Removing broadside null of symmetric long-slot antennas by using a coating layer

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Abstract
This study presents a new concept in the design of symmetric long-slot leaky-wave antennas. Theoretically, a radiation null in the broadside direction of these antennas exists. The main idea of this study is to use a cover or coating layer to convert this null to a peak in the radiation pattern. The presence of the coating on the slot not only changes the leaked mode of the waveguide but also rotates its polarisation by 90°. As a proof of concept, a relatively small long-slot LWA is designed and fabricated on a C-band WR-159 waveguide, which is covered by an FR4 layer. The simulated relative broadside gain of the antenna with the coating over the antenna without the coating tends to infinity because of the presence of the null. Our simple measured results of the radiation pattern confirm the theory with more than 18 dB improvement. The realised gain of the antenna with a coating layer at broadside is 11.1 dBi with 9.8° half-power beam-width.

1 | INTRODUCTION

Long-slot antenna (LSA) is a frequently used type of leaky-wave antenna (LWA), which radiates from a slot embedded on a guiding structure. The antenna has been introduced since 1940 [1, 2], and has been used in various applications such as telecommunication systems [3, 4], aerospace radars and millimetre-wave applications [5, 6]. This simple type of antenna is generally designed to have a high gain and narrow beam, depending on its antenna’s length with its beam direction scanning with frequency. LWAs in general and LSAs especially have a low profile, simple feed network and high power characteristics.

The gradual leakages of power from a slit on the leaking waveguide can generate a narrow beam if they are all towards the same direction. The direction of the beam depends on the phase constant of the waveguide, and if it is less than the free space wave number \( \beta < k_0 \), as it is the case in hollow waveguides, the LSA supports fast wave on the guiding structure [1]. The first type of LSA was a rectangular waveguide with a longitudinal slot on one of its broad walls [1, 7]. However, various types of LSAs have been developed later on with uniform [8] or meandered [5], and periodic [9, 10] leaking structures on the waveguides. Long-slot dielectric-filled rectangular waveguides could support leaky modes [3, 11]. From the polarisation point of view, most LWAs have linear polarisation, with the axial and transverse slots on a rectangular waveguide supporting orthogonal polarisations [9].

Three types of conventional LSAs are summarised in Figure 1. The first one is a centred axial long-slot, shown in Figure 1(a). It is a well-known fact that no power from a narrow centred axial slot can be radiated as it does not cut any of the electric current lines. Therefore, in order to make the antenna radiates, the slot is shifted from the centre of the broad wall, as shown in Figure 1(b). Also, the leakage rate in LSA can be controlled by changing the slot’s offset from the waveguide’s centreline. The main disadvantage of this type of slot is its high side-lobe level (SLL). Therefore, meandered LSAs have been designed in order to have better radiation characteristics, as shown in Figure 1(c). The width of the slot and its curvature is one of the effective methods of controlling the leakage rate and its SLL [5, 12]. However, a meandering long-slot has a worse cross-polarisation level than a straight long-slot [5] and has an asymmetrical radiation pattern. A centred axial slot, if made symmetrically wider, as shown in Figure 2(a), can start radiating symmetrically as a result of cutting the current lines, but with a deep null in its broadside direction as a result of the electric fields with opposite directions and thus the equivalent magnetic current cancellation from opposite sides of the centreline.

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layer in Section 3. In Section 4, the simulation and the measurement results of the idea are presented. Finally, the study is concluded in Section 5.

2 | THEORETICAL BACKGROUND

Having a slot on a rectangular waveguide changes the propagating modes of a waveguide. Its well-known dominant TE\(_{10}\) and TE\(_{20}\) modes now face leakage loss in addition to the contribution of the upper free space in the propagation.

Without any coating layer, the first and the second modes remain TE as long as the slot width is small. Making the slot wider, the second mode becomes TM. In any case, the cut-off frequencies severely go down.

When forming the slotted waveguide into an LWA, the beam direction is defined by the phase constant (\(\beta\)) of the waveguide. At the same time, it is the leakage or attenuation constant (\(\alpha\)) of the antenna besides its leaking length, which determines the beam-width. The antenna’s SLL is dependent on the field distribution on the slot [1, 2]. The well-known relation for obtaining beam direction [1] is:

\[
\cos \theta_0 \approx \frac{\beta}{k_0}
\]

where \(k_0\) is the propagation constant in free space, and \(\theta_0\) is the angle of the main beam from the end-fire of the LWA. The beam-width of the antenna, \(\Delta \theta\), is approximated from Equation (2) [1, 2]:

\[
\Delta \theta \approx \frac{1}{L/\lambda_0 \times \sin \theta_0} \approx \frac{\alpha/k_0}{0.183 \sin \theta_0}
\]

where \(L\) is the length of the longitudinal slot. As mentioned in the previous section, an offset long-slot, as shown in Figure 1 (b), generates unidirectional magnetic currents without any cancellation in broadside direction. However, this produces an asymmetric radiation pattern [13, 14] which is not favourable in some cases. Another disadvantage of this type of slot is its high SLL due to the fact that it has a flat current amplitude distribution throughout the slot. To improve the SLL problem, using a curved slot similar to Figure 1(b) has been suggested by many researchers [13]. By forming the slot’s path, one can control the amplitude of the electric field (magnetic current) on the slot in a way to suppress the amplitude at both ends of the slot.

The main disadvantage of the LSA structures of Figure 1 (b) and (c) is the deviation of their main beam from the broadside direction and its asymmetrical shape. One may suggest that adding another opposite but similar curved slots to the antenna makes the antenna’s radiation pattern symmetrical with a higher gain, as shown with the dash-line in Figure 1(c). Unfortunately, as discussed in the introduction, this idea does not work as it also generates a null similar to a
wide centred slot shown in Figure 2(a). In fact, the electric fields with opposite directions on the opposite slots cancel each other in the broadside direction.

This creates the motivation to solve this problem. The proposed design in Figure 2(b), which is the antenna in Figure 2(a) with a coating layer, is able to convert the above-mentioned null of the broadside to the peak of the radiation, making it a normal radiation pattern for most applications.

Putting a coating layer on the waveguide always makes the propagating mode hybrid. However, this is not the reason for the elimination of the null. The theoretical analysis of this phenomenon is discussed in Section 3. In this study, our focus is on a wide symmetrical slot.

3 ANALYSIS OF COATED LONG-SLOT LWA

The effect of coating on LSA performance was studied analytically many years ago by Whetten and Balanis [15] and others [16] showing the well-known rotation of beam direction due to the presence of a dielectric layer on top. However, the above-mentioned analyses and other similar works did not include the effects of coating on a symmetrical slot and null removal as it does not radiate towards broadside direction.

The fundamental mode of a waveguide with a longitudinal slot is TE_{10}. This is the mode that produces the antisymmetrical E_x distribution on the slot in Figure 3(a) and nearly zero E_z has been shown in Figure 3(b), resulting in the E_y antenna radiation pattern with a null in the middle. Therefore, in order to change the antenna’s pattern, one needs to change the radiating mode on the slot. Placing a substrate-like dielectric slab (with e_r > 1) on the slot allows the excitation of the dominant TM_0 mode in the above slab from the waveguide dominant mode, TE_{10} [17], which has an E_z component as shown in Figure 3(c). This electric field result in the TE_{10} mode on the slot, which is E_x-field in both cases, namely coated and without coating. However, it is E_y which removes the null from the radiation pattern, as shown in Figure 3(c). That is why the antenna still has an end-fire radiation pattern near the horizon where \( \phi \) becomes 90 or −90 degrees. It is worth mentioning that the radiation of leaking waves from dielectric slab structures has been worked out since many years ago by using different radiating structures [18].

Figure 4(a) shows the distribution of the fundamental mode of a metallic waveguide, which is TE_{10} mode. By creating an air-filled slot on the waveguide, in any shape or format, the waveguide still supports TE modes due to the homogeneity of the dielectric material, which is the air here. Figure 4(b) and (c) demonstrate the first two propagating modes of the slotted waveguide, which are both TE\(_2\) at the beginning of the slot where it is still narrow, namely less than 23 mm. The first one is similar to the slot mode with \( f_e = 1.96 \text{ GHz} \) and the second one similar to normal waveguides TE_{10} mode \( f_e = 4.1 \text{ GHz} \). As long as the slot has an offset, the first mode of the waveguide, Figure 4(b) is excited, resulting in a normal E_y radiation pattern with a peak in the broadside direction. However, when the slot is symmetrically at the centre of the waveguide, the first mode is not excited, and instead, the second mode, namely the TE mode shown in Figure 4(c), is excited. The radiation from this mode has a broadside null with an aperture E-field distribution as shown in Figure 3(c). Due to the symmetrical structure of the slot, the radiation from the left and right sides of the slot cancel each other resulting in a null at broadside direction which is shown in Figure 5(a).

The idea here is to excite TM_0 slab mode in the coating layer, having E_z component in the axial direction in order to stimulate E_y radiation from the antenna. Any TM_0 mode in slab has three components, E_z, E_x and H_y [17]. The electric field components on the slot also have exactly the same components as shown in Figure 3 which produce the equivalent surface magnetic currents of \( \overline{M}_{\text{ex}} \) and \( \overline{M}_{\text{ez}} \), as shown in Figure 2(a). The later, namely \( \overline{M}_{\text{ez}} \), is not to excite H_z in TE modes of the dielectric slab as its distribution is antisymmetric with respect to x-direction while H_z is symmetrical in the form of \( A \cos(k_x x)e^{-jz} \). The former, namely \( \overline{M}_{\text{ex}} \), only excites the propagating modes of slab waveguide with H_x, which are TM modes. Among TM modes, it is only the dominant TM_0 mode that has the cut-off frequency of zero \( (f_e = 0) \), and the rest of higher-order modes are evanescent in our working frequency. Due to the zero cut-off frequency of TM_0, one can infer that this idea is valid even if the coating layer is electrically very thin. In conclusion, from this point of view, the excited second TE mode of the waveguide couples its energy to the dominant TM_0 mode of the covering slab, through the equivalent magnetic current on the slot, namely \( \overline{M}_{\text{ex}} \) component.

From another point of view, by placing a coating layer on the slot, the propagating medium of the waveguide becomes inhomogeneous, comprised of dielectric on top and air at the bottom. Therefore, the propagation of previously mentioned TE and TM modes is no longer valid. The propagating modes...
are, in reality, transformed into hybrid modes, which are shown in Figure 4(d) and (e).

4 | DESIGN AND MEASUREMENT OF PROPOSED LWA

4.1 | Proof of concept design

As a proof of concept, a WR-159 waveguide with the dimension of $40.38 \times 20.19 \times 400$ mm ($A \times B \times L$) is designed and simulated. The length of the long-slot ($L_d$) is 300 mm with 25 mm width ($W$), which is located on the broad wall of the waveguide. The two ends of the long-slot are tapered with a length of 33 mm ($L_w$) in order to have a better SLL, which is shown in Figure 2(a).

In order to verify this concept, the antenna is manufactured from aluminum material in two upper and lower pieces by CNC with both ends connected to SMA connectors. The upper and the lower parts are screwed to each other from the top side, where the shaped FR-4 cover is also attached to them. The simulated and measured results from the antenna are in good agreement with each other, as discussed in the following.
As Figure 5(a) shows, the radiation pattern has a deep null on the broadside of the antenna, with the two main lobes split to the two sides of the slot, each having 8.7 dBi of absolute realised gain at 5.6 GHz and 10.8° half-power beam-width (HPBW). The main component of the radiation pattern is $E_\theta$ which is confirmed in Figure 5(b). As expected, by putting a 1.524 mm lossy FR-4 sheet on top of the symmetric LSA, the null is eliminated, converting it to a peak of the radiation pattern, as shown in the absolute value of the radiation pattern, shown in Figure 6(a). The analysis of modes in Section 3 claims that the broadside component of the radiation pattern is $E_\theta$ with two $E_\varphi$ end-fire lobes. This is also confirmed by Figure 6 (b) and (c) showing both $\theta$ and $\varphi$ components of the radiation pattern, respectively. Figure 6 illustrates that the coated symmetric LSA may well radiate towards the broadside direction with 11.1 dBi of realised gain, and 15.4 dB of directivity at 5.6 GHz and 9.8° HPBW.

Our simulations illustrate that by increasing the value of dielectric constant ($\varepsilon_r$), the realised gain of the antenna at the broadside direction is gradually increased, converting the null to the peak. This is shown in Figure 7, where the increase of $\varepsilon_r$ from 2 to 7 increase the realised gain from 3 to 15 dBi. Although the slope of the increase in gain is not sharp, one can infer that the idea works for $\varepsilon_r > 3$. As we used the FR-4
substrate with an uncertain dielectric constant changing between 3.9 and 4.9, this would result in a change of around 1 dB in the realised gain. Also, by increasing the value of $H_c$ (the thickness of the dielectric layer) from 0.5 to 3 mm, the realised gain at the broadside direction gradually increases, as shown in Figure 7. The behaviour of the realised gain becomes vice versa going above $\varepsilon_r$ of 8 and $H_c$ of 3. It is also observed that the resulted beam rotation is less than 2 degrees. Besides that, the loss tangent of the dielectric coating reduces efficiency as expected. A tanδ of 0.025 for the FR-4 reduces the radiation efficiency by 10% compared to the lossless case.

The simulated and the measured $S$-parameters of the proposed antenna are illustrated in Figures 8 and 9, with a 1.4 GHz input impedance bandwidth (25%). For the sake of showing the concept, the length of the antenna is chosen only about 6$\lambda$, resulting in a low $S_{12}$ value of about $-2.5$ dB and $-4$ dB in 5.6 GHz for the coated antenna and the antenna without coating layer, respectively. The simulation and measurement of $S$-parameters are in acceptable agreement.

The comparisons between the simulated and measured radiation patterns are also illustrated in Figures 10 and 11 for both cases of with coating and without coating, respectively. The radiation pattern in Figure 11 is normalised to the peak value in Figure 10. The simulated direction of the copolarised radiation beam, $E_{\theta}$, is 47° from the horizon. The results clearly show the effectiveness of the coating layer to remove the radiation null with more than 18 dB improvement between the peaks of the main beams with and without coating. In the measurement, the direction of the main beam is changed to 50°, mainly due to the small air gap between the antenna and the layer [19]. The simulated cross-polarisation level of the antenna is almost negligible and cannot be seen in Figure 10.
The measured cross-polarised level of the radiation is at −15 dB. In the antenna without the coating layer, the simulated electric field level in broadside direction, namely $\varphi = 90^\circ$ direction, is much less compared to the coated case as expected. Naming the $E_\varphi$ field again as a copolarised field, its maximum is around −12 dB, which is quite high, as shown in Figure 11. The discrepancy is mainly due to the uneven air gap between the antenna and the coating layer in addition to other fabrication tolerances. The simulated cross-polarised radiation, namely $E_\varphi$, is almost negligible and cannot be observed in this scale. The main parts of the radiation, in this case, are at side angles near $\varphi = 0^\circ$ and $\varphi = 180^\circ$ as can be seen in Figure 5(a).

4.2 | Longer design with high SLL

The above-mentioned proof-of-concept design is relatively short, with low directivity and low SLL. In order to increase the antenna’s gain, either the length of the radiating slots should be increased or the slot’s width. The latter has a limited effect while having some side effects. Therefore, another design in the same band by using a longer symmetric curved axial slot on the same WR-159 waveguide is presented having higher directivity and higher SLL. This design also produces a symmetric radiation pattern with a peak in the direction of the broadside.

As shown on the right side of Figure 12, the curved slot in this design is much longer (approximately 204) and has a tapered curve and thus tapered current distribution. The antenna also has a good impedance matching within the same band. The simulated directivity of the new coated antenna is almost 19 dBi with an SLL of 20 dB and HPBW of 7 degrees, as shown in Figure 12. In order to verify the effect of the coating layer, the normalised radiation pattern of the new antenna with and without using the coating layer is overlaid, showing the conversion of the null to the peak of the pattern with 21 dB difference between the peak levels. As the antenna’s physical length is more than 1 m, the antenna has not been fabricated.

5 | CONCLUSION

A simple but novel idea of using a coating sheet to remove the broadside null of the symmetric long-slot LWA was discussed here. This layer enabled the coupling of $\text{TE}_{10}$ mode energy to $\text{TM}_0$ slab mode, which generates a peak at the broadside direction and $90^\circ$ of polarisation rotation. The simulated and the measured results confirmed the idea by
testing it on a C-band 300 mm LSA. The designed antenna had a beam at 50° from the horizon, 11.1 dBi realised gain, 1.4 GHz impedance bandwidth (25%) and 9.8° HPBW.

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