Improved Design of Uniform SIW Leaky Wave Antenna with SUPpression of Unwanted Mode

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ABSTRACT In this paper, periodic perturbations are employed on the broad wall of a substrate integrated waveguide (SIW) long slot leaky-wave antenna (LWA) to eliminate the excited unwanted mode. The presence of unwanted mode in the uniform LWA is identified by using the amplitude and phase of the electric field at the slot. Using the electric field data in the structure, propagation constants and amplitudes of desired and unwanted modes are obtained. In order to preserve the desired leaky mode and suppress the unwanted mode, periodic transverse slots are added to one side of the uniform longitudinal slot. Suppressing unwanted mode results in good consistency between the desired and designed radiation characteristics. Comparison between two LWA designs, with and without suppressing unwanted mode, for achieving -25 dB sidelobe level (SLL) and beam direction of 40° at 17 GHz, demonstrates high accuracy of the proposed design procedure. A prototype of the modified antenna is fabricated, and measured results are presented at 16, 17, and 18 GHz for validation.

INDEX TERMS Periodic perturbations, Leaky wave antenna, Substrate integrated waveguide, Suppressing unwanted mode.

I. INTRODUCTION

Longitudinal long slot LWAs have been widely studied and used due to their simple structure and good performance [1-3].

The existence of a uniform longitudinal slot, perturbs the main TE\textsubscript{10} mode of the rectangular waveguide and causes propagation of a leaky mode. In order to obtain a specified radiation pattern, the aperture field’s amplitude and phase distributions of the leaky mode must be properly tapered along the antenna. These taperings can be achieved by changing the geometrical parameters of the structure, such as meandering the slot [1] or waveguide walls [4], [5]. The slotted perturbations may lead to the excitation of unwanted modes which their features of propagation cannot be controlled [6]. These unwanted modes are leaky wave or surface wave modes.

The existence of unwanted leaky mode was figured out by observation of unwanted radiated beams of uniform longitudinal slots on the narrow wall [7-8] and broad wall [9] and it was called “slot mode”. The presence of slot mode can also be demonstrated by the observation of aperture fields [10].

Excitation of unwanted leaky mode causes radiation interference between desired and unwanted modes. This spoils the radiation pattern by creating an undesired beam or broadening the main beam. For this reason, some investigations have been done for identification and suppressing the slot mode radiation [7], [8], [11]. Suppression of the slot mode by thin-film metal or dielectric sheet in [7], causes a significant gain drop. In [8] and [11], periodic transverse slots are added perpendicular to the longitudinal slot on the narrow wall to change the slot mode propagation from a fast wave to a slow wave. In this manner, some amount of power is guided in the waveguide and absorbed at the load.

Recently, an improved method for design of uniform LWA has been proposed with considering the unwanted mode [12]. This consideration, results in precise calculation of the leakage constant of the desired leaky mode.

In this paper, we modify the design method presented in [12], by suppression of the unwanted mode. This modification results in better agreement between the desired and designed radiation patterns. Suppression of the unwanted mode is achieved by properly adding periodic transverse slots to the uniform longitudinal slot.
FIGURE 1. Geometry of straight long slot LWA based on SIW structure.

FIGURE 2. Phase constants of leaky mode and unwanted mode for different values of $x_0$ and $w$, which give the beam direction of $\theta_m = 40^\circ$.

FIGURE 3. Leakage constants of leaky mode and unwanted mode for different values of $x_0$ and $w$, which give the beam direction of $\theta_m = 40^\circ$.

FIGURE 4. Cross section view for the geometry of straight long slot LWA.

FIGURE 5. Amplitude of leaky-wave mode and unwanted mode on lines 1 and 2 for different values of $x_0$ and $w$, which give the beam direction of $\theta_m = 40^\circ$.

To provide a comparison, we design two SIW LWAs. The first antenna is designed based on the initial method expressed in [12], and the second one is designed using the modified method presented in this work.

II. DESIGN PROCEDURE

In this section, a modified long slot SIW LWA with the suppressed unwanted mode is designed. The goal is to achieve a Taylor amplitude distribution for -25 dB SLL and a fixed phase constant corresponding to a beam pointing angle of $\theta_m=40^\circ$ at 17 GHz. The slot length is set to $L=180$ mm. The SIW substrate is Rogers5880 with dielectric constant, loss tangent, and height equal to $\varepsilon_r = 2.2$, $\tan\delta = 0.0009$, and $h=0.787$ mm, respectively.

A. IDENTIFICATION OF UNWANTED MODE IN UNIFORM LWA

To identify the unwanted mode, we first consider a general structure of a long slot SIW LWA, as shown in Fig. 1. In this structure, the diameter of vias and the distance between them are $d=1$ mm and $s=2$ mm. The width of the SIW is $w$, the width of the longitudinal slot is $w_s$, and the offset of the slot from the centerline is $x_0$. In this design, $w_s$ is set to 0.8 mm, and $w$ and $x_0$ are varied to make the desired leakage constant, $\alpha$, and phase constant, $\beta$, distributions along the slot. As expressed in [12], by using the HFSS full-wave simulator, the study of the simulation patterns, and using $\cos(\theta_m) \approx \beta/k_0$, different values of $w$ and $x_0$, which give $\theta_m=40^\circ$ or $\beta/k_0=0.766$, are obtained.

After obtaining these pairs of $x_0$ and $w$, the method explained in [12] is used to obtain the leakage and phase constants of the leaky mode in the presence of the unwanted mode. This method is based on modeling the near electric field along the slot by

$$E_y = A_1 \times e^{-\alpha_1 r} e^{-j\beta_1 r} + A_2 \times e^{-\alpha_2 r} e^{-j\beta_2 r}$$

which composed of two traveling waves with two propagation constants of $\gamma_1$ and $\gamma_2$ ($\gamma = \alpha + j\beta$). Figs. 2 and 3 show leakage and phase constants of the leaky and unwanted modes. The solid curve in Fig. 2 shows that the phase constant of the leaky mode is approximately 273 rad/m which is corresponding to the desired beam direction of $\theta_m=40^\circ$. The dashed line in Figs. 2 and 3 show the phase and leakage constants of unwanted mode. At the center frequency of 17 GHz, $k_0$ is equal to 356 rad/m. Hence, according to Fig. 2, the unwanted mode for some values of $x_0$ and $w$ is a leaky wave ($\beta<k_0$), and for other values, it is a surface wave ($\beta>k_0$). In both cases, excitation of the unwanted mode reduces the performance of the antenna.

B. SUPPRESSION OF UNWANTED MODE FROM THE UNIFORM LWA

The geometry of cross section of a LWA with a long straight slot is shown in Fig. 4. Using the method explained in [12],
Transverse slots are started from the longitudinal slot and can be continued to the sidewall. The design parameters along the structure are SIW width, \( w \), longitudinal slot width, \( w_s \), transverse slot width, \( w_t \), offset from the centerline, \( x_0 \), the distance between transverse slots, \( p \), and distance of transverse slots from the sidewall, \( d_w \).

To show the effect of added transverse slots, we simulate this structure with geometrical parameters of \( w=9.4 \) mm, \( x_0=1.15 \) mm, \( w_t=0.8 \) mm, \( p=4 \) mm, \( w_s=0.4 \) mm, and \( d_w=3 \) mm. The amplitude and phase distributions of the electric field on the longitudinal slot with 140 mm length are shown in Figs. 7 and 8 with a dashed line. These near field data are obtained on a straight line in the middle of the slot by using HFSS full-wave simulation. Fitting these curves with amplitude and phase of Eq. (2), gives the leakage and phase constants of the existing mode in the structure.

\[
E_y = A \times e^{-az} e^{-j\beta z}
\]  

(2)

To provide a comparison, the amplitude and phase distributions of the electric fields on the slot in the uniform LWA without suppression of the unwanted mode are added in the insets of Figs. 7 and 8. The fitted curves shown in the insets are obtained using Eq. (1), as explained in [12]. As pointed out in [12], the periodic behavior of the amplitude distribution of the electric field is due to the existence of two modes in the structure. Suppression of the unwanted mode, as shown in Fig. 7, leads to exponential behavior of amplitude distribution which demonstrates the existence of one mode in the modified structure.

Although in [8] and [11] periodic transverse slots are used, it should be noted that those designs are narrow-wall-related slitted waveguide, which are different from our broad-wall-related design. In fact adding periodic transverse slots on the narrow wall in [8] and [11] will not perturb the dominant TE_{10} mode because they will not cut the currents on this wall. Therefore, these transverse slots will not influence the operation of the original narrow-wall slitted waveguide; they just work as series inductors to slow down the propagation speed of the slot mode (fast wave unwanted mode) and to transform it to a slow-wave unwanted mode. Comparatively, in our case, these transverse slots cut the longitudinal currents of the unwanted mode on the broad wall and perturb the part of the waveguide which excites the unwanted mode to fully suppress the slow-wave/fast-wave unwanted mode.

C. DESIGN OF UNIFORM LWA WITH SUPPRESSING UNWANTED MODE

To simplify the design procedure, we consider only two varying parameters, \( x_0 \) and \( w_s \), and choose \( w_t=0.4 \) mm, \( p=4 \) mm, and \( d_w=3 \) mm as fixed parameters. Choosing a constant value for \( d_w \), results in different lengths of transverse slots along the antenna. It is worthy to note that a better suppression of unwanted mode can be achieved by increasing the values of \( d_w \) and \( p \) in cost of increasing the cross-polarization level. Fig. 9 shows the leakage constant of
FIGURE 9. Leakage constants of leaky mode for different values of $x_0$ and $w$, which give the beam direction of $\theta_m = 40^\circ$. 

FIGURE 10. Required leakage constant for the realization of Taylor amplitude distribution for different values of antenna efficiencies.

FIGURE 11. SIW width and slot offset along the modified antenna.

leaky mode obtained using Eq. (2) and the method expressed in section II-B, for different values of $x_0$ and $w$, which give the beam direction of $\theta_m = 40^\circ$. Fig. 10 shows the required $\alpha(z)$, for different values of radiation efficiency, $\eta$, obtained based on the method expressed in [12]. This $\alpha(z)$ is required for realizing a -25 dB SLL Taylor amplitude distribution using a SIW with the width of $w = 9.1$ mm. The solid line is for maximum achievable $\eta$, which is corresponding to the maximum realizable leaky mode’s leakage constant of the structure. Using the realizable and required leakage constants shown in Figs. 9 and 10, appropriate values of $x_0$ and $w$ along the length of the antenna are achieved as shown in Fig. 11.

III. SIMULATION AND MEASUREMENT RESULTS

The final structure is tuned and modified to have a straight slot as that of [4]. Two cavities are used at the feed and load parts. There is a 50 $\Omega$ load at the terminating output port. Fig. 12(a) shows the final schematic structure of the modified design. To provide a comparison, the structure of the initial antenna (based on the method of [12] and without suppressing unwanted mode) is also shown in Fig 12(b). Fig. 13 compares the simulation results of H-plane normalized co/cross-polarization radiation patterns at 17 GHz for the initial antenna and the proposed modified antenna in this paper. The theoretical desired pattern is also presented in this figure.

Table I compares the simulated results of initial and modified antennas with those of theory. Note that the presence of the unwanted mode in the initial antenna and its radiation from some parts of the slot results in the deviation of half-power beamwidth (HPBW) and SLL from the desired theoretical values. Suppression of this unwanted mode leads to better consistency between theoretical and simulated results in the modified design. In addition, the efficiency of the modified antenna is slightly improved compared to that of the initial design.

| Theoretical and Simulated Results for the Initial and Modified Designs | Theory | Initial | Modified |
|---|---|---|---|
| SLL (dB) | -25 | -20.7 | -25.4 |
| Beam direction (deg) | 40 | 40 | 40.2 |
| HPBW (deg) | 9.4 | 10.4 | 9.9 |
| Efficiency | 0.81 | 0.70 | 0.73 |
| Gain (dB) | - | 15.47 | 16.15 |
SIW LWA on a single layer Rogers5880 substrate is shown in Fig. 14. Fig. 15 shows the simulated and measured results for scattering parameters of the modified antenna. The desired operating frequency in this work is 17 GHz; however, in addition to this frequency, we present the radiation patterns at two other frequencies. The measured and simulated radiation patterns at 16, 17, and 18 GHz are shown in Fig. 16. Good agreements are achieved between simulated and measured results. Table II contains the simulated and measured results. Table II contains the simulated and measured results. Figure 15. Simulated and measured results for scattering parameters of the presented modified antenna.

Table II

|          | 16 GHz | 17 GHz | 18 GHz |
|----------|--------|--------|--------|
| SLL(dB)  | -23    | -23.8  | -25.4  |
| Beam direction (deg) | 50.5  | 49.3  | 40.2  |
| HPBW (deg) | 10    | 8.9   | 9.9   |
| Gain (dB) | 15.6  | 14.2  | 16.15 |

IV. CONCLUSION

A modified design of a uniform LWA with suppression of unwanted mode is presented in this paper. The electric field data on a straight slot is used to obtain the leakage and phase constants of the leaky mode. The periodic behavior of amplitude and phase distributions of the near field shows the existence of a leaky mode and an unwanted mode. Using periodic transverse slots, added on one side of the straight slot, the unwanted mode is suppressed. To validate the advantage of suppressing unwanted mode, two LWAs with and without suppressing unwanted modes are designed at 17 GHz. The presented antennas have Taylor amplitude distribution and linear phase distribution along the antenna to achieve a predefined SLL of -25 dB and beam direction of 40°. Simulation results of two antennas show better agreement between simulated and desired radiation patterns for the antenna with suppressed unwanted mode. In order to validate the design of the modified antenna, the proposed antenna has been fabricated and measured. Good agreement is achieved between simulated and measured results.

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