

# Graded-Index Metamaterial-Enhanced Ground-Penetrating Radar for Shallow Buried Object Detection

Mohamed Zidan, and Mohamed Ismail

**Abstract**—A graded-index metamaterial metasurface is proposed to enhance electromagnetic wave penetration and target detectability in air-coupled ground-penetrating radar (GPR) systems. The metasurface is designed using a scalable LC-based unit cell operating at 3.5 GHz and arranged to provide field focusing to the target. Results demonstrate improved field focusing and successful detection of a shallow buried metallic object compared to the conventional case.

**Index Terms**—Metamaterial, Graded Index Metamaterial, Ground Penetrating RADAR.

## I. INTRODUCTION

GROUND-penetrating radar (GPR) is a non-destructive electromagnetic sensing technique widely used for subsurface investigation, including landmine detection, underground utility mapping, pavement inspection, and archaeological exploration. GPR systems typically employ ultra-wideband (UWB) signals to balance penetration depth and spatial resolution; however, performance is often limited by impedance mismatch at the air–soil interface, attenuation in lossy soils, and wavefront distortion due to subsurface heterogeneity [1].

Several approaches have been proposed to alleviate these limitations, such as antenna optimization, resistive loading, ground-coupled configurations, and advanced signal processing techniques [2]. While these methods can improve specific performance aspects, they do not fundamentally address the electromagnetic discontinuity between free space and soil, leading to significant reflection losses and reduced energy coupling.

Metamaterials, composed of subwavelength artificial unit cells, enable engineered electromagnetic properties beyond those of natural materials [3]. In radar and sensing applications, they have been used for antenna miniaturization, beam shaping, and impedance matching [4]. In GPR systems, metamaterial-based solutions have shown improved coupling and directivity; however, many rely on resonant elements, resulting in narrowband operation and increased losses that are unsuitable for UWB GPR.

Graded-index (GRIN) metamaterials offer a broadband alternative by enabling continuous refractive index variation, allowing smooth wave transformation and reduced reflections.

Mohamed Zidan is with the Department of Electronic and Communication Engineering, IEAT, Egypt. (e-mail: m.nooh@ieec.org).

Mohamed Ismail is with the Microstrip Department, Electronics Research Institute (ERI), El-Nuzha, Cairo 11843, Egypt (e-mail: mismail@eri.sci.eg).

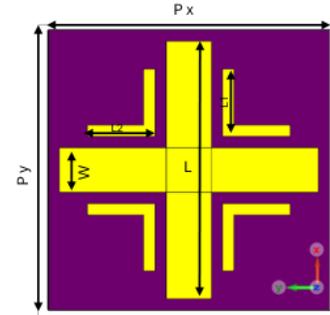


Fig. 1. Unit cell geometry ( $P_x = 25$ ,  $P_y = 25$  mm,  $L = 23$  mm,  $W = 3$  mm,  $l_1 = 7$  mm,  $l_2 = 7$  mm)

Despite their successful application in microwave lenses and transition layers, their use in GPR remains limited.

In this work, a graded-index metamaterial is proposed to enhance electromagnetic wave penetration and beam directivity in air-coupled GPR systems, leading to improved detection of shallow buried objects.

## II. GRADED-INDEX METAMATERIAL DESIGN AND ANALYSIS

### A. Unit Cell Design

The graded-index metasurface is constructed using metamaterial unit cell designed to exhibit a controllable effective permittivity through geometrical scaling. The unit cell is composed of conductive patterns printed on both faces of a dielectric substrate, forming an equivalent inductive–capacitive (LC) resonant structure. By varying the physical dimensions of the metallic inclusions, the effective capacitance and inductance of the unit cell are modified, resulting in a tunable effective permittivity while maintaining subwavelength operation.

The geometry of the proposed unit cell is illustrated in Fig. 1. The periodicity of the structure is chosen to be electrically small with respect to the operating wavelength, ensuring wide bandwidth response. The dual-sided configuration enhances capacitive coupling and enables a wider tuning range of the effective electromagnetic parameters compared to single-layer designs.

The unit cell is designed to operate around a center frequency of 3.5 GHz, which is well suited for ground-penetrating radar applications targeting shallow subsurface objects buried in sandy soil. This frequency offers a favorable

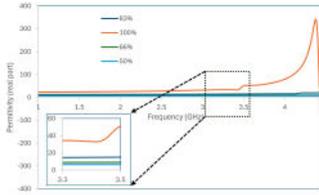


Fig. 3. Effective permittivity at different scaling factors

compromise between penetration depth and spatial resolution, making it particularly effective for detecting superficial buried objects while minimizing excessive attenuation. Moreover, the unit cell exhibits wideband behavior, which is essential for ultra-wideband GPR systems and graded-index implementations.

To realize the graded-index behavior, the unit cell dimensions are uniformly scaled down to 50% of the original geometry while preserving the overall topology. This scaling strategy enables continuous tuning of the transmission phase and effective permittivity without introducing abrupt discontinuities. As shown in Fig. 2, the transmission amplitude remains high across all scaling factors. The minimum transmission occurs for the largest unit cell size and remains acceptable, with a value of approximately 0.55. The transmission phase varies by more than  $80^\circ$  across the scaling range at the design frequency of 3.5 GHz. This phase agility is sufficient to compensate for the propagation phase delay associated with spherical wavefronts radiated by the GPR antenna, enabling effective wavefront flattening and focusing in the final metasurface structure.

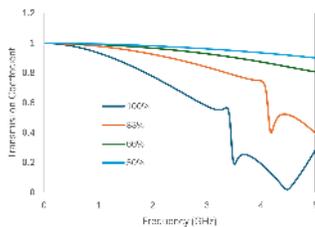


Fig. 2. Transmission coefficient at different scaling factors

The effective dielectric constant of the unit cell is extracted using standard retrieval techniques based on the simulated scattering parameters. Fig. 3 shows the variation of the effective permittivity as a function of the unit cell scaling factor. A wide tunability range is observed, which is essential for implementing a graded refractive index profile. Importantly, the extracted permittivity remains stable and weakly dispersive up to 4.4 GHz, ensuring broadband operation and minimizing phase distortion within the intended GPR frequency band.

These characteristics confirm that the proposed LC-based two-faced unit cell is well suited for the realization of a graded-index metasurface for ground-penetrating radar applications, providing wideband performance, strong phase control, dual polarization and stable dielectric behavior in the frequency range of interest.

### B. Graded-Index Metamaterial Configuration for GPR

A graded-index (GRIN) metamaterial metasurface is synthesized using the proposed LC-based unit cell to enhance GPR performance in dry sand environments. The metasurface consists of a  $12 \times 12$  array of unit cells placed between the antenna and the soil medium. The effective permittivity is highest at the center of the metasurface and gradually decreases toward the edges by scaling the unit cell dimensions, enabling phase compensation across the aperture and improving wave penetration into the ground.

To evaluate target detection capability, a metallic object is embedded in the dry sand layer at a burial depth of 2 cm. This configuration represents superficial subsurface targets commonly encountered in GPR applications. The graded permittivity distribution transforms the spherical wavefront radiated by the antenna into a more collimated field propagating into the sand, thereby enhancing energy coupling and target illumination.

The simulated electric field distribution shown in Fig. 4 confirms the effectiveness of the proposed metasurface. When the GRIN metasurface is employed, a clear field concentration is observed within the sand layer and around the buried metallic element, indicating good penetration and detectability.

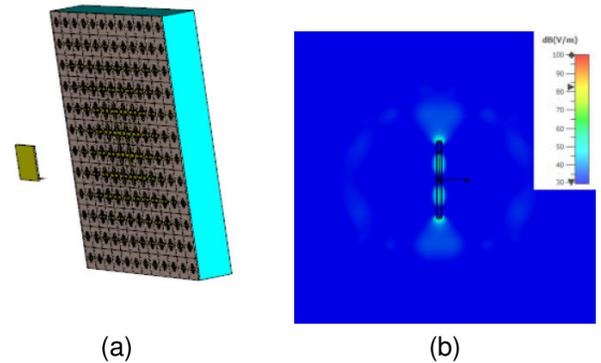


Fig. 4. (a) Experiment setup. (b) Electric field distribution.

### III. CONCLUSION

The proposed graded-index metamaterial metasurface improves electromagnetic coupling and field focusing in air-coupled GPR systems. Simulations confirm enhanced penetration into dry sand and clearer illumination of shallow metallic targets. These results demonstrate the potential of GRIN metasurfaces to increase detectability in near-surface GPR applications.

### REFERENCES

- [1] D. J. Daniels, *Ground Penetrating Radar*, 3rd ed. London, U.K.: IET, 2004.
- [2] A. S. Turk and G. D. Tatoğlu, “Antenna design for ground penetrating radar systems,” *J. Electromagn. Waves Appl.*, vol. 24, no. 18, pp. 2561–2574, 2010.
- [3] N. Engheta and R. W. Ziolkowski (eds.), *Metamaterials: Physics and Engineering Explorations*. Wiley-IEEE Press, 2006.
- [4] J. Geng, L. Liu, and S. Yang, “Metamaterial-inspired antenna for improved air-coupled GPR sensing,” *IEEE Geosci. Remote Sens. Lett.*, vol. 13, no. 4, pp. 542–546, Apr. 2016.