Dual Beam Sinusoidally Modulated Reactance Surface Antenna

Lorena Pérez-Aguilar, Elena Abdo-Sánchez, Teresa M. Martín-Guerrero, Carlos Camacho-Peñalosa
lpa@ic.uma.es, elenaabdo@ic.uma.es, teresa@ic.uma.es, ccp@ic.uma.es
Dpto. de Ingeniería de Comunicaciones, Universidad de Málaga – Andalucía Tech,
E.T.S. Ingeniería de Telecomunicación, Bulevar Louis Pasteur 35, 29010 Málaga, Spain.

***Abstract*—In this work, a planar dual beam Sinusoidally Modulated Reactance Surface (SMRS) antenna is presented. Our method is based on the implementation of a surface impedance modulated by the superposition of two sinusoidal functions. In particular, the full process of designing a dual beam antenna that radiates at -14° and 28° off broadside at 10 GHz is described. In a second proposed structure, manipulation of the side lobe level (SLL) is achieved by varying the leakage constant along the antenna with negligible changes in the pointing directions. SLL reductions of 3.4 dB and 1.8 dB for each of the synthesised beams are obtained through full wave simulations, as well as gains 13.4 dBi and 13.6 dBi respectively. An excellent agreement between theoretical and simulated results is observed.**

I. Introduction

The evolution towards 5G communication networks is increasing the complexity of current wireless systems. Multi-sector antennas have been widely used in cellular networks to increase channel capacity. However, the implementation of the desired multiple narrow beams usually requires the use of large antennas, which aggravates the issue of lack of space at base stations. In this context, planar leaky wave antennas (LWAs) that allow simultaneous radiation in two separated beams have the potential to be a promising solution due to their low profile and cost, high gain and simple feeding.

A Sinusoidally Modulated Reactance Surface (SMRS) refers to a metasurface whose impedance fluctuates following a sinusoidal pattern along the longitudinal direction. It is well known that a periodic variation of the surface reactance causes part of the energy from the propagating travelling wave to be shed into free space, so it supports the generation of leaky waves [1].

The foundation of this work is Oliner's and Hessel's exhaustive analysis of guided waves on sinusoidally modulated reactance surfaces, in which the propagation properties of leaky waves in relation to the spatial period, amplitude and average value of the sinusoidal modulation function are described [2]. We have extended this analysis to the superposition of two sinusoidal functions with the aim of designing a dual beam leaky wave antenna. Our method could also be interpreted as an application of the holographic theory to a one-dimensional structure [3]. According to the holographic design principle of metasurfaces, the impedance is determined by generating the interference pattern between the reference wave that illuminates the antenna and the desired radiation pattern evaluated at the surface. In our case, considering that the reference wave is a surface wave and the radiation pattern is a superposition of pencil beams pointing to the target directions, it can be easily demonstrated that the holographic method leads to the same impedance function proposed in this paper.

One of the most notable merits of SMRS antennas is that appropriate changes of the design parameters along the surface can lead to nearly independent control of the leakage constant, α, and the phase constant, β. Consequently, a variation of the illumination of the antenna, controlled by α, can be achieved with almost negligible effect on the pointing direction, determined by β, which provides more flexibility on the synthesis of radiation patterns.

In this work, we take advantage of this independent control of α and β to reduce the side lobe level (SLL) of a double beam SMRS. The details of the design procedure and simulation results are presented in the following sections.

II. Theory

An SMRS refers to a metasurface whose impedance fluctuates sinusoidally along the longitudinal direction. Assuming z-axis as the direction along the SMRS, the surface impedance, η_{surf}, can be expressed as [2]

$$\eta_{surf}(z) = j\eta_0 X' \left[1 + M\cos\left(\frac{2\pi z}{a}\right)\right] \tag{1}$$

where η_0 is the free-space wave impedance, M is the modulation factor, a is the spatial period of the sinusoidal function and X' is the average surface reactance normalised by the free-space wave impedance. In this paper, we consider η_{surf} to be inductive, so it allows the propagation of TM-surface waves [4]. Due to its periodic profile and according to Floquet's theorem, the fields on the SMRS can be expressed in terms of spatial harmonics. The propagation wave number along the surface, $\kappa = \beta - j\alpha$, and the tangential wave number of the nth spatial harmonic,

$$k_{zn} = \kappa + \frac{2\pi n}{a} = \beta_n - j\alpha, \quad n = 0, \pm 1, \pm 2... \tag{2}$$

are related to the transverse wave number, k_{xn}, by

$$k_{xn} = \sqrt{k_0^2 - k_{zn}^2} = \sqrt{k_0^2 - \left(\kappa + \frac{2\pi n}{a}\right)^2} \tag{3}$$

where k_0 is the free space wave number ($k_0 = 2\pi/\lambda$). Under certain conditions and similarly to other types of non-uniform LWAs, when the nth harmonic becomes a fast wave ($\beta_n < k_0$) a radiating leaky wave can be generated. In [2], Oliner and Hessel studied the propagation and radiation characteristics of sinusoidally modulated reactance surfaces. In particular, they demonstrated theoretically that under small values of

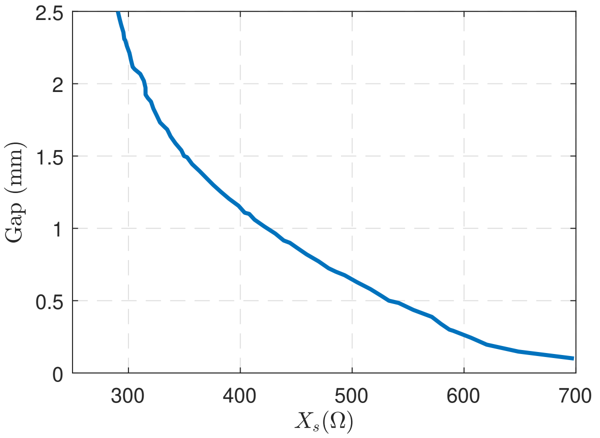


Figure 1. Surface reactance vs. gap size between cooper strips over a grounded dielectric slab with ARLON AD-600 ($\varepsilon_r = 6.15$), at 10 GHz.

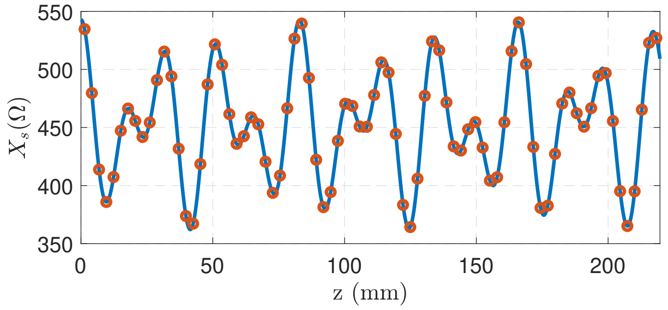


Figure 2. Surface reactance modulation function (continuous line) and sampling (o) for a dual beam antenna pointing towards $\theta_1 = -14°$ and $\theta_2 = 28°$, with normalised average surface reactance $X' = 1.2$ and modulation factors $M_1 = M_2 = 0.1$.

the modulation factor, M, the dispersion relation can be approximated as

$$\kappa = \beta - j\alpha = k_0\sqrt{1+X'^2} - \frac{M^2}{4}\frac{k_0 X'^2}{\sqrt{1+X'^2}} \times \left[\frac{1}{1-\frac{j}{X'}\sqrt{1-\left[\sqrt{1+X'^2}-\frac{2\pi}{k_0 a}\right]^2}} + \frac{1}{1-\frac{j}{X'}\sqrt{1-\left[\sqrt{1+X'^2}+\frac{2\pi}{k_0 a}\right]^2}}\right] \quad (4)$$

The parameters a and X' can control the phase constant, β, whereas M controls the leakage factor, α.

For a unidirectional excitation, the radiation angle measured from broadside due to the radiation of the nth harmonic can be obtained from

$$\theta_n = \arcsin\left(\frac{\beta_0 + \frac{2\pi n}{a}}{k_0}\right) \quad (5)$$

where β_0 stands for the phase constant of the fundamental spatial harmonic, $n = 0$. As seen in (4), β_0 is function of the three characteristic parameters of a SMRS (X', M, a). However, it is worth mentioning that in the cases of small spatial modulation ($M << 1$), the phase constant β_0 could be approximated by its value in the case of no modulation ($M = 0$), given by

$$\beta_0(M=0) = k_0\sqrt{1+X'^2}. \quad (6)$$

In this work, we have implemented a modulated reactance surface and extended the SMRS concept by using a superposition of two sinusoids as our impedance modulation function, which should be expressed as

$$\eta_{surf}(z) = j\eta_0 X'\left[1 + M_1\cos\left(\frac{2\pi z}{a_1}\right) + M_2\cos\left(\frac{2\pi z}{a_2}\right)\right] \quad (7)$$

where M_1, M_2, a_1 and a_2 are respectively the modulation factors and the spatial periods of each sinusoid. As it was demonstrated by the holographic theory [3], this method could also be interpreted as a superposition of the Floquet modes generated by each periodic function. When the structure is excited and both $n = -1$ harmonics are fast waves, it gives rise in the far field to two separated beams whose radiation angles are given by (5). This approach will be used in this paper to design a planar dual beam LWA.

III. Antenna Design and Results

A. Dual beam SMRS design procedure

With the aim of designing a dual beam LWA, a procedure similar to the one used for the construction of a single beam SMRS has been followed, which is carefully explained in [5]. The surface reactance is implemented by sampling the continuous modulation function at several equispaced points. Then, the impedance of each of the samples is physically realized as a gap between two metal strips on top of a grounded dielectric slab. A mapping between the size of the gap and its associated reactance value can be obtained using a full wave simulator, such as ANSYS HFSS, and applying the transverse resonance condition to the equivalent line model of a single gap, as described in [5]. Fig. 1 shows the variation of the surface reactance with the gap size to be used in this work. The mapping curve was obtained for the dielectric ARLON AD-600 ($\varepsilon_r = 6.15$) with thickness $d = 2.5$ mm, at an operating frequency of 10 GHz.

By means of (7), we obtained the modulated surface reactance required to implement a dual beam SMRS pointing towards $\theta_1 = -14°$ and $\theta_2 = 28°$. The resulting function consists of a superposition of the two sinusoids which, individually, are able to radiate in each desired direction. From (5), the periods of both sinusoids can be found for the $n = -1$ spatial harmonic, yielding $a_1 = 16.6$ mm and $a_2 = 27.46$ mm respectively. Computing (5) for a_2, it can be seen that a parasitic beam from the $n = -2$ spatial harmonic is also present at $\theta_{n=-2} = -39°$. In order to achieve beams with equal gains, approximately, both modulation factors are set to the same value, being $M_1 = M_2 = 0.1$. Finally, the normalised average surface reactance is set to $X' = 1.2$.

Our designed antenna has a height of $d = 2.5$ mm ($\lambda/12$) and a width of $w = 30$ mm (λ). The total length is set to $l = 21.97$ cm, which is equivalent to $8a_2$ or, approximately, $13.2a_1$. Our reactance surface is composed of 80 equispaced samples of the impedance function given by (7), depicted in Fig. 2. A representation of the aforementioned antenna

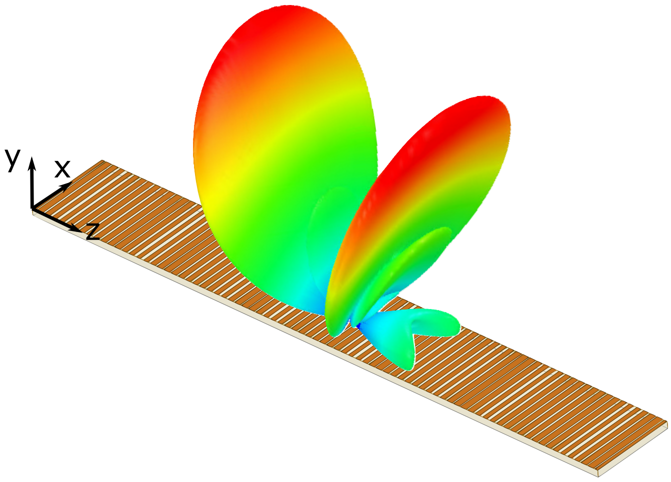


Figure 3. 3-D plot of the proposed dual beam antenna with normalised average surface reactance $X' = 1.2$ and modulation factors $M_1 = M_2 = 0.1$, and its expected radiation pattern pointing towards $\theta_1 = -14°$ and $\theta_2 = 28°$.

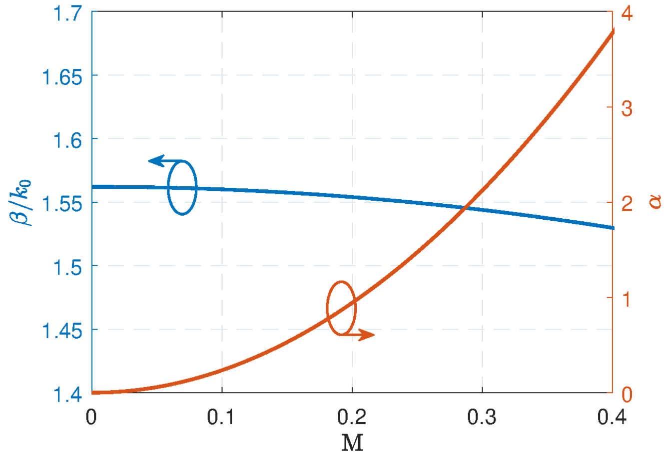
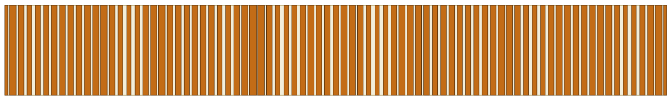
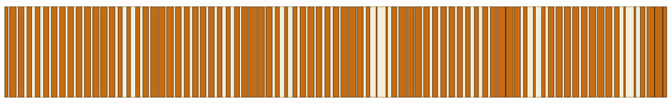


Figure 4. Variation of β/k_0 and α according to M for an SMRS with spatial period $a = 27.46$ mm and normalised average surface reactance $X' = 1.2$ at an operating frequency of 10 GHz.



(a) $M_1 = M_2 = 0.1$



(b) $M_1 = M_2 = M(n)$

Figure 5. Top view of designed dual beam SMRS antennas. (a) Case $M_1 = M_2 = 0.1$. (b) Case $M_1 = M_2 = M(n)$.

together with its expected radiation pattern is shown in Fig 3. It should be noted that since the selected periods are not rationally related, the synthesised surface impedance does not follow a periodic variation. This quality was purposely sought to prevent the presence of additional spatial periodicities, since that could lead to the generation of undesired Floquet modes. Consequently, as Fig. 3 shows, the appearance of our antenna is not what would be expected for a periodic LWA, although its performance can be explained in the same terms.

B. Independent control of phase and leakage constants

As stated in Section II, the variables X' and a control the phase constant, β, while M controls the leakage constant, α. It is well known from basic LWA theory that β determines the pointing direction, whereas a variation of α is able to alter the radiation efficiency, beamwidth and sidelobe distribution of the antenna. A higher value of M leads to a higher leakage factor and, therefore, to a shorter antenna effective length. One of the most notable properties of SMRS is that, under certain conditions, it allows nearly independent control of the phase and leakage constants [6]. Using the dispersion relation given by (4), we can represent the variation of β and α according to M, keeping X' and a at the initial design values, as Fig. 4 shows. It should be noted that, for small values of M, β remains almost constant whereas α varies over a wide range. Hence, a non-uniform distribution of the leakage constant can be achieved by slightly modifying the values of M_1 and M_2 along the surface with negligible effect on the pointing angle.

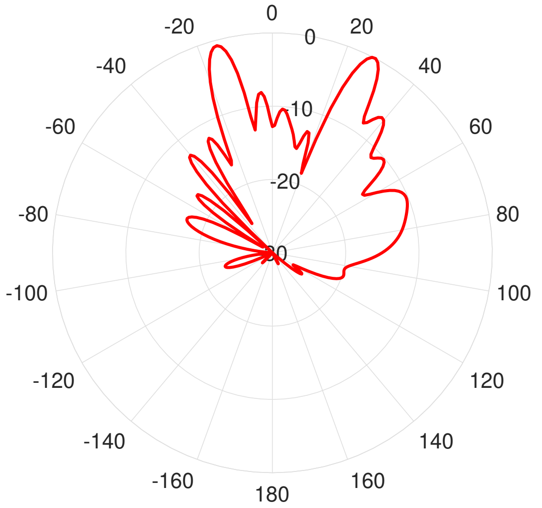
According to the above mentioned approach, we included a longitudinal variation of the modulation factor, $M(n)$, determined by

$$M_1 = M_2 = M(n) = \begin{cases} 0.1 + 0.0026n, & \text{if } n < 40. \\ 0.2, & \text{if } n \geq 40 \end{cases} \quad (8)$$

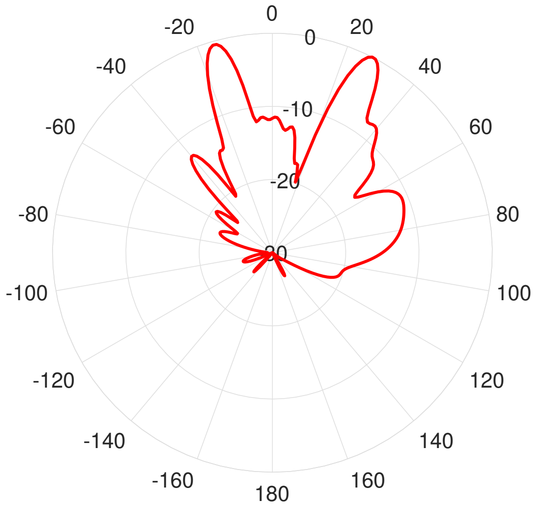
where n stands for the index of the synthesised impedance sample, with $n = 0, 1, ...79$. As can be inferred from Fig. 4, a linear increase of M along the surface will translate into an exponential variation of alpha, which will consequently result in a more uniform illumination of the antenna, all in approximate terms. A higher value of M means a larger amplitude of the modulated surface impedance function. However, due to the limitations of the chosen physical implementation only a range of reactance values can be effectively synthesized. In consequence, the increase of M can be maintained only in the first part of the antenna. In the second half, M is set to its highest value so possible reflections are avoided and radiation efficiency is improved.

C. Simulation results

All theoretical designs presented in this work have been verified through full wave simulation, performed with ANSYS HFSS at an operating frequency of 10 GHz. Fig. 5 illustrates the top view of the two proposed surfaces. Fig. 5.a. corresponds to the case where M_1 and M_2 are constant along the antenna, while in Fig. 5.b. M varies with each sample according to (8). The radiation patterns obtained for both designs are shown in Fig. 6. The directions of highest gain are approximately $\theta_1 = -14°$ and $\theta_2 = 25°$. In the first design, gains of 12.2 dBi and 12.9 dBi were obtained for each beam, respectively, whereas 13.4 dBi and 13.6i dB were obtained in the second one. Therefore, higher and more symmetrical gains are found in the latter case. The presence of the parasitic spatial harmonic $n = -2$ radiating at $\theta_{n=-2} = -39°$ can also be observed, as deduced in III-A.



(a) $M_1 = M_2 = 0.1$



(b) $M_1 = M_2 = M(n)$

Figure 6. Radiation patterns of designed dual beam SMRS antennas. (a) Case $M_1 = M_2 = 0.1$ (b) Case $M_1 = M_2 = M(n)$.

Comparing both diagrams it can be verified that the pointing directions of the main beams do not change considerably despite the antennas have a different illumination. This confirms that the leakage rate can be controlled nearly independently of the phase constant, as predicted by theory. A side lobe level reduction of 3.4 dB is achieved for the beam pointing at -14°, while a 1.8 dB reduction was obtained for the one pointing at 28°. Furthermore, a large decrease in the number and level of additional side lobes can also be observed for the second design.

It is expected that the construction and experimental characterisation of the designed antenna will be available for presentation during the conference.

IV. Conclusions

A dual beam leaky wave antenna has been presented. The structure consisted of a one-dimensional metasurface whose impedance was modulated by the superposition of two sinusoids. After a theoretical analysis, a full design procedure of an antenna that radiates at -14° and 28° at 10 GHz has been described in detail. A physical implementation based on copper strips printed over a grounded dielectric slab has also been proposed, providing the curve that maps the value of the synthesised reactance with the size of the gap between strips.

Independent control of leakage and phase constant has been verified theoretically and by simulation. Using this property, an improved second design has been proposed in which the illumination of the antenna has been modified, with negligible changes in the radiation directions. By means of full wave simulation, a reduction of the side lobe level of 3.4 dB and 1.8 dB between the former and the latter design has been verified, as well as a large decrease in the number of side lobes. Each of the beams exhibited a gain of 13.4 dBi and 13.6 dBi respectively. An excellent agreement between theory and simulation has been found. It is expected that the construction and experimental characterisation of the designed antenna will be available for presentation during the conference.

Acknowledgements

This project has received funding from the Spanish *Ministerio de Ciencia, Innovación y Universidades (MCIU)*, the *Agencia Estatal de Investigación (AEI)* and the *Fondo Europeo de Desarrollo Regional (FEDER)* (Programa Estatal de I+D+i Orientada a los Retos de la Sociedad) under grant RTI2018-097098-JI00. It has also been undertaken within the context of a Research Collaboration Grant of the *I Plan Propio de Investigación y Transferencia* of the University of Málaga.

References

[1] S. Pandi, C. A. Balanis, and C. R. Birtcher, "Analysis of wideband multilayered sinusoidally modulated metasurface," *IEEE Antennas and Wireless Propagation Letters*, vol. 15, pp. 1491–1494, 2016.

[2] A. Oliner and A. Hessel, "Guided waves on sinusoidally-modulated reactance surfaces," *IRE Transactions on Antennas and Propagation*, vol. 7, no. 5, pp. 201–208, 1959.

[3] B. H. Fong, J. S. Colburn, J. J. Ottusch, J. L. Visher, and D. F. Sievenpiper, "Scalar and tensor holographic artificial impedance surfaces," *IEEE Transactions on Antennas and Propagation*, vol. 58, no. 10, pp. 3212–3221, 2010.

[4] R. E. Collin and F. J. Zucker, *Antenna Theory. Part 2.* McGraw-Hill, 1969.

[5] A. M. Patel and A. Grbic, "A printed leaky-wave antenna based on a sinusoidally-modulated reactance surface," *IEEE Transactions on Antennas and Propagation*, vol. 59, no. 6, pp. 2087–2096, 2011.

[6] D. Yang and S. Nam, "Tapered unit cell control of a sinusoidally modulated reactance surface antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 17, no. 12, pp. 2479–2483, 2018.