

# Planar Antennas Based on Surface-to-Leaky Wave transformation

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**Abstract**— Advances in spiral circularly polarized surface wave antennas are presented. Such antennas are designed by using the concept of modulation of surface reactance. The surface impedance is reconstructed by printing a dense texture of sub wavelength metal patches on a grounded dielectric slab. The final devices are planar thin antennas with a simple layout and feeding. Numerical results are present and discussed for a prototype.

## I. INTRODUCTION

This paper presents recent advances on a new typology of planar circularly polarized LW antennas excited by a single-point feed. The basic structure we are dealing with is constituted by variable, spiral-shaped modulated surface impedance. The surface is excited by a cylindrical surface wave (SW) and converts it into a circularly polarized LW. To illustrate the basic process, a simple vertical dipole is used as a feeder.

The design process is based on describing the local interaction between an elemental angular wavefront of cylindrical SW and the corresponding elemental angular sector of the spiral, by means of a 2D problem of a sinusoidal reactance excited by a planar SW. The latter is treated by means of the Oliner-Hessel method described in [1]. This local interaction can be interpreted as the holographic principle illustrated in [2]. This interpretation is given in [3].

This paper is structured as follows. In section II the local canonical problem is presented as a basis step for the design of antennas based on modulation of surface reactance. The complex propagation constant of the cylindrical surface wave is discussed on the basis of the local 2D sinusoidally-modulated surface-impedance solution given by the Oliner-Hessel procedure. Section III presents the interaction of the exciting surface wave with a spiral impedance surface. Also, an interpretation of the circularly polarized radiation produced is provided. Section IV presents the procedure and the main design guidelines used to reconstruct the modulated surface reactance by using printed patches on a grounded dielectric slab. Section V presents the numerical results for a prototype that is going to be discussed, based on a grounded slab with a texture of dense printed patches with gradually modulated sizes. The final conclusions in Section VI discuss the main features of this class of antennas.

## II. LOCAL CANONICAL PROBLEM

Consider a structure with a surface reactance given by

$$X_s(x) = X_s \left[ 1 + m \cos\left(\frac{2\pi}{a}x\right) \right] \quad (1.1)$$

as depicted in Fig. 1. The surface is assumed infinite and invariant along the  $y$  direction and is excited by a  $TM_0$  surface wave. In the canonical problem the surface wave is assumed to propagate along the  $x$  direction, impinging along the direction of variation of the surface reactance. Therefore no variation is assumed present in the fields in the  $y$  direction.

In the general case of oblique incidence, the scattering problem of the SW impinging on the modulated medium must be treated with a 3D boundary value approach [4]. That is the solution of the problem requires the simultaneous presence of both TM and TE basic modes. However, in the special case of normal incidence, a TM-TE field decomposition is always possible since TM and TE modes are decoupled and can be treated independently. Our study is based on such an assumption which allows us to use results provided in [1].

As shown in [1], the presence of the periodic medium affects more or less quantitatively the wave number of the SW, depending on the characteristics of the impedance modulation. Let  $\beta_{sw}$  be the value of the phase constant for the SW propagating in the unperturbed medium. The modulation of the surface reactance changes the value of the phase constant into  $\tilde{\beta}_{sw} = \beta_{sw} + \beta_{\Delta}$ . If the relative amplitude of the modulation is low, namely the modulation index  $m$ , the value of  $\beta_{\Delta}$  is negligible. That is the SW propagates with a phase constant almost similar to the one associated to the mean value of reactance.

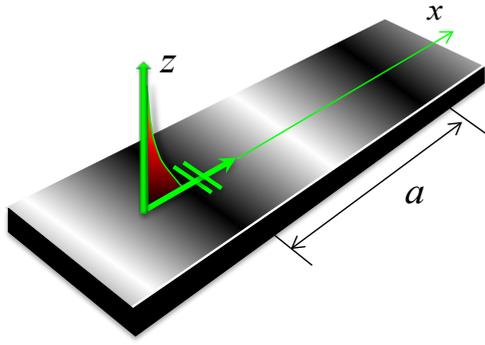


Fig. 1 Geometry for the local canonical problem. The SW propagates along x axis on a structure with a modulated surface reactance assumed infinite along the x direction. Also, the structure is supposed infinite and invariant along the y direction.

It can be shown that for adequate modulations the wave number becomes complex, namely  $\tilde{\beta}_{SW} = \beta_{SW} + \beta_{\Delta} - j\alpha$ , leading to a leaky radiation. The radiation phenomenology is due to a local interference between the modulated surface and the SW wave-number. Such interference leads to a transformation of the bounded SW into an unbounded leaky wave (LW). Due to the periodicity of the structure, the field representation in the periodic medium can be given in terms of Floquet modes. Namely, the propagation constant of the SW is given by

$$k_{zn}^{(j)} = (k_j^2 - k_{xn}^2)^{1/2}, \quad k_{xn} = k_{x0} + \frac{2\pi}{a}n, \quad n \in \mathbb{Z} \quad (1.2)$$

$$k_{x0} = \beta_{SW} + \beta_{\Delta} - j\alpha$$

where the index  $j$  refers to the  $j$ th medium in which the propagation is calculated. As shown in [5], the period  $a$  is sufficiently small, the propagation constant associated to the modal index  $n = -1$  falls in the visible part of the spectrum. This means that  $k_{z,-1}$  in the free space medium may have a real value. That is, the mode -1 propagates along  $z$  in contrast to the fundamental SW component  $n=0$  which decays exponentially along  $z$ . Furthermore, it is possible to observe that the complex -1 indexed wavenumber possesses an imaginary part. The imaginary part is responsible for decay along  $z$  consistently with the radiation leakage. For appropriate values of the period  $a$ , it is also possible that other negative indexed modes radiate energy. Such higher order modes generally possess lower magnitudes with respect to the -1 indexed mode.

### III. TM SURFACE WAVE INTERACTION WITH AN INHOMOGENEOUS SPIRAL SHAPED IMPEDANCE

Let us now consider a circular surface which possesses an Archimedean spiral reactance sinusoidally modulated along the radial direction. The following expression is the analytical description of such a surface.

$$X(\rho, \varphi) = X_s [1 + m \sin(\beta_{SW} \rho - \varphi)] \quad (1.3)$$

The surface is fed by a SW launched by a feeder (for example a small vertical dipole) located in the centre of the structure (see Fig. 2).

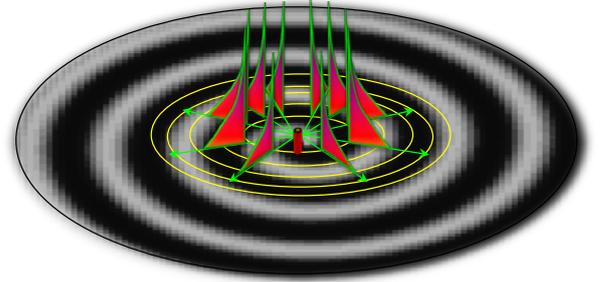


Fig. 2 Surface wave exciting the surface impedance. The surface reactance is sinusoidally modulated with an Archimedean spiral shape. The interaction mechanism between the SW and the surface reactance is approximately the same as in the local canonical problem.

In this case, a rigorous formulation should consider that the SW impinges on the periodic layer not exactly with normal incidence, but with a certain angle. Anyway, the previous considerations on the interaction of the SW with the modulated reactance can still hold on. Indeed, if the angle between the local propagation direction vector and the vector normal to the periodic modulation is small, it is reasonable to assume a weak coupling between TM and TE modes. Therefore, in a first approximation, TM and TE modes can still be treated independently with a small hybridization hypothesis. Such assumption is more reasonable if an initial settlement not modulated zone is added.

In the assumption  $\tilde{\beta}_{SW} \approx \beta_{SW}$ , the modulation periodicity along each ray is equal to  $\lambda_{SW}$ , and the difference between the interception with the spiral of two rays separated by  $90^\circ$  is  $\lambda_{SW}/4$ . Therefore, the dominant Bragg radiation associated to any elemental sector of spiral is directed broadside. Furthermore, any pair of elemental sectors separated by  $90^\circ$  gives rise at broadside to orthogonal and quadrature-phased components respectively, thus justifying the circular polarization. Fig. 3 illustrates the previous concept.

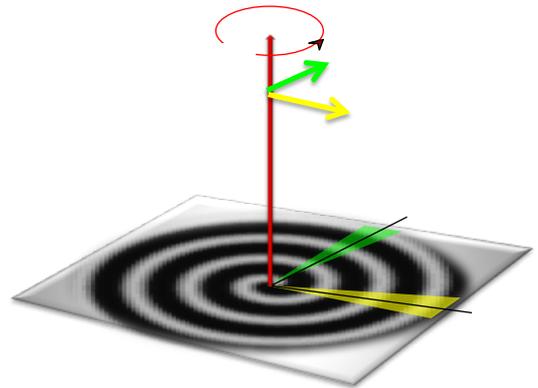


Fig. 3 Excitation of the Archimedean surface impedance. Each radial sector has a modulation periodicity equal to a SW wavelength allowing a broadside radiation. Any orthogonal sectors are excited by the SW with quadrature phase giving rise to a circularly polarized broadside radiation.

#### IV. MODULATION BY USING PRINTED PATCHES

The surface impedance is synthesized by printing a dense texture of square metal patches on a grounded slab with constant period and variable sizes. Each patch has different size slowly varying from a patch to the adjacent one. Thus, to analyse the coupling of a single patch with the rest of the structure, we assume it as embedded in a locally periodic FSS-like lattice. We identify the local texture in a point with a local periodic printed structure that matches adiabatically the local geometry. Thus, for each local periodic structure, a TM mode (with reference to the normal to the antenna surface) transmission-lines is defined as associated with the dominant Floquet mode (Fig. 4). Due to the square shape of the patch, rigorously a small TM/TE hybridization with oblique incidence should be considered. Anyway we decided to neglect it for simplicity, since the small area of the chosen patches determines an unimportant cross-polarization effect. By using the Foster reactance properties of the FSS-network, the pole-zero matching method [6] is applied to find an analytical approximation of the FSS admittance matrix.

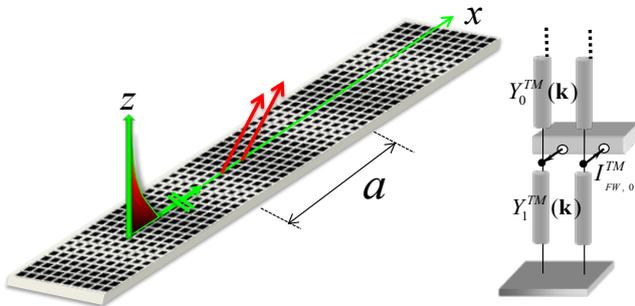


Fig. 4 Local 2D problem for a printed patch holographic antenna and the equivalent transmission line model for the TM dominant surface wave ( $Z_0^{TM} = \zeta k_z/k, Z_1^{TM} = \zeta_1 k_z/k_1$ ).

A data base is constructed analysing some patches as samples. The values of the impedance of the analysed patches are interpolated to find the surface reactance as a function of the patch size. The function is then inverted and the impedance map is used as a look-up table to determine the size of the patch, once the desired impedance value is given.

#### V. PROTOTYPE

Here numerical results are presented for a prototype of a spiral patch antenna that is going to be realized. Experimental results will be presented at conference time. The basic structure is composed of a grounded dielectric slab with a dense texture of printed patches excited by a coaxial probe. Working frequency is set to 17 GHz.

##### A. Feeder

The surface wave launcher is composed of a small vertical probe excited by a coaxial line. In order to perform the impedance matching a circular slotted hat is placed in the top of the dielectric surface. Also, such a configuration allows to have a good efficiency of power launched in TM surface wave with respect to the total input power.

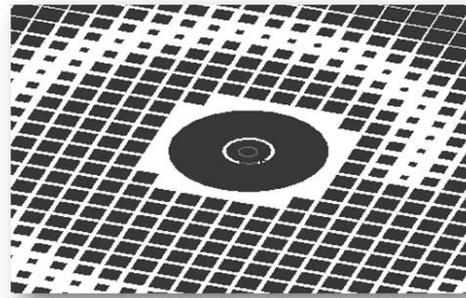


Fig. 5 Detail of the feeder of the structure. A vertical probe is fed by a coaxial cable to launch a  $TM_0$  surface wave. A slotted circular top had is used to perform impedance matching and to increase the efficiency of the feeder as a surface wave Launcher

##### B. Antenna

The antenna is realized on Roger RO4350B substrate with a thickness of 1.905 mm. Relative dielectric constant is 3.66. Square patches are printed on a regular lattice. Each elementary cell of the lattice has a square shape with side of 1.8 mm. The variation of the impedance is realized by varying the side of the patch between 1.7 mm and 0.5 mm. The realized average value of the surface reactance is  $X_s = 261 \Omega$ . The modulation index  $m$  is set to 30% in order to span the all range of the realizable impedance. The final structure has a radius of  $5.9 \lambda$  at 17 GHz and involves 10556 patches. The aperture field is sampled with 8 patches every surface wavelength. Fig. 6 shows the final layout.

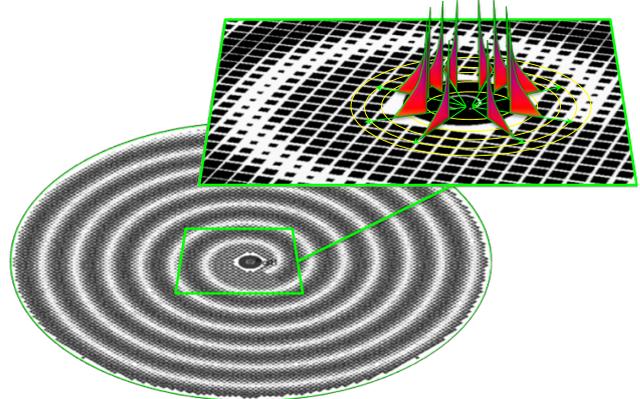


Fig. 6. Layout for the simulated patch lens antenna. The modulated surface impedance is realized by a dense texture of square patches. The surface is excited by a SW launched by a vertical short electric dipole located in the centre of the structure

In the following, the resulting gain from the numerical simulation for both co-polar and cross-polar components are presented.

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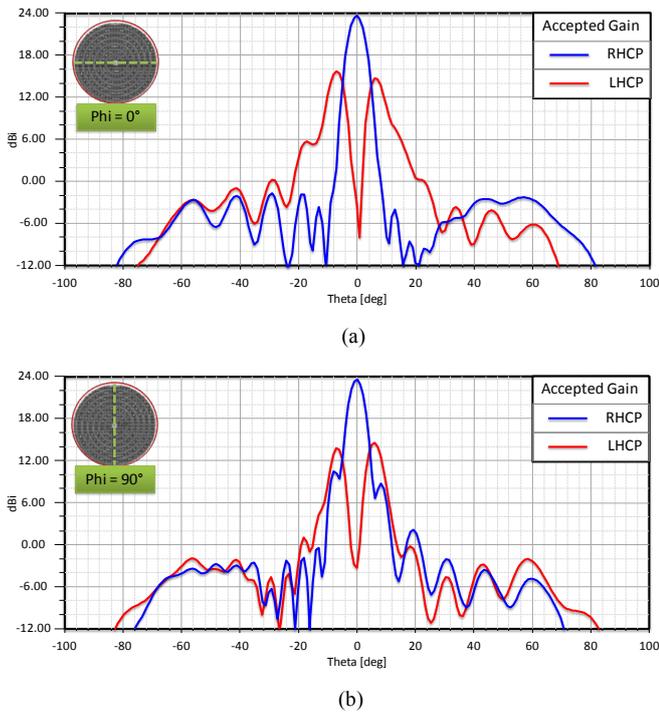


Fig. 7. Gain for the both co-polar and cross-polar components of the simulated prototype antenna. The diagrams are shown for two orthogonal azimuthal angle: (a)  $0^\circ$  and (b)  $90^\circ$

## VI. CONCLUSIONS

In this paper leaky wave broadside circularly polarized antennas based on surface impedance modulation were presented. The impedance surface has an Archimedean spiral profile excited by a  $TM_0$  surface wave. To modulate the surface impedance of a grounded dielectric slab a dense texture of printed metal sub wavelength patches were used. The exciting SW is provided by a small vertical probe located at the centre of the structure. The probe is fed by a coaxial line and is top loaded by a slotted circular patch to perform input impedance matching.

Numerical result were provided for a prototype that is going to be constructed showing the performances of such antennas. Experimental results will be shown during the oral session. The final layout results in a simple thin flat devices with good polarization properties in the broadside direction and with a simple feeding. Experimental measurement will be discussed during the oral session.

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