Suppression of the Slot-Mode in a Slitted Waveguide using Dielectric-Filling

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***Abstract*—In this paper, we propose a method to suppress the slot-mode in uniform rectangular waveguide based leaky-wave antennas (LWAs). In the method, the use of a dielectric-filled waveguide is shown to completely suppress the propagation of the slot-mode thereby eliminating the influence of this mode in the radiated electric field from the LWA. The characteristics of the slot mode and fundamental leaky mode are first studied using the transverse equivalent network of the LWA structure using both air-filled and dielectric-filled waveguide models and the suppression effect is confirmed by full-wave simulation.**

Keywords—Antenna radiation patterns, leaky-wave antennas (LWAs), waveguide antennas

I. Introduction

The rectangular waveguide based uniform leaky-wave antenna (LWA) with a longitudinal slit along the narrow wall has been studied by numerous scholars [1] – [3] and, owing to the ease of fabrication and electronic scanning of one spatial dimension simply by changing the frequency, has found application in areas such as millimeter wave imaging [4] which is our primary target application. Such applications often depend upon the appropriate tapering of either the phase constant (β) or the attenuation constant (α) of the fundamental (leaky) mode propagating along the length of the waveguide [5] – [8]. As such, the existence of an additional mode alongside the leaky mode would influence the radiated electric field and is therefore unwanted.

This mode, called the slot-mode, was shown to exist and was attributed to the parallel edges of the longitudinal slit [9]. To suppress the radiation of this mode, a method using shorter transverse slots introduced along the length of the longitudinal slit was introduced in [10], [11] though it was still propagating within the waveguide as only the radiating slit was modified.

Therefore, in this work we show that it is possible to suppress the propagation of the slot-mode within the waveguide by using a dielectric-filled waveguide as indicated, though only in passing, in our previous work [8]. This paper therefore explores this phenomenon in greater detail by comparison against the transverse slot method. As the slot-mode is prevented from propagating, it naturally follows that it will be suppressed from radiating. The extraction of the LWA wave number and verification of the proposed method is discussed in Section II.

II. Wave Number Extraction and Simulation Results

To extract the wave number of the LWA models to be used to confirm the proposed method, the transverse resonance method [1], [2] using the equivalent network model shown in Fig. 1. In the model, ε_r^{WG} represents the dielectric constant of the dielectric material within the waveguide of the LWA.

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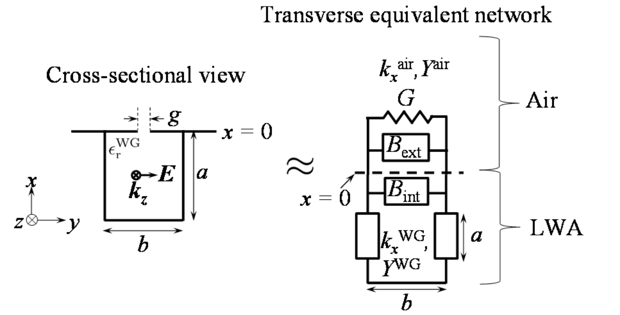

Fig. 1. Transverse equivalent network of the uniform rectangular waveguide leaky-wave antenna.

By taking the reference plane as $x = 0$, G represents the radiated energy from the antenna, B_{ext} represents the non-radiated energy outside the waveguide whereas B_{int} represents the non-radiated energy inside the waveguide. The longitudinal slit width is represented by g, the broad wall height by a and the narrow wall by b. Therefore, assuming operation in TE mode, the characteristic equation representing the network is [1], [2]

$$\frac{k_x^{air}}{\omega\mu_0}\left(\frac{k_x^{air}b}{2}+j\left[\frac{k_x^{air}b}{\pi}\ln\left(\frac{\pi e}{\gamma k_x^{air}d}\right)\right]\right)$$
$$+\frac{k_x^{WG}}{\omega\mu_0}\left(-j\cot(k_x^{WG}a)+j\left[\frac{k_x^{WG}b}{\pi}\ln\frac{\pi g}{2b}\right]\right)=0 \qquad (1)$$

where $e = 2.718$ and $\gamma = 1.781$.

As (1) is a transcendental equation, it can be solved numerically by appropriately selecting the limits of the desired solution. To confirm the method proposed in this work, a dielectric-filled waveguide with $a = 9$ mm, $b = 5$ mm, $g = 1$ mm and $\varepsilon_r^{WG} = 2.7$ and the limits of the solution for (1) set as $0 \le \beta/k_0 \le 1$ (for modes capable of radiating) and $0 \le \alpha/k_0 \le 1$ in the frequency range of 5 GHz to 20 GHz. For comparison purposes, an air-filled waveguide LWA capable of operating in the same frequency range was also modelled with $a = 20$ mm, $b = 15$ mm, $g = 3$ mm and $\varepsilon_r^{WG} = 1$. The results of the extracted normalized β in of both these models are indicated in Fig. 2.

From figure, the case of the dielectric-filled LWA (black line) had only a single solution for β whereas the air-filled (red lines) case had two solutions of β in the stated solution limits with the solid lines corresponding to the leaky-mode and the dotted line corresponding to the slot-mode. The slot-mode can be seen to radiate closer to the end fire direction compared

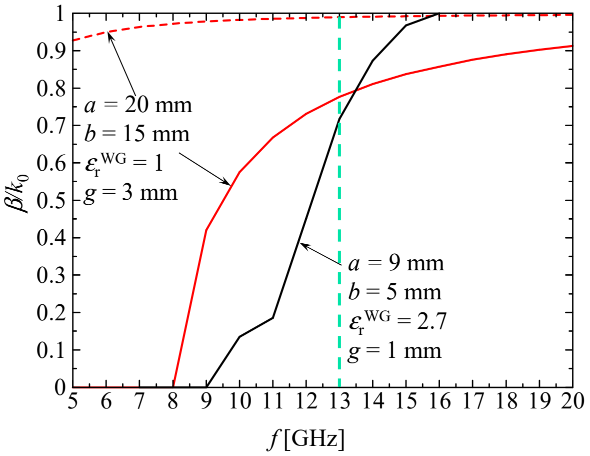

Fig. 2. Normalized phase consant in air-filled ($\varepsilon_r^{WG} = 1$) and dielectric-filled ($\varepsilon_r^{WG} = 2.7$) waveguide LWAs.

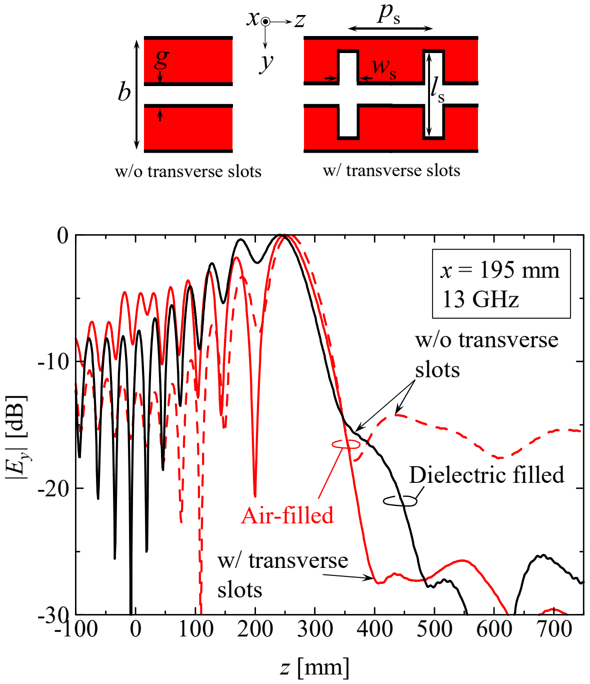

Fig. 3. Normalized radiated electric field from air-filled and dielectric-filled waveguide LWA models extracted from full-wave simulation.

to the leaky-mode (β/k_0 closer to 1) which should allow the detection of this mode from the radiated electric field separately from the leaky mode. From these results, we may therefore conclude that the slot-mode has been suppressed in the dielectric-filled case.

To confirm this conclusion, both the models calculated by the network model were fabricated and calculated using full-wave simulation software with the same physical parameters. Two kinds of models were calculated in the air-filled case, one with the transverse slots used to suppress the slot-mode in [10], [11] (with the short transverse slot being of length $l_s = 12$ mm, width $w_s = 3$ mm and periodicity $p_s = 9$ mm) and one without. The radiated electric field from the three structures was extracted at $x = 195$ mm with both structures being oriented along the z-direction with $z = 0$ coinciding with the center of the LWA models. The comparison between all the cases was made at 13 GHz.

From Fig. 2, the leaky-mode in the air-filled case has an expected radiation direction $\theta_s = \cos^{-1}(\beta/k_0) = 39^\circ$ whereas the dielectric-filled case has $\theta_s = 44^\circ$ with the difference between these two values being small enough to allow comparison with the slot-mode in the air-filled case having $\theta_s \approx 10^\circ$. From Fig. 3, the main component of the air-filled case is at about $z = 250$ mm whereas that of the dielectric-filled case is at about $z = 204$ mm which corresponds to $\theta_s = 38^\circ$ and $\theta_s = 43^\circ$ respectively which show good agreement the expected analytical values. Further, both the dielectric-filled and the air-filled case with (w/) transverse slots have only a single main component of the radiated electric field whereas the air-filled case without (w/o) the transverse slots has an additional component in the region of $z \geq 400$ mm which is attributed to the slot mode. From this analysis, we may conclude that using a dielectric-filled waveguide allows the suppression of the propagation and the subsequent radiation of the slot-mode and may present an alternative to transverse slots.

III. Conclusion

In this work, the suppression of the slot-mode in uniform rectangular waveguide leaky-wave antennas using a dielectric-filled waveguide was proposed. The proposed method was compared with an existing method and the effectiveness of the method confirmed by full-wave simulation. Future work would therefore focus on confirming the proposed approach experimentally.

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