, partially-standing wave amplitude of electric field is formed at the air-ground interface at  $z < 0$ , which indicates essential reflectance from



**Fig. 4.** Permittivity profile, distributions of electric field amplitude  $\hat{E}$  and Poynting vector  $P$  within the air and the ground. The amplitude of incident wave (from the left at  $z < 0$ ) is  $E_{inc} = 4$  a.u.,  $\lambda_0 = 10$  cm,  $R_{gr} \approx 0.27$ .

the interface (Fig. 4). Exponentially decreasing electric field amplitude due to the loss in the ground is observed.

For  $z < 0$ , the resultant Poynting vector  $P$  is  $P = P_{inc} - P_{ref} = P_{inc}(1 - R_{gr})$ . The Poynting vector  $P$  is a constant value in the air and exponentially decreases in the ground. Consequently, because of the reflection from the air-ground interface and small resultant value of  $P \approx 11.68$ , the penetration depth into the ground is limited.



**Fig. 5.** Permittivity profile, distribution of electric field amplitude  $\hat{E}$  and Poynting vector  $P$  within and outside of the chirped multilayer structures. The amplitude of incident wave (from the left at  $z < 0$ ) in both cases is the same  $E_{inc} = 4$  a.u. at  $\lambda_0 = 10$  cm,  $R \approx 0.25$  for the structure “a” and  $R \approx 0.0019$  for the structure “b”.

The distributions of the electric field amplitude  $\hat{E}$  and of the Poynting vector  $P$  strongly depend on the alternation of layers in the chirped multilayer structure. The relevant distributions of electric field amplitude and Poynting vector within and outside the structures are presented in Fig. 5. Due to the absence of losses in the chirped multilayer structures, the Poynting vector  $P$  is constant in them and the electric field amplitude  $\hat{E}$  has an oscillating behavior following the permittivity profiles of multilayer structures. A partially-standing wave amplitude of the electric field is formed in front of the structure in Fig. 5a, indicating higher reflectance  $R$  and  $P \approx 11.93$ . An almost traveling wave pattern is created in front of the structure in Fig. 5b, indicating lower reflectance  $R$  and  $P \approx 15.97$ . The power flow penetrating into the ground increases of approximately 1.34 times, which causes a deeper penetration.

## 4. Conclusions

A wavelength-scale electromagnetic analysis by means of the method of single expression (MSE) permitted to find chirped multilayer structures providing enhancement of air-ground matching, when the electromagnetic source is a monochromatic plane wave. The number and thicknesses of the layers can be optimized to minimize back reflection towards the electromagnetic source. The use of non-uniform (chirped) multilayers can enlarge the reflectance spectrum if compared to the standard quarter-wavelength multilayers. Interesting results have been found for a structure consisting of three bilayers of high and low permittivity, where the highest value of the permittivity does not exceed the permittivity of the ground. Bilayers have increasing thickness towards the ground and a better matching is achieved when the layer closer to the ground has the high permittivity. The reflectance spectra and the distributions of electric field amplitude and Poynting vector within and outside the structures have been calculated. This allowed finding the favorable structures.

Mainly, the novelty of this work is in the application of a non-traditional method, the MSE, to the analysis of multilayers; the method permits an easy calculation of the field amplitude and Poynting vector spatial distributions inside and outside the multilayer and in the presence of lossy media. Further studies are necessary, to design structures providing good results when illuminated by a pulsed electromagnetic wave.

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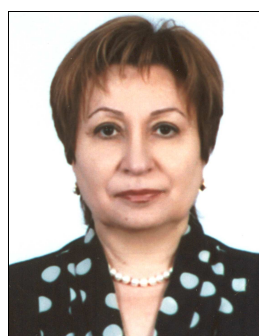
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