Circularly-Polarized Double-Curvature Conformal Leaky-Wave Antenna Based on Holographic Principle

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***Abstract* — The holographic principle offers a promising framework to design double-curvature conformal leaky-wave antennas (CLWAs) with circular polarization (CP). However, conventional design methods based on the holographic technique have limitations such as null creation in the broadside direction for linearly polarized (LP) radiations. Anisotropic unit-cells are generally used in holographic leaky-wave antenna design procedures. Meanwhile, after extraction the surface impedance of the spherical double-curvature structure, the hologram plane is realized with the scalar unit-cell. A monopole launcher, as a surface wave generator, is placed at the center of the structure to excite the hologram. To demonstrate the validity of the design method, a double-curvature CLWA has been implemented on a spherical cap at 15 GHz in broadside direction with a left-handed circular polarization (LHCP). The realized gain of the proposed CLWA is about 21.2 dBi with high polarization purity.**

***Keywords* — Holographic principle, conformal leaky-wave antenna, double-curvature structure, circular polarization.**

I. Introduction

Circular polarization (CP) is necessary for many space applications, including telecommunication links between satellites and base stations and end users on the Earth, to avoid polarization mismatch issues in complex wireless scenarios [1]. CP, including left-handed circular polarization (LHCP) and right-handed circular polarization (RHCP), is also beneficial to future satellite communications [2].

Horn arrays can be a solution, presenting robust and wideband performance. However, they have bulky waveguide beamforming networks [3]. Alternatively, promising solutions are based on leaky-wave antennas (LWAs) and slotted arrays, which provide higher compactness. LWAs present significantly lower profiles as there is no need for complex feeding networks [4].

LWAs are characterized by the gradual leakage of electromagnetic waves (EM waves) over a structure. This phenomenon enables the beam scanning ability by changing the frequency. LWAs can be generally classified into two types: uniform LWA (U-LWAs) and periodic LWA (P-LWAs). In U-LWAs, the beam scanning capability is limited to forward directions only [5]. P-LWAs, on the other hand, offer beam scanning in backward and forward directions through the broadside [6]. Moreover, the main mode of P-LWA is a slow wave, which is transformed into a space wave through periodic perturbations. However, in U-LWAs, the main mode is a fast wave.

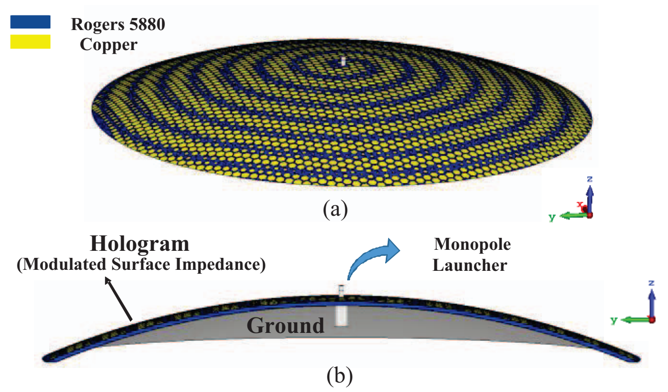

Fig. 1. Schematic of the double-curvature CLWA configuration with monopole launcher.

In P-LWA, periodic modulations are required to make the EM waves leak out to the free space. One way to provide those periodic modulations is using the holographic technique. The holographic principle was first proposed in 1968 by Checcacci [7]. Holography involves recording the amplitude and phase data of reference and object waves onto a pseudo-periodic sinusoidally modulated impedance surface within the interference plane of the hologram. In applications such as holographic-based transmit or reflect arrays, distinct structures are employed to produce space waves acting as reference waves. Surface waves frequently are used as the primary reference wave in the design of LWAs [8]. Holographic LWAs can be activated by surface waves exhibiting cylindrical or planar wavefronts, depending on the launcher's position [9-12].

The holographic technique was also adopted to design conformal LWAs (CLWAs). So far, holographic CLWAs with 1-D and 2-D surface impedance modulations have been designed [13-14]. CLWAs follow specified shapes, either by mounting onto or embedding within curved surfaces. This antenna category has received considerable attention among researchers due to its potential for integrating in various communication applications and minimizing aerodynamic drag in automotive radar systems. The applications of the conformal antennas include aerospace designs, wearable technology, and mobile devices, with distinctions made between single- and double-curvature structures [15-19].

In this paper, the holographic relations to design a double-curvature LHCP CLWA are extracted in details. The proposed CLWA is a center-fed structure with a surface wave, containing a cylindrical wave front. The LWA includes scalar hexagonal unit-cells with a dominant TM mode. This antenna is mounted on a spherical cap with a radius and a solid angle of 30 cm (15λo) and 0.49 steradian, respectively. The realized gain of the LHCP CLWA is about 21.2 dBi at 15 GHz. Also, polarization purity and radiation efficiency of the CLWA are about 21.5 dB and 89%, respectively.

II. DESIGN OF DOUBLE-CURVATURE CLWA BASED ON HOLOGRAPHIC PRINCIPLE WITH CIRCULAR POLARIZATION

Fig. 1 shows a schematic of the double-curvature CLWA configuration. A monopole antenna is used as a reference wave source with a cylindrical wavefront. Based on the holographic principle, the hologram interface plane can record the amplitude and phase of the reference and arbitrary objects with any polarization. The object wave is generated when the reference wave is irradiated to the hologram plane.

The surface impedance distribution for a center-fed hologram plane to generate $\vec{E}_a$ is defined as:

$$\underline{\underline{Z}}_s.\hat{\rho} = j\eta_\circ \left[X_\circ \hat{\rho} + 2\,Im\left\{ \frac{\vec{E}_a}{-J_{sw} H_1^{(2)}(\beta_{sw}\rho)} \right\} \right] \quad (1)$$

where $X_\circ$ and $H_1^{(2)}$ are normalized average of the surface impedance and the first order of the 2nd type Hankel function, respectively. Also, β_{sw} is the phase constant of the surface wave. The reference wave can be assumed in the following simple forms:

$$H_1^{(2)}(\beta_{sw}\rho) \approx \sqrt{\frac{2}{\pi\beta_{sw}\rho}}\, j e^{-j\beta_{sw}\rho} \quad (2)$$

$$\beta_{sw} = \sqrt{1+X_\circ^2}\, k = nk \quad (3)$$

where k and n are the free space propagation constant and refractive index of the medium, respectively. Consequently, the surface impedance distribution of the spherical cap can be written as follows:

$$Z_s = j\eta_\circ \left[X_\circ + \frac{\sqrt{2\pi\beta_{sw}\rho}}{J_{sw}} Im\left\{ \vec{E}_a j e^{j\beta_{sw}\rho} \right\} \right] \quad (4)$$

The aperture field of the object wave ($\vec{E}_a$) is expressed as:

$$\vec{E}_a = E_{ax}(x,y,z)\hat{x} + E_{ay}(x,y,z)\hat{y} + E_{az}(x,y,z)\hat{z} \quad (5)$$

Moreover, the Fourier transform of the aperture field can be written:

$$\vec{E}_{FF}(r,\theta,\varphi) \approx j\frac{ke^{-jkr}}{2\pi r}\left[F_\theta(\theta,\varphi)\hat{\theta} + F_\varphi(\theta,\varphi)\hat{\varphi} \right] \quad (6)$$

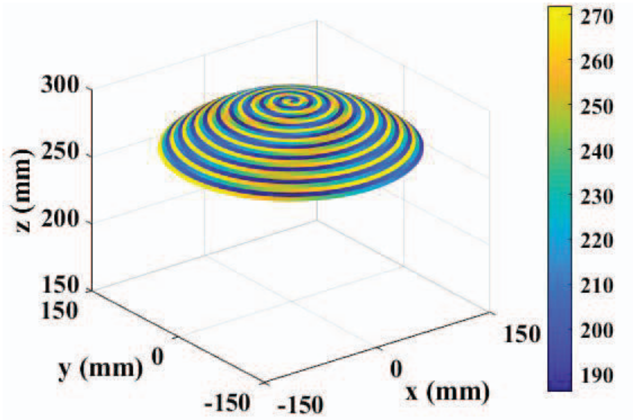

Fig. 2. Surface impedance pattern on a spherical cap with radius of 0.3 m and solid angle of 0.49 steradian (Xo=0.61, M=0.11, f=15 GHz).

$$F_\theta(\theta,\varphi) = \tilde{E}_{ax}\cos\varphi + \tilde{E}_{ay}\sin\varphi - \tilde{E}_{az}\sin\theta \quad (7)$$

$$F_\varphi(\theta,\varphi) = \cos\theta\left(-\tilde{E}_{ax}\sin\varphi + \tilde{E}_{ay}\cos\varphi \right) \quad (8)$$

where $\tilde{E}_x$, $\tilde{E}_x$ and $\tilde{E}_{az}$ are spectrum of x, y and z components of aperture field and are calculated as:

$$\tilde{E}_{ax} = \iint_{ap} E_{ax}(x',y',z') e^{j(k_x x' + k_y y' + k_z z')} dx'dy'dz' \quad (9)$$

$$\tilde{E}_{ay} = \iint_{ap} E_{ay}(x',y',z') e^{j(k_x x' + k_y y' + k_z z')} dx'dy'dz' \quad (10)$$

$$\tilde{E}_{az} = \iint_{ap} E_{az}(x',y',z') e^{j(k_x x' + k_y y' + k_z z')} dx'dy'dz' \quad (11)$$

Also, E_{ay} and E_{ay} can be written as follows:

$$E_{ax}(\theta',\varphi') = \frac{M_x J_{sw}}{\sqrt{2\pi\rho\beta_{sw}}} e^{-jkr\left[\sin\theta\sin\theta'\cos(\varphi-\varphi')+\cos\theta\cos\theta'\right]} \quad (12)$$

$$E_{ay}(\rho',\varphi') = \frac{M_y J_{sw}}{\sqrt{2\pi\rho\beta_{sw}}} e^{-jkr\left[\sin\theta\sin\theta'\cos(\varphi-\varphi')+\cos\theta\cos\theta'\right]} \quad (13)$$

To fulfill the CP condition of $F_\varphi(\theta,\varphi) = e^{\pm j\frac{\pi}{2}} F_\theta(\theta,\varphi)$ for the object wave in broadside direction $(\theta=\varphi=0)$ we will have:

$$M_x = \pm jM_y = Me^{j\varphi'} \quad (14)$$

Therefore, to obtain an LHCP pencil beam from the center-fed spherical cap hologram structure, the following surface impedance is implemented in a fixed radius of R.

$$Z_s \approx \eta_\circ\left[X_\circ + M\cos\left(nk_\circ R\sin\theta' - \varphi' + k_o R\cos\theta' \right) \right] \quad (15)$$

Fig. 2 illustrates the surface impedance pattern on a spherical cap with a radius of 0.3 m and a solid angle of 0.49 steradian. The values of M and X_o in (15), at the design frequency of 15 GHz, are assumed to be 0.11 and 0.61, respectively.

III. Proposed Unit-Cell

In practice, the hologram plane consists of unit-cells. Therefore, the hologram surface impedance pattern can be realized by choosing the appropriate unit-cell. In this work, to excite the CLWA, a monopole launcher is utilized, providing a surface wave with a cylindrical wavefront. Then, it is necessary to use an isotropic unit-cell to create an object wave with high polarization purity. Depending on the type of the launcher excitation mode, the hologram surface can be implemented with grounded or ungrounded unit-cells with the dominant TM and TE modes, respectively. Since the dominant mode of the monopole structure is TM, a grounded hexagonal patch unit-cell is printed on a Rogers 5880 substrate with a thickness of 1.5 mm and a dielectric constant of 2.2. According to the effective wavelength of the design frequency, the period of the unit-cell must be small enough. The geometry dimensions of the proposed unit-cell are shown in the inset of Fig. 3. Considering that the bending radius of the sphere is larger than the period of the unit-cell, the planar approximation is assumed. The dispersion diagram of the proposed unit-cell with different a_p is simulated in the Eigenmode solver of CST software with suitable boundary conditions, shown in Fig. 3. Afterwards, the surface impedance is calculated at 15 GHz as below:

$$Z_s = \eta_0 \sqrt{\left(\frac{\phi}{k\,a}\right)^2 - 1} \tag{16}$$

where ϕ is the phase difference within the unit-cell along the propagation direction of the reference wave.

Normalized average surface impedance and modulation depth of surface impedance are represented by X_o and M respectively, and can be defined as follows:

$$X_0 = \left(max\left(Z_s\right) + min\left(Z_s\right)\right)/2\eta_0 \tag{17}$$

$$M = \left(max\left(Z_s\right) - min\left(Z_s\right)\right)/2\eta_0 \tag{18}$$

Therefore, $X_o = 0.61$ and $M = 0.11$ are obtained at the design frequency of 15 GHz.

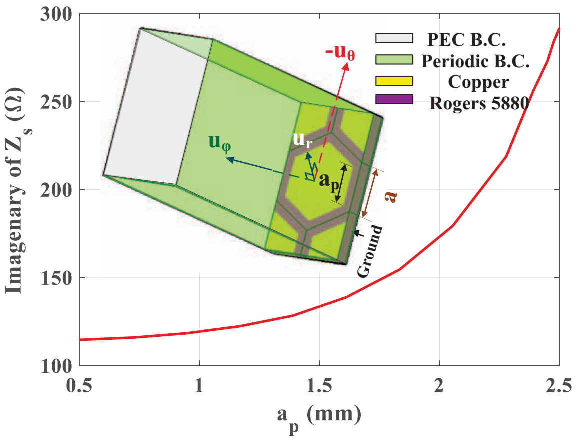

Fig. 3. Proposed hexagonal unit-cell with appropriate boundary conditions and its surface impedance at 15 GHz. (a=2.1 mm, h=1.5 mm).

IV. Implementation of the Proposed Holographic Double-Curvature CLWA and Simulation Results

To validate the design process, the holographic double-curvature CLWA is realized with the proposed unit-cell and simulated by CST Microwave Studio software. Fig. 4 demonstrates the holographic double-curvature LHCP CLWA with a monopole antenna located at the center of the structure.

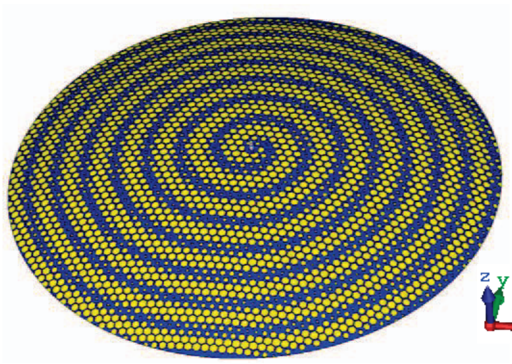

Fig. 4. Holographic double-curvature LHCP CLWA with a monopole antenna in the center of the structure.

According to Fig. 5, the simulated S-parameter is lower than -10 dB within the frequency range of 14-15.8 GHz.

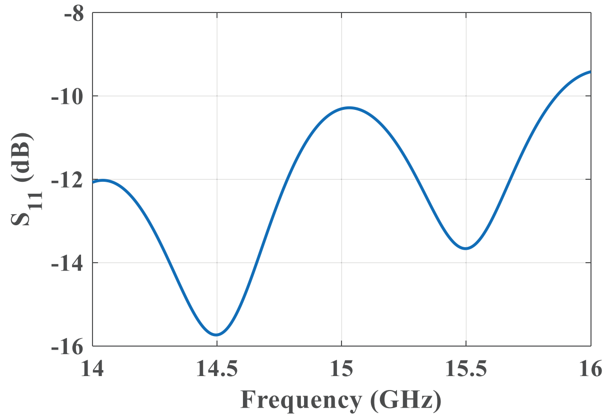

Fig. 5. Simulated S-parameter of LHCP CLWA.

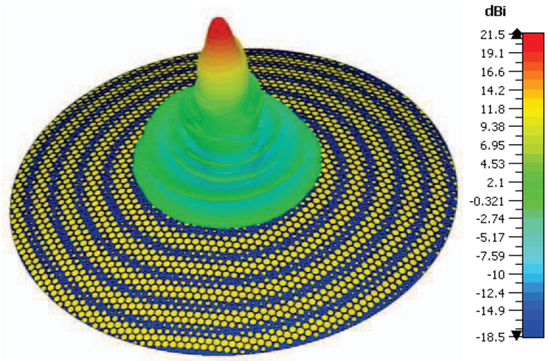

Fig. 6. 3D farfield radiation pattern of the LHCP CLWA at 15 GHz.

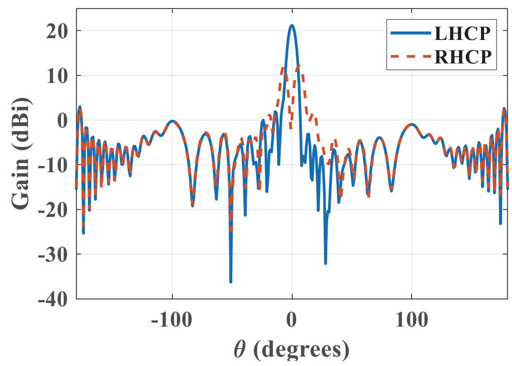

Fig. 7. 2D radiation pattern for Co-pol and Cross-pol of LHCP CLWA at xz plane at 15 GHz.

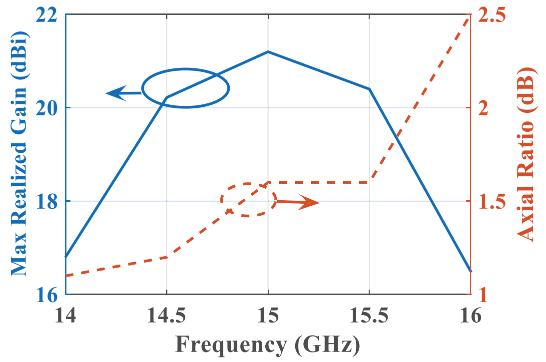

Fig. 8. Maximum realized gain and AR of the LHCP CLWA versus frequency variation.

Fig. 6 shows the 3D farfield radiation pattern of the LHCP CLWA at 15 GHz. The realized gain of the antenna is about 21.2 dBi. Also, the 2D radiation pattern for Co-pol and Cross-pol at *xz* plane is plotted in Fig. 7, demonstrating the polarization purity of about 21.5 dB at 15 GHz. The AR of the proposed CLWA is 1.6 dB at the design frequency. Furthermore, the maximum realized gain and AR of the LHCP CLWA versus frequency variation is illustrated in Fig. 8.

V. Conclusion

This paper presents a novel double-curvature LHCP CLWA based on the holographic principle. The surface impedance distribution is analytically calculated. The CLWA structure is implemented with a hexagonal isotropic unit-cell. The CLWA is fed with a monopole launcher at the center of the hologram. The realized gain, AR, and polarization purity of the proposed antenna are about 21.2 dBi, 1.6 dB and 21.5 dB, respectively.

Acknowledgment

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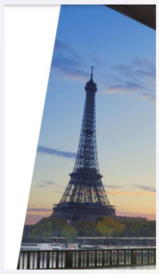

Circularly-Polarized Double-Curvature Conformal Leaky-Wave Antenna Based on Holographic Principle

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Circular-Polarized Conformal LWA Based on Holographic Principle

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- Presentation Outline:
  - Leaky-Wave Antenna
  - Holographic Principle
  - Design Process
  - Implementation of the Structure
  - Conclusion & References

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Circular-Polarized Conformal LWA Based on Holographic Principle

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- Leaky-Wave Antenna:

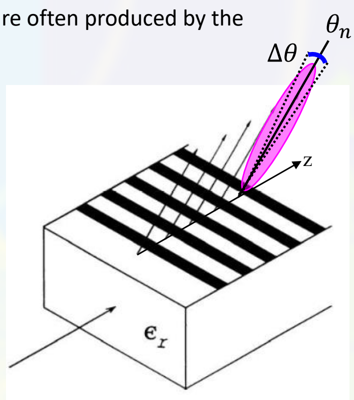
- Leaky-wave antennas (LWAs), belonging to the more general class of traveling wave antennas, are often produced by the progressive leakage of electromagnetic waves over a structure.
- LWAs can be classified into two categories:
  1) Uniform (a fast guided wave)
  2) Periodic (a slow guided wave)
     - periodic modulations create an infinite number of space harmonic based on Flouquet Theorem.
- Advantages of leaky-wave structures are:
  1) Scanning beam by frequency change
  2) Controlling the SLL of the LWAs
  3) High directivity and high realized gain
  4) Low fabrication cost

$$\beta_n = \beta_0 + \frac{2n\pi}{d}$$

$$\sin(\theta_n) = \frac{\beta_n}{K_0} = \frac{\beta_0 + \frac{2n\pi}{d}}{K_0}$$

$$n = 0, \pm 1, \pm 2, \ldots$$

$$\Delta\theta = \frac{1}{\left(\frac{L}{\lambda_0}\right)\cos\theta_n}$$



Circular-Polarized Conformal LWA Based on Holographic Principle

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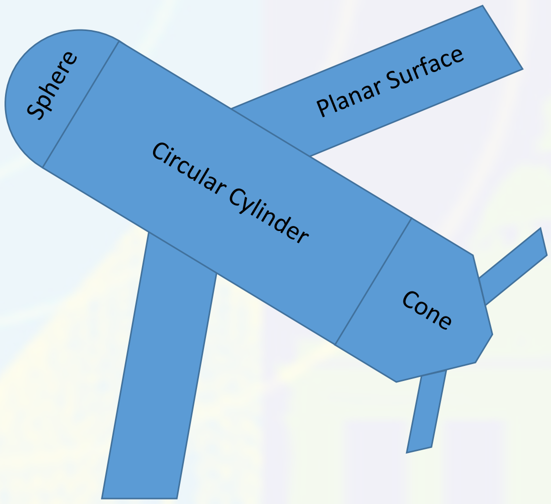
- Conformal Leaky-Wave Antenna:

- Conformal LWA (C-LWA) are of practical interest due to be amounted on curved surfaces, existing on vehicles, airplanes, trains, or ships.

- C-LWA can be integrated in different communications modules and reduce the aerodynamic drags of automotive radars to generate high directional radiation pattern.

- Aerospace designs, wearable antennas, and mobile devices are the largest applications of conformal antennas that are divided into single- and double-curvature from a physical structure viewpoint.



Circular-Polarized Conformal LWA Based on Holographic Principle

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1. Leaky-Wave Antenna
2. Holographic Principle
3. Design Process
4. Implementation of the Structure
5. Conclusion & References

Circular-Polarized Conformal LWA Based on Holographic Principle

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- Holographic Principle

- The idea of the holographic antenna (HA) was first proposed in 1968 by Checcacci et al..
- In HA, a modulated holographic surface generates an objective radiation pattern when it is excited from a known reference field.

- The holographic method is based on two steps:

(1) Recording
- Reference & object waves irradiated to a hologram.

(2) Reconstruction
- Virtual object image can be generated by irradiating the same reference wave to the hologram.

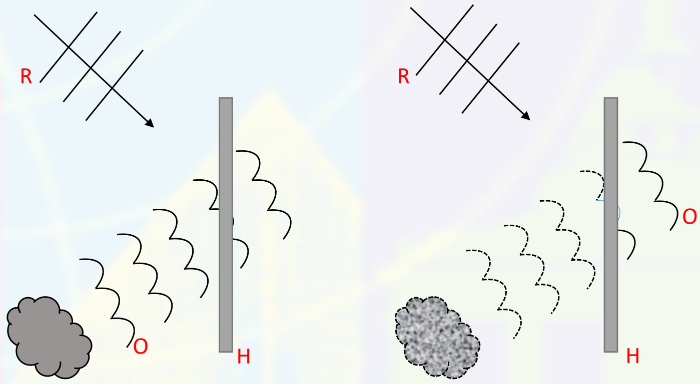

Fig. Steps required for optical imaging by holographic technique.

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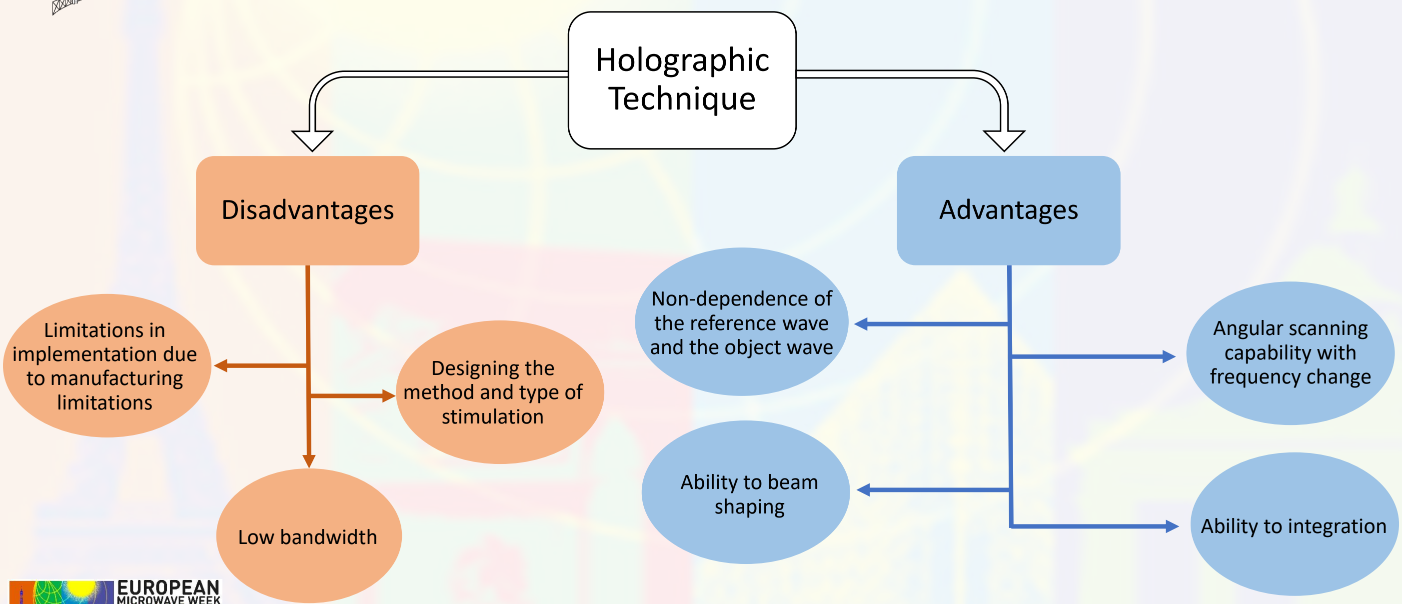

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Circular-Polarized Conformal LWA Based on Holographic Principle

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- Design of Double-Curvature CLWA Based on Holographic Principle with Circular Polarization

- The surface impedance distribution for a center-fed hologram plane to generate $\vec{E}_a$:

(1) $\underline{Z_s}.\hat{\rho} = j\eta_\circ \left[X_\circ \hat{\rho} + 2\,\mathrm{Im}\left\{\frac{\vec{E}_a}{-J_{sw}H_1^{(2)}(\beta_{sw}\rho)}\right\}\right]$

- The reference wave:

(2) $H_1^{(2)}(\beta_{sw}\rho) \approx \sqrt{\frac{2}{\pi\beta_{sw}\rho}}\, j e^{-j\beta_{sw}\rho}$ $\qquad \beta_{sw} = \sqrt{1+X_\circ^2}\,k = nk$

(1) (2) →

$$Z_s = j\eta_\circ \left[X_\circ + \frac{\sqrt{2\pi\beta_{sw}\rho}}{J_{sw}}\,\mathrm{Im}\{\vec{E}_a j e^{j\beta_{sw}\rho}\}\right]$$

- The aperture field of the object wave ($\vec{E}_a$):

(3) $\vec{E}_a = E_{ax}(x,y,z)\hat{x} + E_{ay}(x,y,z)\hat{y} + E_{az}(x,y,z)\hat{z}$

- The Fourier Transform:

(4) $\vec{E}_{FF}(r,\theta,\varphi) \approx j\frac{ke^{-jkr}}{2\pi r}\left[F_\theta(\theta,\varphi)\hat{\theta} + F_\varphi(\theta,\varphi)\hat{\varphi}\right]$

$F_\theta(\theta,\varphi) = \tilde{E}_{ax}\cos\varphi + \tilde{E}_{ay}\sin\varphi - \tilde{E}_{az}\sin\theta$

$F_\varphi(\theta,\varphi) = \cos\theta\,(-\tilde{E}_{ax}\sin\varphi + \tilde{E}_{ay}\cos\varphi)$

Circular-Polarized Conformal LWA Based on Holographic Principle

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- Design of Double-Curvature CLWA Based on Holographic Principle with Circular Polarization

- (4) Where $\tilde{E}_{ax}$, $\tilde{E}_{ay}$,and $\tilde{E}_{az}$ are Spectrums of E_{ax}, E_{ay}, E_{az} :

$$\tilde{E}_{ax} = \int\int_{ap} E_{ax}(x', y', z') e^{j(k_x x' + k_y y' + k_z z')} dx' dy' dz'$$

$$\tilde{E}_{ay} = \int\int_{ap} E_{ay}(x', y', z') e^{j(k_x x' + k_y y' + k_z z')} dx' dy' dz'$$

$$\tilde{E}_{az} = \int\int_{ap} E_{az}(x', y', z') e^{j(k_x x' + k_y y' + k_z z')} dx' dy' dz'$$

- (5) The aperture field of the object wave ($\vec{E}_a$):

$$E_{ax}(\theta', \varphi') = \frac{M_x J_{sw}}{\sqrt{2\pi\rho\beta_{sw}}} e^{-jkr[\sin\theta \sin\theta' \cos(\varphi - \varphi') + \cos\theta \cos\theta']}$$

$$E_{ay}(\rho', \varphi') = \frac{M_y J_{sw}}{\sqrt{2\pi\rho\beta_{sw}}} e^{-jkr[\sin\theta \sin\theta' \cos(\varphi - \varphi') + \cos\theta \cos\theta']}$$

- (6) After fulfilling CP condition:

$$F_\varphi(\theta, \varphi) = e^{\pm j\frac{\pi}{2}} F_\theta(\theta, \varphi) \qquad M_x = \pm j M_y = M e^{j\varphi'}$$

$$Z_s \approx \eta_\circ[X_\circ + M \cos(nk_\circ R \sin\theta' - \varphi' + k_o R \cos\theta')]$$

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- Proposed Unit-Cell

- Calculated surface impedance at 15 GHz: $Z_s = \eta_0 \sqrt{\left(\frac{\phi}{k\,a}\right)^2 - 1}$ $\quad X_0 = \frac{(\max(Z_s) + \min(Z_s))}{2\eta_0} = 0.61 \quad M = \frac{(\max(Z_s) - \min(Z_s))}{2\eta_0} = 0.11$

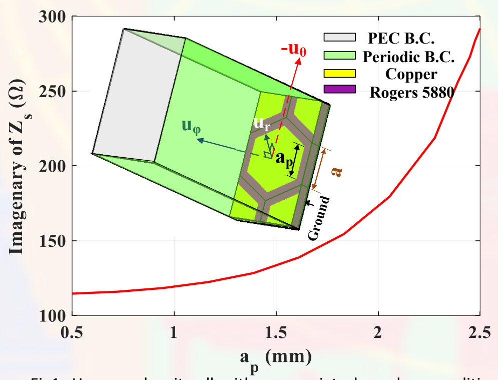

Fig1. Hexagonal unit-cell with appropriate boundary conditions and its surface impedance at 15 GHz. (a=2.1 mm, h=1.5 mm).

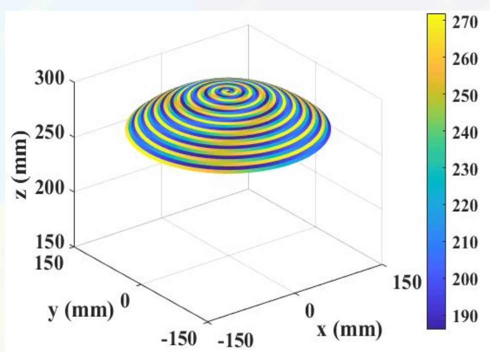

Fig2. Surface impedance pattern on a spherical cap with radius of 0.3 m and solid angle of 0.49 steradian (Xo=0.61, M=0.11, f=15 GHz).

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- Presentation Outline:

  - Leaky-Wave Antenna
  - Holographic Principle
  - Design Process
  - Implementation of the Structure
  - Conclusion & References

Circular-Polarized Conformal LWA Based on Holographic Principle

- Implementation of Double-Curvature CLWA Based on Holographic Principle with Circular Polarization

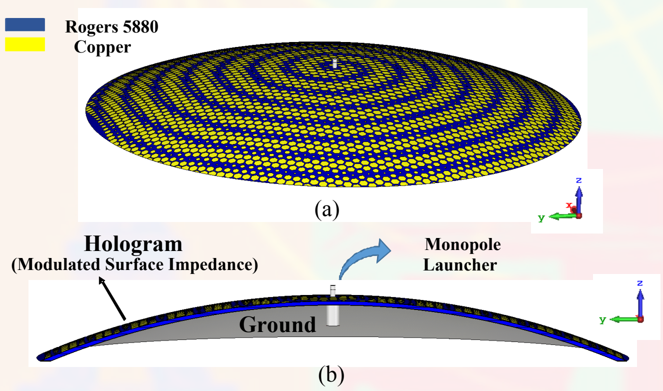

Fig1. Holographic double-curvature LHCP CLWA with a monopole launcher at the center of the spherical cap structure with a radius of 0.3 m and a solid angle of 0.49 steradian. The substrate is Ro 5880 with a thickness of 1.5 mm and a dielectric constant of 2.2.

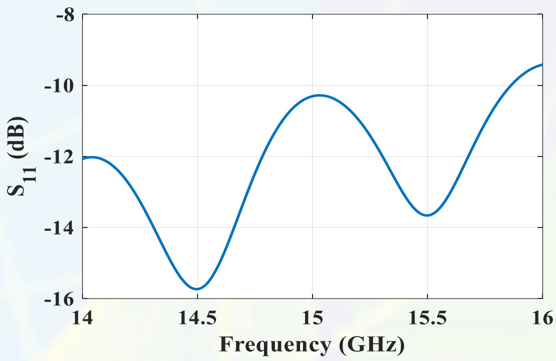

Fig2. Simulated S-parameter of LHCP CLWA.

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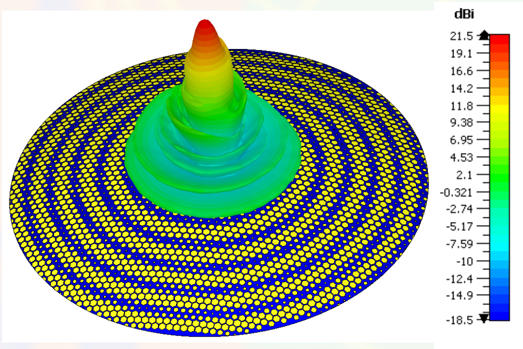

Fig1. 3D farfield radiation pattern of the LHCP CLWA at 15 GHz.

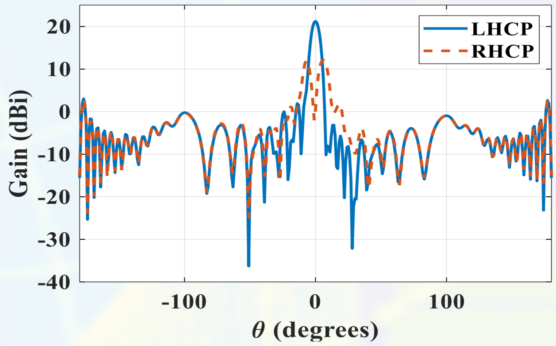

Fig2. 2D radiation pattern for Co-pol and Cross-pol of LHCP CLWA at xz plane at 15 GHz.

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- Implementation of Double-Curvature CLWA Based on Holographic Principle with Circular Polarization

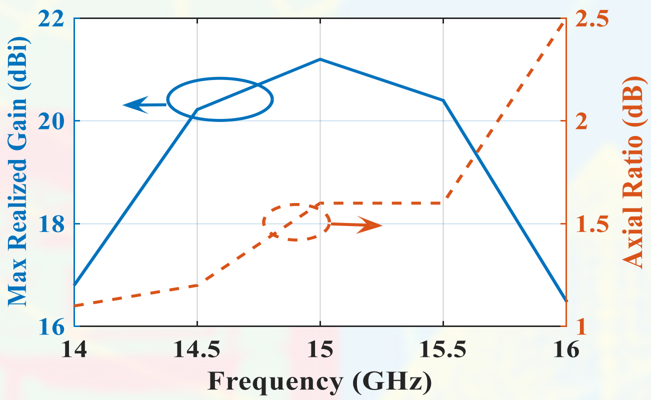

Fig. Maximum realized gain and AR of the LHCP CLWA versus frequency variation.

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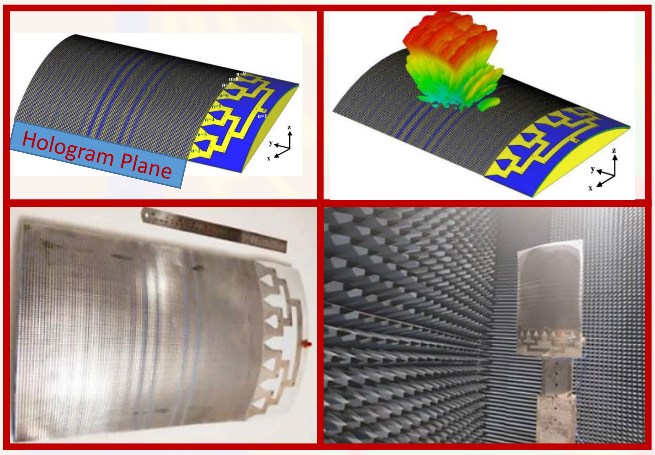
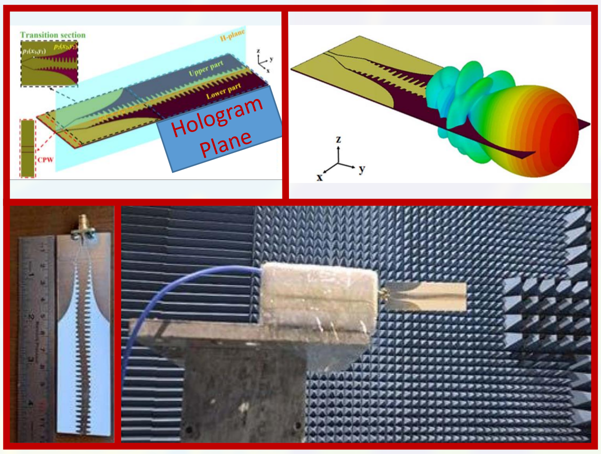
- Previous Holographic-based LWA with different reference waves and desired object waves:



Zadeh, M.A.C. and Komjani, N., **Flat-topped** Radiation Pattern Synthesis of a Conformal Leaky-Wave Holographic Antenna. ***IEEE Transactions on Antennas and Propagation, 2023***.



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Circular-Polarized Conformal LWA Based on Holographic Principle

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- Conclusion

✓ A novel double-curvature LHCP CLWA based on the holographic principle is proposed.

✓ The surface impedance distribution is analytically calculated.

✓ The CLWA is fed with a monopole launcher at the center of the hologram.

✓ The realized gain, AR, and polarization purity of the proposed antenna are about 21.2 dBi, 1.6 dB and 21.5 dB, respectively.

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