Surface Wave Manipulation based on Transformation Optics: from Design to Manufacturing

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***Abstract* - In the last few years, much interest has grown in the control and manipulation of electromagnetic surface waves. The aim of this paper is to present a new design and manufacturing approach based on Transformation Optics. To validate the proposed design, an all-dielectric structure for surface wave propagation will be presented: the device shows good performance in terms of wide bandwidth, polarization independence, and easy-to-fabricate, with potential applications for antennas, sensors, imaging and telecommunications.**

***Index Terms* — Surface Wave, Transformation Optics, Antenna design, Manufacturing process.**

1. Introduction

A large amount of interest in the study of electromagnetic guided waves has re-emerged due to new requirements in engineering applications. A particular class of such waves, namely surface waves, has been a topic extensively studied over the past few years [1]. Surface waves typically arise at the interface between two different media or stratified structures. Controlling and manipulating surface waves properties, is of great importance in many application concerning absorption [2], radiation [3], sensing and communications [4]. To this regard, a peculiar application in the field of antennas is to design invisibility cloak devices, in order to effectively render invisible an object, from impinging electromagnetic waves. Several approaches have been proposed in the past: scattering cancellation approach [5] Frequency Selective Surfaces (FSS) technology [6]; Transmission-Line Networks [7]; Parallel-Plate [8] and the more recent use of metamaterials [9]. Unfortunately, all such approaches suffer from several drawbacks, i.e. being dependent on the geometry and shape of the object to cloak, not being suited for electrically large dimensions, relying on material properties not easily found in nature, being extremely sensible to material losses and polarization dependent.

The aim of this work is to present a Transformation Optics (TO) based device able to control and tailor electromagnetic surface waves: first the design approach will be presented; then, the manufacturing process will be shown; finally, the device will be tested in the frequency range of 8 – 12 GHz and the related results reported.

2. The TO design approach

TO [10] establishes a link between geometries and materials properties, which control the properties of electromagnetic waves. In the past, several studies were focused on the design of space wave cloaks such as three-dimensional [11, 12], non-Euclidean [13], quasi-optical [14] and carpet cloaks [15]. There are some notable bottlenecks such that materials used in the design must be dispersive, inherently narrow band and anisotropy.

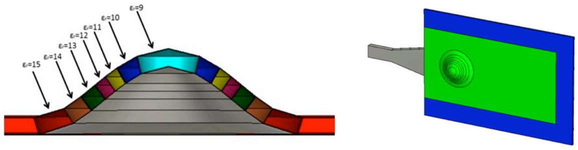
Here we present a solution to control and manipulate the surface wave propagation, in order to cloak an object. By following the TO approach used in [16], the required permittivity distribution of the device is evaluated by equating the two ray orthogonal paths: the circular (of fixed radius), and the radial one (of fixed angle):

$$\frac{n'(\theta)}{n(\theta)} = \frac{\sqrt{R^2(\theta)+R'^2(\theta)} - R(\theta)\cos(\theta) - R'(\theta)\sin(\theta)}{R(\theta)\sin(\theta)} \quad (1)$$

Curved geometries and graded index media are combined to create an isotropic and omnidirectional surface wave cloak.

3. Realization, manufacturing and characterization of the cloaking device

Let's have a rotationally symmetric curved metallic surface on which waves can propagate, as shown in Fig 1a. The cloak device is realized by layering multiple dielectrics on the cosine-curved metal object. The structure is discretized in distinct layers which permittivity varies in the range 9 - 15. This index profile will ensure the propagation characteristics of a flat plane are emulated by the curved one, thus making the metallic object invisible to waves.



(a) (b)

Fig. 1. (a) Metallic cosine profile and Graded-index profile; (b) The simulated and realized setup.

The permittivity values, in each layer, have been achieved using alternative dielectric mixtures with different volume fractions and particle sizes. The device was fabricated using a series of novel techniques and the materials used are similar to those described in [17, 18]. Optical microscopy characterization was used to verify homogeneity and to measure the permittivity values of the materials in the range 8 - 12 GHz, exhibiting a stable dielectric constant over the whole frequency band. The manufacturing technique was used to fabricate three different samples: the simple flat plane case (sample 1, our reference), a uniform dielectric distribution over the metallic bump (sample 2), both of them with relative permittivity of 15, and the graded index structure (sample 3).

4. Results

The device is illuminated by using a pyramid horn antenna as shown in Fig 1b. An absorbing layer is used to reduce reflections at the boundaries. Simulations were solved using a full-wave, commercial, electromagnetic solver (CST 2014). Measurements were developed using an NSI planar scanner, with a monopole probe positioned perpendicular to the surface.

All materials were simulated and measured by using actual manufactured electrical properties (in terms of real and imaginary part). In order to quantify the reliability of the device, we evaluated the normal component of the electric field E_z along a sample line (whose length is 60mm), after the metallic bump. Results are shown in Figure 2.

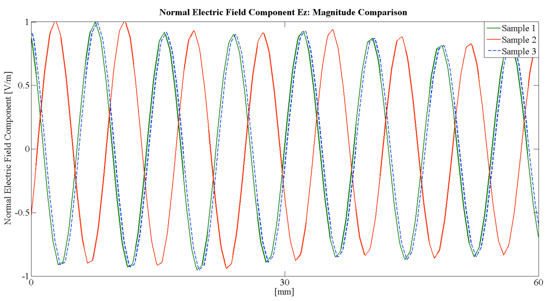


Fig. 2. Normal electric field component comparison along the sample line for all the 3 samples considered.

5. Conclusion

In this paper, a new all-dielectric structure for surface wave propagation on curved objects was presented. A new model was developed in order to design the surface wave device and link the electromagnetic characteristics with its engineered materials as well as their geometrics. The device was designed, simulated and manufactured in the frequency range of 8 - 12GHz. It showed good performance as it is insensitive to wave polarization as well as broadband.

The proposed device can be applied for the control and manipulation of electromagnetic surface waves, involving antennas, sensing devices and absorbers.

References

[1] J. A. Polo, T.G. Mackay, A. Lakhtakia, "Electromagnetic Surface Waves: A Modern Perspective", *Elsevier*, 2013.

[2] A.P. Feresidis, G. Apostolopoulos, N. Serfas, and J.C. Vardaxoglou, "Closely Coupled Metallo-dielectric Electromagnetic Band-Gap Structures Formed by Double-Layer Dipole and Tripole Arrays," *IEEE Transactions on Antennas and Propagation*, vol. 52, pp. 1149-1158, 2004.

[3] S. Wang, A.P. Feresidis, G. Goussetis, and J.C. Vardaxoglou, "Low profile resonant cavity antenna with artificial magnetic conductor ground plane," *Electronics Letters*, vol.40, pp.405-406, 2004.

[4] F. Yang , Y. Rahmat-Sammi and A. Kishk "Novel surface wave antennas for wireless communications", *IEEE Antennas Propagation Symp.*, 2005.

[5] P.-Y. Chen, J. Soric, and A. Alù, “Invisibility and Cloaking Based on Scattering Cancellation,” Advanced Materials, vol. 24, no. 44, pp. OP281–OP304, 2012.

[6] B. A. Munk, Frequency Selective Surfaces: Theory and Design. John Wiley & Sons, 2005.

[7] P. Alitalo, O. Luukkonen, L. Jylha, J. Venermo, and S. A. Tretyakov, “Transmission-Line Networks Cloaking Objects From Electromagnetic Fields,” IEEE Transactions on Antennas and Propagation, vol. 56, no. 2, pp. 416–424, 2008.

[8] P. Alitalo and S. A. Tretyakov, “Electromagnetic cloaking of strongly scattering cylindrical objects by a volumetric structure composed of conical metal plates,” Phys. Rev. B, vol. 82, no. 24, p. 245111, Dec. 2010.

[9] X. Ni, Z.J. Wong, M. Mrejen, Y. Wang, and X. Zhang, “An ultrathin invisibility skin cloak for visible light,” Science, vol. 349, pp. 1310-1314, 2015.

[10] R. Yang and Y. Hao, “An accurate control of the surface wave using transformation optics,” *Optics Express*, vol. 20, pp. 9341-9350, 2012.

[11] J. B. Pendry, D. Schurig, and D. R. Smith, “Controlling Electromagnetic Fields,” *Science*, vol. 312, no. 5781, pp. 1780–1782, Jun. 2006.

[12] U. Leonhardt, “Optical Conformal Mapping,” Science, vol. 312, no. 5781, pp. 1777–1780, Jun. 2006.

[13] U. Leonhardt and T. Tyc, “Broadband Invisibility by Non-Euclidean Cloaking,” *Science*, vol. 323, no. 5910, pp. 110–112, Jan. 2009.

[14] J. Li and J. B. Pendry, “Hiding under the Carpet: A New Strategy for Cloaking,” *Phys. Rev. Lett.*, vol. 101, no. 20, p. 203901, Nov. 2008.

[15] X. Ni, Z.J. Wong, M. Mrejen, Y. Wang, and X. Zhang, “An ultrathin invisibility skin cloak for visible light,” *Science*, vol. 349, pp. 1310-1314, 2015.

[16] R.C. Mitchell-Thomas, T.M. McManus, O. Quevedo-Teruel,, S.A.R. Horsley, and Y. Hao, “Perfect Surface Wave Cloaks,” *Phys. Rev. Lett.*, vol. 111, 213901, 2013.

[17] C. Mateo-Segura, A. Dyke, H. Dyke, S. Haq and Y. Hao, “Flat Luneburg Lens via Transformation Optics for Directive Antenna Applications,” *IEEE Transactions on Antennas and Propagation*, vol. 62, pp. 1945-1953, 2014.

[18] O. Quevedo-Teruel, W. Tang, R. C. Mitchell-Thomas, A. Dyke, H. Dyke, L. Zhang, S. Haq and Y. Hao, “Transformation Optics for Antennas: Why limit the bandwidth with Metamaterials?” *Scientific Reports*, vol. 3, 1903, 2013.