A New Broadband Microstrip Leaky – Wave Antenna

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Abstract − This paper presents a novel design of a curve tapered leaky-wave antenna (LWA). An FDTD code was used to extract the propagation constant of a microstrip LWA and to run a simple algorithm to design its layout. A physical grounding structure along the length of the antenna allows the adoption of a simple feeding planar line and the reduction of sidelobes. Moreover, the proposed design of LWA has interesting performance both for its bandwidth, (up to 33% for VSWR< 2) and for its gain (more than 12 dBi peak power gain at 10.5 GHz), compared with conventional planar microstrip LWAs which work in the same frequency range but with narrower bandwidth (20% VSWR< 2) and peak power gain less than 10 dBi. A prototype of a LWA proposed, was made showing a good agreement between experimental and theoretical results.

Keywords: Leaky wave, broadband antennas, FDTD, and tapered antenna.

I. INTRODUCTION

Substantial enhancements were achieved since pioneering studies [1,2] on microstrip leaky-wave antennas (LWA), and they are now very popular and widely used in applications thanks to their advantages of low-profile, easy matching, narrow beamwidth, fabrication simplicity, and frequency/electrically scanning capability. In some applications the mainbeam variation of LWA should be as low possible. In these cases it is possible to use a tapered microstrip LWA in which each section of the antenna, irradiates in specific ranges of frequency, obtaining therefore a fixed mainbeam. It's equivalent to a broadband antenna.

Unfortunately in these structures the impedance mismatch between the different sections of LWA, and the fundamental mode perturbation, that is a bound mode, reduce the bandwidth of LWA. Slots in the microstrip conductor are possible solutions to eliminate the fundamental mode [1]. Suitable metal walls down the centerline connecting the conductor strip and the ground plane can be considered alternatively, as shown in Fig. 1 determining the possibility to reduce the width of the antenna simplifying its feeding structure [3].

We have studied and designed a broadband tapered LWA, with a simple algorithm, as discussed in the following sections, showing the experimental results of a LWA prototype made using the proposed design, which is in a good agreement with theoretical results.

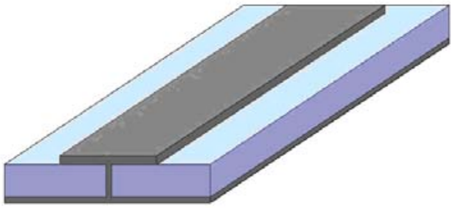


Fig. 1. Travelling half antennas.

II. CHARACTERISTICS OF MICROSTRIP LWA

The radiation mechanism of higher order modes on microstrip LWA is attributed to a traveling wave instead of the standing wave as in patch antennas and above cutoff frequency, where the phase constant equals the attenuation constant ($\alpha_c = \beta_c$), it is possible to observe three different range of propagation: bound wave, surface wave and leaky wave. While at low frequency, below the cutoff frequency, we have the reactive region due to evanescent property of LWA. We can explain the character of microstrip LWA trough the complex propagation constant $k = \beta - j\alpha$, where β is the phase constant of the first higher mode, and α is the leakage constant of the guided mode.

The main-beam radiation angle of LWA can be approximated by,

$$\theta = \cos^{-1}\left(\frac{\beta}{K_0}\right) \tag{1}$$

where θ is the angle measured from the endfire direction and K_0 is the free space wavenumber.

From equation (1) we can observe that the leaky mode leaks away in the form of space wave when $\beta < K_0$, therefore we can define the radiation leaky region from the cutoff frequency to the frequency at which the phase constant equals the free-space wavenumber $(\beta = K_0)$. For $(\beta > K_0)$ we have the bound mode region and for $K_0 < \beta < K_s$, exists a narrow frequency range in which we can have surface-wave leakage.

II. DESIGN OF BROADBAND LWA

The dispersion equation is the main instrument of analysis to determine the range of propagation of the antenna. Generally the solution of that equation can be obtained through a full-wave analysis such as spectral domain analysis (SDA) [4], or with a transverse resonance approximation according to [5]. Recently an FDTD code which uses a PML boundary condition has been introduced in [3] to extract the propagation constant of a microstrip LWA. Using this code we can obtain in a simple way the radiation leaky region for a different geometry of LWAs. Moreover, the idea to replace slots with a physical grounding structure along the length of the antenna connecting the conductor strip and the ground plate, allow using only half of the structure due to image theory, strongly reducing the computational costs to run a FDTD code.

A transverse electric field E_z was used in 3D FDTD code, to excite the antenna using a sinusoidal source with a cubic ramp over the first three periods according to [3], located inside the substrate. A PEC was used to modeled ground plane and all conductors, while PML were applied to all other boundaries directly in contact with the antenna to suppress the reflection of travelling wave. A recursive least-squares procedure was used to determine the constants α and β by matching a known exponential curve to the transverse electric field amplitude, retrieved from 3D FDTD data (see Fig. 2), along the length of the antenna. The symbol α was found from the peak values, while β was found from the zero crossings, as shown in Fig. 3. The dispersion characteristics curve of Fig. 4, obtained by FDTD code, shows a good agreement with transverse resonance approximation derived by Kuestner [5].

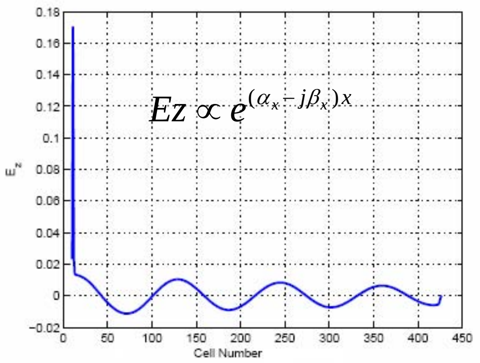


Fig. 2. A transverse electric field E_z data retrieved by FDTD code.

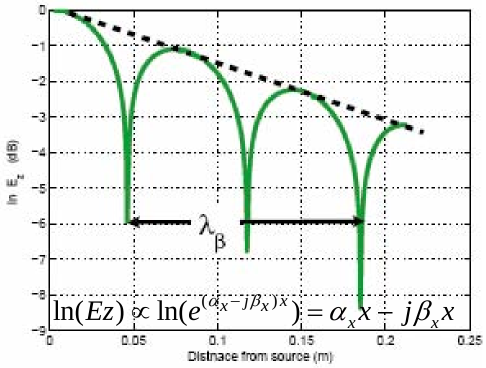


Fig. 3. The logarithmic curve of transverse electric field E_z data used to determine the propagation constant.

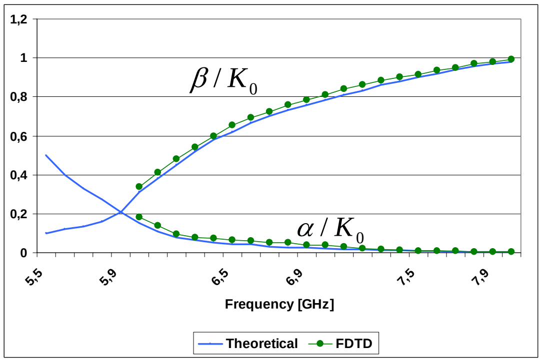


Fig. 4. Theoretical and FDTD dispersion characteristics of leaky wave first high mode.

Moreover, to validate the FDTD code we have calculated and plotted the relationship between the relative permittivity of the substrate and the propagation constant, and the relationship between the thickness of the substrate and the propagation constant. The good agreement of these curves, with the theoretical transverse resonance approximation [5], as shown in Figs. 5 and 6, confirms the validity of the numerical FDTD code used.

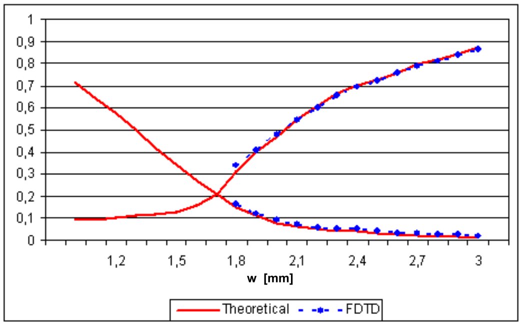


Fig. 5. Theoretical and FDTD dependence between the relative permittivity of the substrate and the propagation constant at f= 6.7 GHz, w = 15mm, h = 0.787 mm.

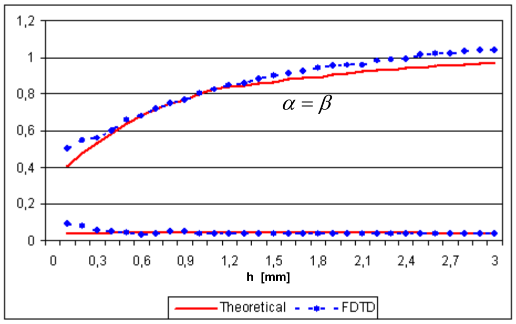


Fig. 6. Theoretical and FDTD dependence between the thickness of the substrate and the propagation constant at f= 6.7 GHz, ε_r = 2.32, h = 0.787 mm.

Through the dispersion characteristic equation, evaluated with FDTD code, we can obtain the radiation region of the leaky waves indicated in the more useful way for the design of our antenna,

$$\frac{c}{2w_{eff}\sqrt{\varepsilon_r}} = f_c < f < \frac{f_c\sqrt{\varepsilon_r}}{\sqrt{\varepsilon_r - 1}}. \qquad (2)$$

From equation (2) we can observe that the cutoff frequency increases when the width of the antenna decrease, shift toward high frequencies, the beginning of the radiation region as shown in Fig. 7. Therefore it is possible to design a multisection microstrip antenna [as Type I antenna in Fig. 4], in which each section able to radiate at a desired frequency range, can be superimposed, obtaining an antenna with the bandwidth more than an uniform microstrip antenna. In this way every section should be into bound region, radiation region or reactive region, permitting the power, to uniformly radiated at different frequencies.

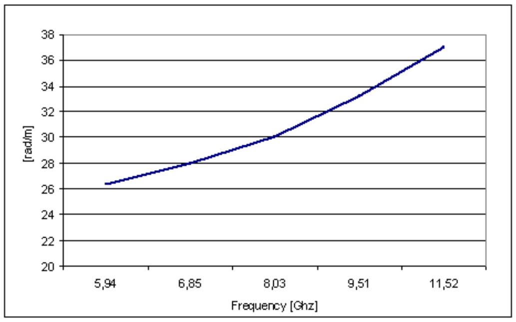


Fig. 7. Cutoff freq. of multisections microstrip LWA .

Using the same start width and substrate of Menzel travelling microstrip antenna (TMA) [1], and total length of 120 mm, we have started the iterative procedure mentioned in [6] to obtain the number, the width and the length of each microstrip section. From Menzel TMA width, we have calculated the f_{START} (onset cutoff frequency) of the curve tapered LWA, than, choosing the survival power ratio ($\tau = e^{-2\alpha_i L_i}$) opportunely, at the end of the first section, we have obtained the length of this section. The cutoff frequency of subsequent section (f_i), was determined by FDTD code, while the length of this section was determined, repeating the process described previously. This iterative procedure was repeated, until the upper cutoff frequency of the last microstrip section.

The presence of ripples in return loss curve and the presence of spurious sidelobes shows the impedance mismatch and discontinuity effect of this multisection LWA that reduce the bandwidth. A simple way to reduce these effects is to design a tapered antenna in which the beginning and the ending, respectively, of the first and the last sections are linearly connected together (as the Type II antenna in Fig. 8).

Alternatively, this idea was to design a LWA using a physical grounding structure along the length of the antenna, with the same contour of the cutoff phase constant or attenuation constant curve ($\alpha_c = \beta_c$), obtained varying the frequency, for different width and length of each microstrip section as shown in Fig. 3, employing the following simple equation (3),

$$\beta_c = c_1 f^2 + c_2 f + c_3 \qquad (3)$$

obtained from linear polynomials interpolation, where c_1 = 0.0016, c_2 = 0.03, c_3 = -15.56.

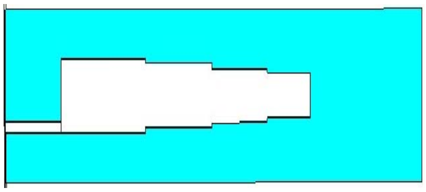
The antenna layout (as the Type III antenna in Fig. 8), was optimized through a 3D electromagnetic simulator, and the return loss and the radiation pattern was compared with Type I antenna and Type II antenna.

III. SIMULATION RESULTS

An asymmetrical planar 50 Ω feeding line was used to excite the first higher-order mode while a metal wall down the centerline connecting the conductor strip and the ground plate was used to suppress the dominant mode for Type I - III. The chosen substrate had a dielectric constant of 2.32 and a thickness of 0.787 mm, while the total length of the leaky wave antenna was chosen to be 120 mm.

The leaky multisection tapered antenna Type I was open-circuited, with a 15 mm start width, and 8.9 mm of final width obtained according to [6]. For LWA layout Type I, we used four microstrip steps, for layout Type II we tapered the steps linearly, while the curve contour of the LWA layout Type III, was designed through equation (3).

Figure 9 shows the simulated return loss of three layouts. We can see that the return loss (S11) of Type I is below -5 dB from 6 to 10.3 GHz, but only three short-range frequencies are below -10 dB. S11 of Type II is below -5 dB from 6.1 to 9.1 GHz, and below -10 dB from 6.8 to 8.6 GHz. At last, S11 of Type III is below -5 dB from 6.8 to 11.8 GHz, and below -10 dB from 8.0 to 11.2 GHz. In Fig. 10 are shows the mainlobe direction at 9.5 GHz for the different Type I to Type III. We can see a reduction of sidelobe and only few degrees of mainlobe variation between Types I to III. Moreover, in Fig. 11 is shown the variation of mainlobe of antenna Type III, for different frequency, while in Fig. 12 is shown the trend of gain versus frequency of the same antenna. It is clear that, the peak power gain is more than 12 dBi, which is almost 3 dBi higher than uniform LWAs.


(a) Type I


(b) Type II

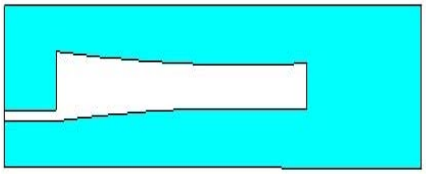
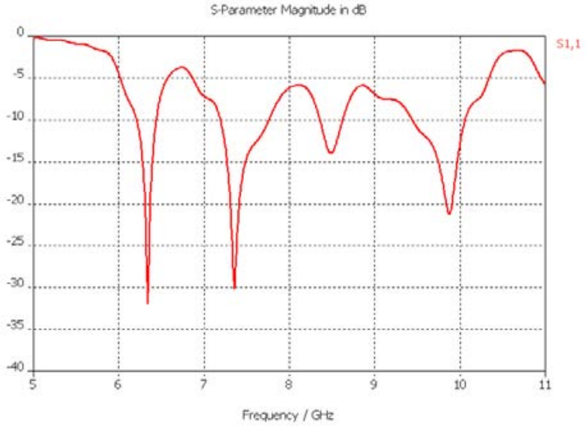

(c) Type III

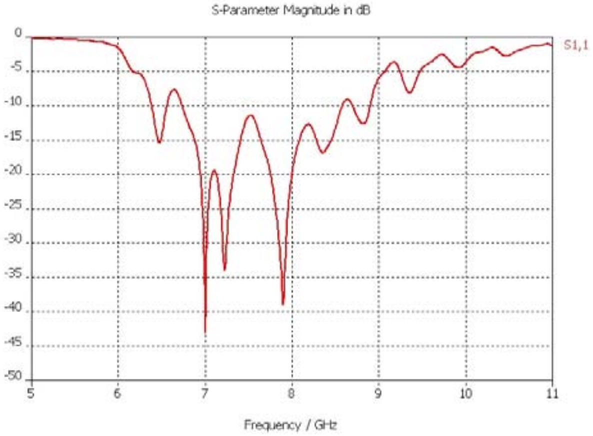
Fig. 8. Layout of leaky wave antennas types I-III. A physical grounding structure was used to connect the conductor strip and the ground plane.

Finally, the simulated VSWR is less than 2 and between 8.01 and 11.17 GHz (33%), yielding an interesting relative bandwidth of 1.39:1, as shown in Fig. 13, compared with uniform microstrip LWAs (20% for VSWR < 2) as mentioned in [7].

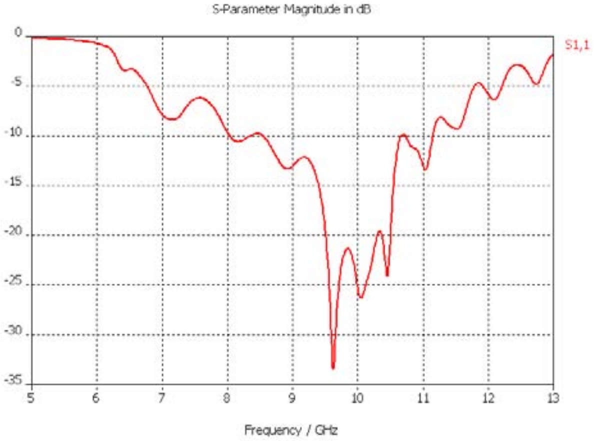
These results indicate a high performance of Type III LWA: high efficiency excitation of the leaky mode, increases of the bandwidth, improves the return loss and reduction of 19% of metallic surface with respect to uniform LWA. Moreover, these results are in a good agreement whit the experimental results of return loss and radiation pattern of a prototype (shown in Fig. 14) made using a RT/Duroid 5880 substrate with thickness of 0.787 mm and relative dielectric constant of 2.32, as shown in Figs.15 and 16.



(a) Type I

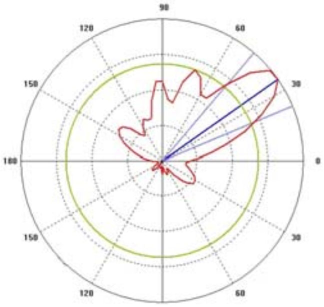


(b) Type II

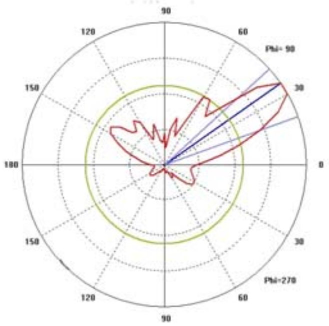


(c) Type III

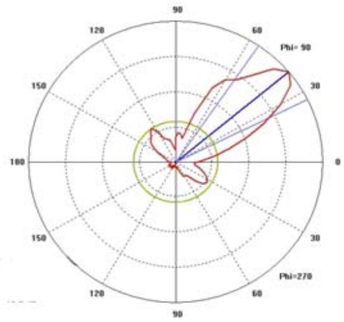
Fig. 9. Simulated return loss of types I-III LWA.



(a) Type I



(b) Type II



(c) Type III

Fig. 10. Radiation patterns of electric field (H plane) of types I-III, LWA at 9.5 GHz.

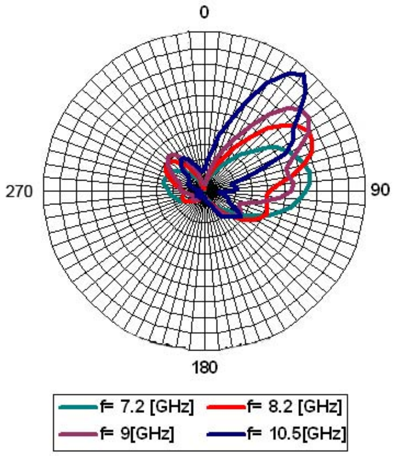


Fig. 11. Simulated radiation patterns of E field of LWA type III for different frequencies.

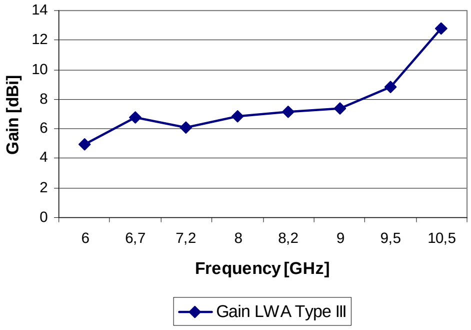


Fig. 12. The gain versus frequency of the LWA type III.

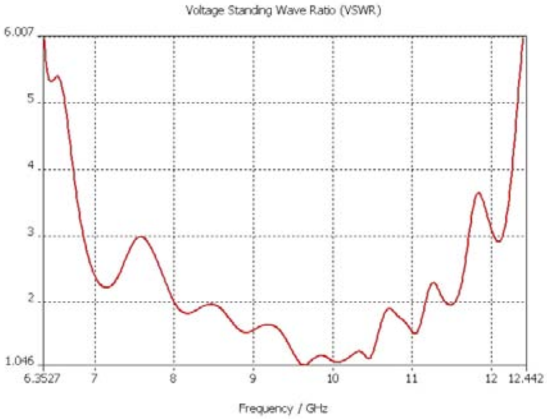


Fig. 13. Simulated radiation patterns of E field of LWA type III for different frequency.

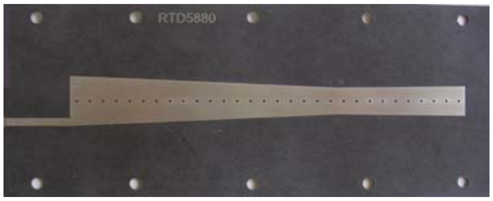


Fig. 14. A prototype of tapered LWA with holes made in the center line of the antenna.

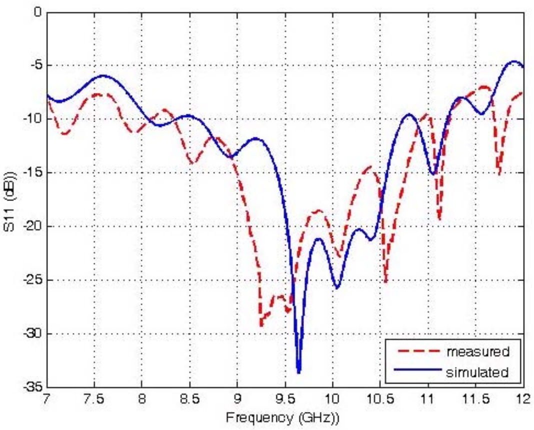


Fig. 15. Experimental and simulated return loss of LWA type III.

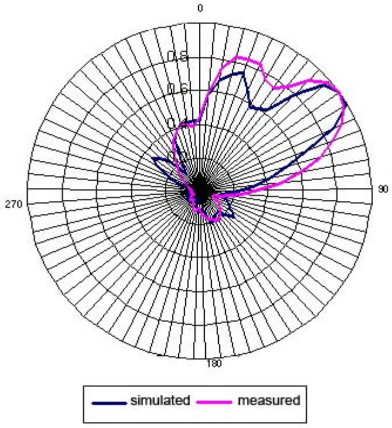


Fig. 16. Measured and simulated radiation patterns of E field of LWA type III (at 8 GHz on the right).

IV. CONCLUSIONS

A novel technique which provides broadband tapered microstrip leaky-wave antennas with high added value has been introduced in this study, from 8 to 11 GHz. The propagation constant evaluated with FDTD code was used to design the layout, with the same contour obtained from the interpolation of the cutoff frequency points, for different widths and lengths of each microstrip section, and with a physical grounding structure along the length of the antenna.

The experimental and simulation results shown the good performance of a curve tapered microstrip leaky wave antenna, with reference to conventional uniform microstrip LWAs (wider band and higher gain), and indicate that this structure is attractive for the design of high performance microstrip leaky-wave antennas for microwave and millimeter wave applications.

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