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Width-Modulated Microstrip Line Unit Cell: A Basic Element for Dispersion Engineered Surfaces for Reflectarray and Holographic Applications

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Abstract—**Dispersion characteristics of different classes of width-modulated microstrip line based unit cells forming High Impedance Surfaces (HISs) are investigated. The HISs consist of a periodic arrangement of macro unit cells, formed by sequential repetitions of similar elementary unit cells. Within the single unit cells, mono- and multi-layer metallization configurations are proposed and numerically characterized, which lead to interesting phenomenon of controlling the position and width of the band-gap and provide a key element for efficient dispersion engineering. The effects of the modulation on periodic and quasi-periodic structures are discussed. The modulation parameter of the different metallization within the macro unit cells are changed, which allows competently controlling the reflective phase over a wide frequency band. The proposed modulation mechanism is well suited for the synthesis of reflectarrays and/or holographic surfaces.**

Index Terms—**Dispersion Engineering, Holography, Metasurfaces, Periodic structures, Frequency Selective Surface (FSS), Reflectarray**

I. INTRODUCTION

Recent research in reflectarrays (RAs) and holographic antennas (HAs) have gained significant attention of the antenna community. Periodic and quasi-periodic structures [1] have emerged as good candidates for these applications, and the research concentrated on exploring the new geometry of unit cell elements. The periodic arrangement of unit cells in a predefined way gives rise to a structure exhibiting band-gap(s) and regions of bounded and unbounded waves across the surface. These properties help in the design of surfaces for RA and HA applications. The functioning of RAs is based on the concept of phase compensation at element level. This cannot be achieved by the periodic arrangement and a properly designed quasi-periodic assembly emerges as a practical solution. In the quasi-periodic case, the dimensions of the single cells are modified to achieve co-phase re-radiation for concentrating the scattered waves in a specific direction. Many phase compensation schemes have recently been developed [2]. For RA configuration [3] the incident field is completely reflected making the structure suitable for the RA application, whereas controlling the phase of the reflected wave when the incident wave can couple to surface waves results in a region suitable for HA applications [4]-[7]. In both of these applications the effective control of the phase has been proven to be extremely critical. A design for holographic surface is presented in [4], where a method is described for controlling the electromagnetic surface wave propagation and radiation from complex metallic shapes. Scalar surfaces can be implemented using a simple lattice of square metal patches with variable gap widths, while tensor surfaces can be implemented by introducing slits with different rotation angles inside the patch [5].

The printed nature of these structures has the advantage of easier manufacturing than a conventional parabolic reflector antenna and their pattern performance is similar although over a narrower range of frequency. The bandwidth limitation is a consequence of the non-linear variation in the reflection phase, mainly due to the high Q of the resonators, whose resonant frequencies define the band limits. Bandwidth may also be limited when the element size is changed to produce the required progressive phase distribution across the aperture. For high quality RAs, a smooth phase response over a larger than 360° range is desired [2]. A possible solution has been demonstrated using dissimilar size patch elements for single [3] and dual-frequency [4] operations. In configurations using patches, smooth phase responses are difficult to be achieve since independent control of the sizes of the patches should be considered, but the close positioning of the patches with respect to each other makes independent control a serious concern. An alternative architecture, presented in [4], consists of a two-layer array of resonant ring elements that

are widely employed as frequency selective surfaces. However, most of the structures provide substantial control of phase but with discontinuities, leading to radiation losses and add additional complexity in the design.

The authors of the present paper have been extensively working on unit cells based on modulated lines [7-14]. Several possible combinations and their effectiveness in quasi-periodic and stacked configurations have been demonstrated in the recent past. In this paper we summarize some of our main results, explaining the potential and advantages of a width-modulated microstrip line geometries in periodic, quasi-periodic and stacked realizations. In particular, we focus on the effective phase contrivance achieved with these geometries. The structure is continuous across each single layer; the smooth transitions across the cells highlight the possibility of providing a structure without discontinuities, which eliminates spurious radiation. On the other hand, the coupling between adjacent rows manifests in a weaker manner than for the standalone resonators.

The paper is organized as follows: in Section II a short description of the idea behind the use of modulated line is presented. Section III deals with a quasi-periodic configuration. It is followed by a multilayer configuration described in Section IV. Finally, some concluding remarks are provided in Section V.

II. MODULATED LINE GEOMETRY

The idea of the modulated microstrip line based periodic structure has been introduced in [8] and extension to quasi-periodic arrangement has been proposed in [9]. In this section some aspects of the considered structure are summarized and its characteristics as a reflector surface are discussed.

A. Theoretical background

An example of a modulated line unit cell of dimensions D_u and D_v is shown in Fig. 1. When varying the width of the microtrip line, a change in the effective dielectric constant within the unit cell is obtained. The phase between the input and output ports (defined orthogonally with respect to the modulation direction) is controlled by the modulation itself. A particular instance is represented by a sinusoidal modulation around an average value of ε_{avg}, with amplitude of M_u as described by equation (1):

$$\varepsilon_{eff}(u) = \varepsilon_{avg}\left[1 + M_u\sin\left(2\pi\frac{u}{D_u}\right)\right] \qquad (1)$$

In this formulation, the period of the modulation equals the dimension of the unit cell in the longitudinal direction u; M_u (<1) and ε_{avg} are called the modulation parameters. The sinusoidal modulation in (1) has been chosen because it allows the dispersion diagram to be expressed in a closed form in terms of Mathieu's and Hill's functions for the TE and TM polarized field respectively propagating within the structure in the direction of the modulation.

The variation expressed in (1) is obtained by varying the width 'W' of the microstrip line between a minimum and maximum widths W_{min} and W_{max}, respectively. The shape of the line is obtained by projecting the given expression in (1) on the $\varepsilon_{eff}(W)$ curve. In [8] such relationship was obtained numerically, and coupling between the parallel lines was fully taken into account. In a similar manner, any given modulation $\varepsilon_{eff}=\varepsilon_{eff}(u)$ can be synthesized. For the sinusoidal modulation, the dispersion diagrams computed with an in-house implementation of the method [8, 9] have been compared with the analytic expression and further checked experimentally; the results (not reported here) agree very well.

Fig.1 shows an example of geometry of a unit cell. The overall dimensions of the unit cell are D_u = 4.5 mm and D_v = 4 mm. The substrate material is alumina with relative permittivity ε_r = 10.2 and thickness h = 1.58 mm. The width of the microstrip line has been varied between W_{min} = 0.4 mm and W_{max} = 3.9 mm, which corresponds to a maximum modulation index M_u = 0.186 for the given configuration.
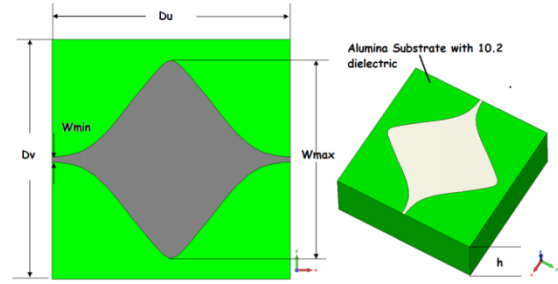

Fig. 1. Example of the geometry of unit cell with D_u = 4.5 mm, D_v = 4.0 mm and modulation constant M_u = 0.186.

The generic dispersion diagrams in Fig. 2(a) corresponding to a sinusoidal modulation show the variation of the dispersion relations for the first four modes for different values of M_u, including the case M_u = 0, i.e., absence of modulation. The limits of the band-gaps depend on M_u, while the position is basically determined by ε_{avg} [1]. In the first band-gap, below the light-line, the incident field will be completely reflected, making the structure suitable for RA applications. As the frequency goes higher and the dispersion curves cross the light-line, the fields are no longer bounded, and radiation of surface wave occurs. A comparative study between numerical and analytic data has been reported in [8] and will not be repeated here. The control of the radiation of the surface waves by the shape of the microstrip line, and in particular by the modulation parameters, allows implementation of leaky-wave or holographic antennas. A similar control mechanism based on variation of surface wave impedance has been recently demonstrated for a polar leaky-wave antenna in [7]. The lack of periodicity in the non-modulated case, i.e., the case of parallel constant-width lines, brings the limit of the first Brillouin zone to infinity, because the longitudinal periodicity of the unit cell has an undefined length. Such a configuration will not radiate because its dispersion curve will always be below the light-line.

B. Electromagnetic behavior and the effect of modulation parameters

Figures 2 (b) and (c) show the effect of the modulation parameters on the phase of the reflected field from the surface at the air-microstrip interface. The data are for normal incidence and for the electric field vector orthogonal to the modulation direction. The central frequency shifts from 14.8 GHz for zero modulation ($M_u = 0$), where no band gap exists, to 9.93 GHz for maximum modulation of the line with $M_u = M_u(\text{max}) = 0.186$.
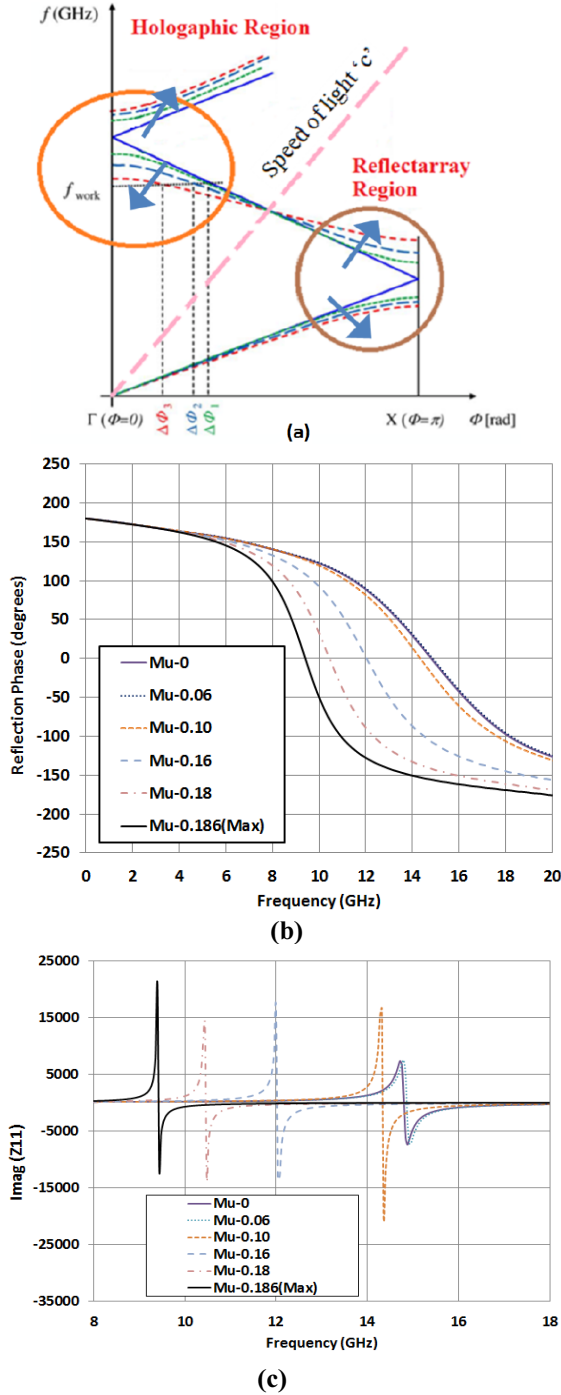

(a)

(b)

(c)

Fig. 2. (a) Generic dispersion diagram of width-modulated microstrip line, the modulation index M_u is considered as a parameter; (b) Reflection phase of single unit cell with normal incidence (for the unit cell defined as in Fig.

1) (c) Surface impedance for different values of M_u (normal incidence). Taken from [11]; copyright EurAAP; used with permission.

In the analysis the width of the microstrip line at the two ports has been maintained constant. This corresponds to a variation of both ε_{avg} and M_u. As stated above, a shift of the position of the band gap is expected, which is associated to a variation in its size. The data in Fig. 2(b) reflect these assumptions

III. QUASI-PERIODIC ARRANGEMENT OF WIDTH-MODULATED LINE

In the next step of the analysis, a macro unit cell obtained by cascading different modulated but similar unit cells has been considered [13]; a quasi-periodic sequential arrangement of four unit cells is shown in Fig. 3. In particular, unit cells with values of $M_u = 0$, 0.6, 0.16 and 0.186 have been considered and cascaded. To simplify the notation, these four geometries have been denoted by D, C, B and A, respectively. Fig. 3(a) is an example on how such a macro unit cell can be used to build a 2D aperture, while in Fig. 3(b) the phase variation difference between the input and output ports of the similar unit cells is sketched. Among the many possible combinations in this study, two cases, namely the sequences DCBA (Fig. 3c) and ABBA, have been analyzed more in detail. First, it has been positively checked that in the cases of ABCD and DCBA, the incident field sees the same surface impedance (not reported).
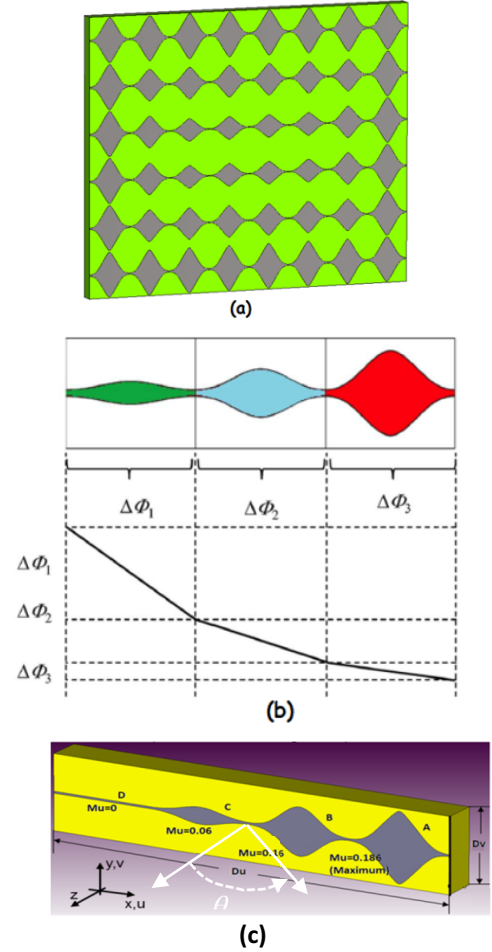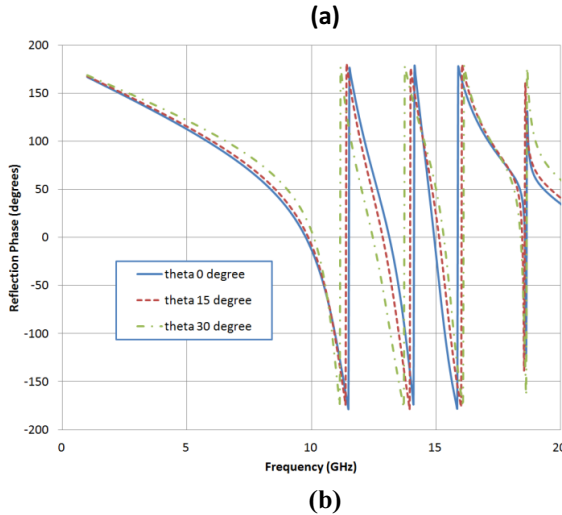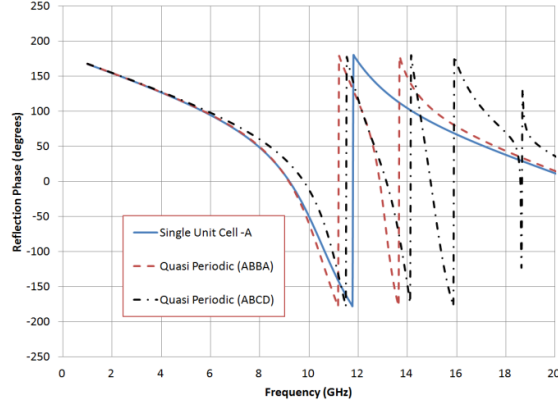

(a)

(b)

(c)

3

(a)

(b)

Fig. 4. Comparisons of single unit cell A and the macro unit cells ABBA and ABCD configurations (a); Oblique incident performance of the ABCD configuration (b).

In contrast to this, ABBA is a type of skew symmetrical structure whose response with respect to the ABCD configuration will be different for the phase of the reflected field, i.e., for the impedance, as it can be observed in Fig. 4(a). To generate the data for normal and oblique incidence the structure has been considered with periodic boundary conditions both in the longitudinal and transverse directions. Floquet modes were used on the macro unit cell in the commercial solver [15] for all these analysis. The idea behind this comparison is to demonstrate the controllable reflection phase.

As expected, at low frequencies, the responses are similar, and the differences appear above 15 GHz mainly because of the intersection between the dispersion curves with the light-line for some of the unit cells (see Fig. 2(a)). Above the light-line, the impinging electromagnetic wave couples to the surface waves.

The generated wave propagates along the structure and scatters in a different positions with respect to the incident point. Its phase depends on the load, i.e., the local wave impedance, seen by the surface wave, and on the distances

between the incident and radiation points that are different for the two considered configurations. Consequently, the reflection phases differ, as illustrated in Fig. 3(b).
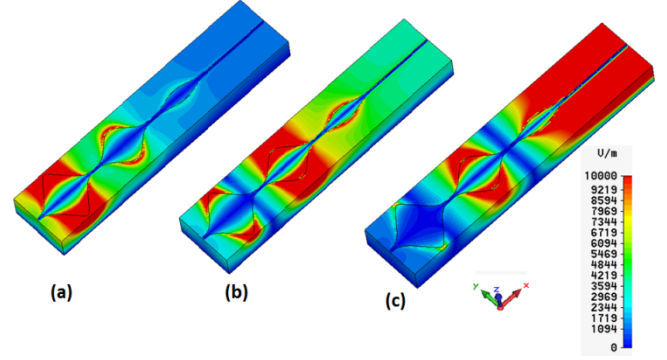

Fig. 5. Electric field distributions on the surface at (a) 10.36, (b) 14.05, (c) and 16.03 GHz (normal incidence). Reprinted with permission from [10].

Fig. 5 shows the electric field intensity at three frequencies in a plane parallel to the interface for the ABCD configuration for normal incidence. It is evident that the resonance of each element (single unit cell) occurs independently when the coupling with the adjacent elements in the longitudinal direction is small. This observation indicates that the quasi-periodic configurations allow the controlling of the surface impedance and phase at any desired frequency point by considering a different unit cell.

In addition to the field distribution on the dielectric–air interface, the fields inside the dielectric at a height of 0.78 mm from the ground (middle of dielectric surface) have also been analyzed. A significant amount of field is present inside the dielectric, but it is localized around a resonating single unit cell, as can be observed from Fig. 5. The periodic condition imposed on the lateral walls allows extending the field amplitude from $-D_y/2$ to $+D_y/2$, with the same value for each resonance. A change in such behavior is expected for a quasi-periodic arrangement in the y-direction as well. Furthermore, one can observe that due to the symmetry of the structure with respect to the x-axis, the field on the symmetry axis is null. This phenomenon is analogous to a folded dipole (with the cold point in the middle of the non-fed arm), where this point can be used to ground the structure, for fixing. Here, this can allow inserting vias and/or active components. Investigations of the two above mentioned phenomena are currently undergoing.

IV. MULTILAYER ARRANGEMENTS OF WIDTH-MODULATED LINE

As an extension of the quasi-periodic 2D arrangement discussed in the above section, a 3D volumetric realization has been proposed in [14]. In this section the behavior of three-layer grounded arrays of width-modulated microstrip lines are analyzed. Close to the resonances, a 360° phase variation of the reflected field can be easily and efficiently achieved by varying the modulation across different layers. Moreover, a suitable choice of modulation may lead to bandwidth enhancement of the array. In addition, the structure is continuous and smoother transitions across the

cells highlight the possibility of providing a structure without discontinuities, which eliminates spurious radiation.
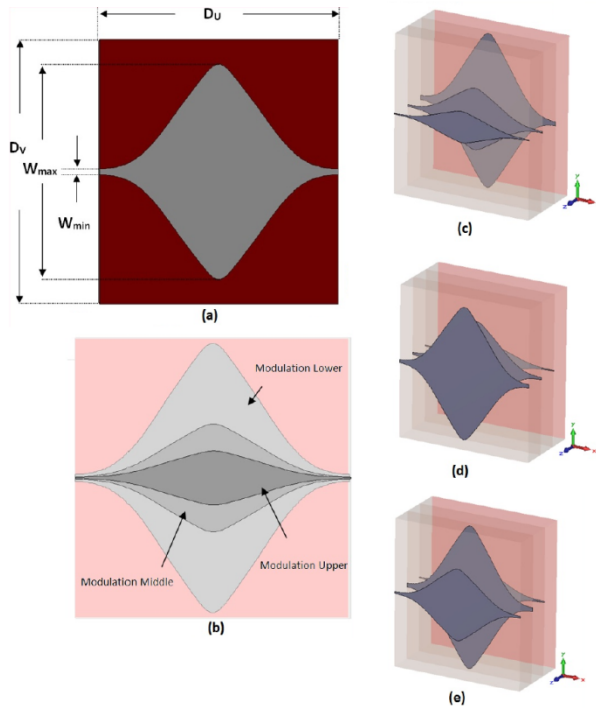

Fig. 6. Width-modulated microstrip line (a) Multi-layer modulated microstrip structure with variable modulations (b). Multi-layer modulated unit cell with maximum modulation in the lower- (c) in upper- (d) and in the middle- layer (e). Taken from [14]; copyright EurAAP; used with permission.

Multi-layer unit cell configurations, evoking a Yagi-Uda antenna configuration, with three modulated microstrip line widths are shown in Fig. 6. Fig. 7 (top) shows the results of some combinations of lines with various widths that have been stacked together. For one of the considered combination, a progressive phase shift of up to 700° within the single band gap region has been obtained. It corresponds to the situation where the modulation indexes in the three layers are equal, and $M_u = 0.186$. Such a configuration represents a system of identical strongly coupled resonators, with slightly different resonance frequencies. This, in turn, produces a wider phase variation in the frequency band, defined by the lower and upper resonance frequencies. Fig. 7 (bottom) gives the imaginary values of surface wave impedance. It shows a significant variation in the impedance, resulting band-gaps that arise because of the changing modulations across different layers.

V. Conclusions

Extension of a recently introduced width-modulated microstrip line based modulation mechanism has been presented and discussed for several combinations of quasi-periodic stacked arrangements. The results of the numerical analysis of the proposed configurations confirm that the proposed surface modulation mechanism can be effectively

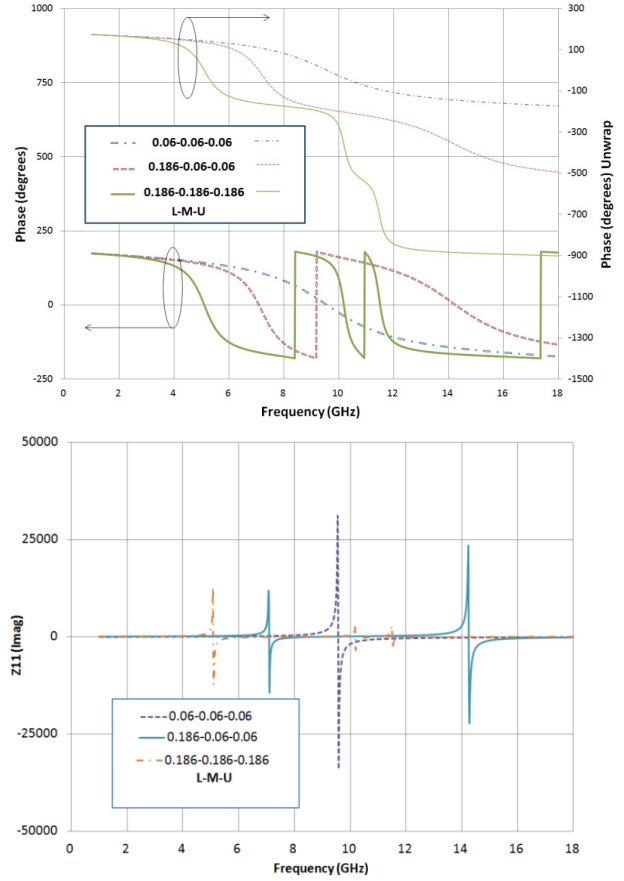used in the synthesis of holographic surfaces and reflectarrays.

Fig. 7. Variation of the reflection phase (top) and of the imaginary part of the surface impedance (bottom) for three different combinations of M_u in each layer as shown in Fig.5 (L-M-U indicates lower-, middle and upper layer modulation index respectively). Taken from [14]; copyright EurAAP; used with permission.

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Ladislau Matekovits was born in Arad (Romania), on November 19, 1967. He received the degree in Electronic Engineering from Institutul Politehnic din Bucuresti, Bucuresti, Romania and the Ph.D. (Dottorato di Ricerca) in Electronic Engineering from Politecnico di Torino, Turin, Italy in 1992 and 1995 respectively. Since 1995 he has been with the Electronics Department of the Politecnico di Torino, first with a post-doctoral fellowship, then as a Research Assistant. He joined the same Department as Assistant Professor in 2001 and was appointed as Senior Assistant Professor in 2005. In late 2005 Dr. Matekovits was Visiting Scientist at the Antennas and Scattering Department of the FGAN-FHR (now Fraunhofer institute), Wachtberg, Germany. Beginning July 1, 2009, he has been a Marie Curie Fellow at Macquarie University, Sydney, NSW, Australia. He has been visiting academic at the same institution in 2013.

His main research activities concern numerical analysis of printed antennas and in particular development of new, numerically efficient full-wave techniques to analyze large arrays, optimization techniques and active and passive metamaterials.

Dr. Matekovits is the recipient of various awards in international conferences, including the 1998 URSI Young Scientist Award (Thessaloniki, Greece), the Barzilai Award 1998 (young scientist award, granted every two years by the Italian National Electromagnetic Group), and the Best AP2000 Oral Paper on Antennas, ESA-EUREL Millennium Conference on Antennas & Propagation (Davos, Switzerland). He is member of several conferences program committees. He was Assistant Chairman and Publication Chairman of the European Microwave Week 2002 (Milan, Italy). He serves as reviewer for different journals, including the IEEE Transactions on Antennas and Propagation and the IEEE Antennas and Wireless Propagation Letters.

Yogesh Ranga received the Ph.D. degrees in electronics engineering from the Macquarie University, Sydney, Australia in 2011. He joined the Commonwealth Scientific and Industrial Research Organization (CSIRO) as Post-Doctoral Research Fellow and also appointed as honorary research fellow at Macquarie University in year 2011. Dr Yogesh is currently serving as Chair of the IEEE New South Wales (NSW) MTT/AP Joint Chapter, IEEE NSW GOLD Affinity group and a member of the IEEE NSW Committee. He has served in technical program committees of international conferences and reviewer for the IEEE Transactions on Antennas and Propagation, the IEEE Antennas and Wireless Propagation Letters and the PIER Journal of Electromagnetic Waves and Applications (PIER/JEMWA). Prior to joining to CSIRO, he worked with CST Microstripes (earlier known as Flomerics India Pvt Ltd.) as Quality Assurance Engineer and SAMEER, IIT

Powai as Research Scientist. His research activities include ultrawideband communication, printed antennas, low noise amplifiers and metasurfaces.

Editorial Comment

This paper discusses a novel technique for creating Metasurfaces by using width-modulated microstrip line. Such structures are useful for many applications, including Reflectarrays and Holgographic surfaces. The dispersion characteristics of waves propagating along these surfaces, and/or their reflection properties are engineered by using the techniques mentioned in this work.