Beam Shaping Considerations in a Symmetric Leaky Wave Antenna for Broadside Radiation

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1. Introduction

Techniques to control the antenna aperture distribution to shape the far-field beam are very well known, and have found applications in traveling wave antennas [1] and conventional (beam scanning) leaky wave antennas (LWAs) [2, 3]. However, such techniques do not appear to have been applied to the symmetric (center-fed) LWAs for broadside radiation. In this paper, we first review the suitability of classical tapered distributions to the symmetric LWA. Secondly, the possibility of attaining partial aperture control using reflective terminations is introduced. And finally, measured results from a microstrip based LWA are presented and discussed.

2. Tapered Distribution in Symmetric Broadside LWA

Classical tapered line source distributions such as $\cos^2$ and Taylor n-bar [4] assume a constant phase across the aperture. This assumption is compatible with conventional LWAs, as long as the phase constant β is designed to be constant throughout the aperture [2, 3]. The presence of β simply scans the main beam per $\sin\theta=\beta/k_o$. In contrast, for the center fed LWA, the phase is distributed symmetrically as $-\beta|x|$, where x is the array axis and x=0 is the feed point [4]. The only way to maintain compatibility with the constant phase assumption, then, is to maintain $\beta=0$ across the aperture, which is not normally attainable in realistic LWA designs [4, 5]. In fact, it has been pointed out that one maximum beam at broadside exists in a symmetric LWA for small, but non zero, values of β [4, 5]. Therefore, if one uses a classical line source distribution in the symmetric LWA for broadside radiation, some amount of phase error is inevitable. Furthermore, since β is a strong function of frequency, the phase error also varies with frequency. A resonant series-fed linear array [7] may, in theory, minimize this phase error, however, such an array is extremely narrow band and it cannot be described as a traveling wave antenna or as a LWA.

It can be shown that the approximate design equation for the attenuation constant, $\alpha(x)$, required to achieve the desired amplitude distribution $|A(x)|$ [1, 2] is:

$$2\alpha(x) = \frac{|A(x)|^2}{\dfrac{P(0)}{P(0)-P(L/2)}\displaystyle\int_0^{L/2}|A(x')|^2\,dx' - \int_0^{x}|A(x')|^2\,dx'} \tag{1}$$

where L is the LWA length. Eq. (1) was derived assuming that the ratio of the power loss due to radiation per unit length to the power guided in the line $P_r(x)/P(x)=2\alpha(x)$. Such an assumption is valid when the line is low loss, i.e., $\beta>>\alpha$ [6]. However, in the symmetric LWA for broadside radiation, β is comparable to α, such that the validity of Eq. (1) and the assumption of a priori separability between $\alpha(x)$ and $|A(x)|$ are questionable.

The foregoing discussion implies that systematic design of tapered distribution for the symmetric broadside LWA appears far less promising compared to its beam scanning counterpart, at least when considering the classical approach. Consequently, a simpler alternative to the tapered distribution may be desirable.

3. Reflective Terminations in Symmetric Broadside LWA

In the conventional LWA, reflective terminations are normally not considered since the reflected wave creates a parasitic beam in the direction $-\theta_m$, where θ_m is the peak beam direction. However, in the symmetric broadside LWA, the two beams at $\pm\theta_m$ combine into one beam at broadside [4, 5] such that reflective terminations can be considered. Assuming that L is sufficiently long such that the reflected wave reaching x=0 is negligible, and that A(x) is proportional to the equivalent voltage on the transmission line (TL) equivalent circuit, we have:

$$\begin{aligned} V_{ap}(x) &= e^{-jk_{LW}(x-L/2)} + \Gamma_L\, e^{+jk_{LW}(x-L/2)}, 0 \le x \le L/2 \\ &= e^{+jk_{LW}(x+L/2)} + \Gamma_L\, e^{-jk_{LW}(x+L/2)}, -L/2 \le x \le 0 \end{aligned} \tag{2}$$

where the leaky wavenumber $k_{LW}=\beta - j\alpha$ and Γ_L is the voltage reflection coefficient. Note that partial aperture control may be attained by manipulating the reflected wave. The advantage of this method is its simplicity and predictability due to the constant k_{LW} across the aperture. However, the degree of control afforded is limited and this technique appears to be incompatible with double stub microstrip realizations such as depicted in [7].

The aperture distributions and the corresponding radiation patterns that are attained with Γ_L=-1, 0, 1 are shown in Fig. 1 for k_{LW}/k_o =0.03 – j0.03 and P(L/2)/P(0)=0.1 and L=12 λ_o. Note that for Γ_L=-1, the $|V_{ap}|$ is nearly triangular which explains the low sidelobe level (SLL), where in the Γ_L=1 case, $|V_{ap}|$ tends toward a constant distribution which explains the narrower beamwidth and higher SLL.

In Fig. 2, the $\alpha(x)/k_o$ obtained from Eq. (1) and the radiation patterns are shown for the Γ_L=-1 case (with k_{LW}/k_o=0.03 – j0.03), $\cos^2$ (with k_{LW}/k_o=0.044 – j $\alpha_1(x)/k_o$), and Taylor n-bar=4 for 35 dB SLL (k_{LW}/k_o=0.055 – j $\alpha_2(x)/k_o$), where $\alpha_1(x)/k_o$ and $\alpha_2(x)/k_o$ correspond to the normalized attenuation constant distributions for the $\cos^2$ and Taylor patterns, respectively, for P(L/2)/P(0)=0.1 after the phase errors are included. To ensure that the Taylor and the $\cos^2$ cases are at or above cutoffs, the indicated β/k_o values (0.044, 0.055) are chosen to be fixed at the maximum values of $\alpha_1(x)/k_o$ and $\alpha_2(x)/k_o$ for the corresponding distributions (Fig. 2a). Note that with the phase errors, the theoretical 35 dB SLL Taylor pattern degrades to 26.5 dB SLL which is comparable to 25.8 dB SLL exhibited by the Γ_L=-1 pattern. Furthermore, notice that all the peaks of the Γ_L=-1 pattern (including SLL) are below that of the $\cos^2$ distribution. Also, note that the beamwidth of the Γ_L=-1 pattern is very similar to that of the Taylor pattern (Fig. 2b). These observations suggest that the simpler Γ_L=-1 case performs comparably to the more elaborate distributions once the phase errors are included, at least for the nominal k_{LW}/k_o values.

4. Measured Results

The symmetric LWA structure based on the cell shown in Fig. 3a [8] was manufactured using a standard etching process. The LWA consists of 2x11 cells and it is center fed using an F-SMA connector. The measured k_{LW}/k_o value is shown in Fig. 3b. Three of such LWAs were built for each termination case: 50Ω, short, open.

The measured patterns at 3.4 m ($0.9L^2/\lambda_o$ at 7.8 GHz) at 7.75 GHz where k_{LW}/k_o=-0.045 – j0.034, are shown in Fig. 4a. Note that while the main beamwidth behaviors are obvious, with the Γ_L=1 case being the narrowest and Γ_L=-1 being the widest, and that SLL of Γ_L=1 being the highest, the SLL comparison between the Γ_L=0 and -1 is not straightforward due to the finite measurement distance and the probable random errors due to manufacturing tolerances. It can be observed that at 3.4 m, the highest SLL of the Γ_L=-1 (24.5 dB) is only marginally better than the Γ_L=0 case (23.3dB). These results seem consistent with the findings in [7] which states that achieving SLL better than 25-30 dB are doubtful when employing series-fed arrays.

Notice also that while the theory predicts that the far off broadside SLL of the Γ_L=-1 falls off quickly as expected from a triangular distribution (Fig. 1), this is not seen in the measurement. This appears to be caused by the manufacturing tolerances which introduce random amplitude and phase errors. From a simple ideal TL model of the LWA cell, the maximum amplitude and phase errors were estimated to be 10% and 3^{o}, respectively when assuming that the tolerance on each L_1 and L_2 (Fig. 3a) of ±1 mil (25.4 μm). The computed theoretical patterns at 3.4 m with no error and maximum errors after 100 random tests are compared with the measured data and shown in Fig. 4b. As a result of the random errors, the far out SLL falls off less quickly. Note that the measured far off broadside SLL generally appear between the no error and maximum error plots. This indicates that the measured SLL is consistent with the assumed level of errors.

5. Conclusions

The feasibility of beam shaping broadside symmetric LWA using classical tapered distributions was reviewed. It was found that such a design strategy of the broadside symmetric LWA is more error laden than the conventional LWA. A simpler method using reflective terminations was introduced and was found, in theory, to perform comparably to a couple of tapered distributions. Measurement results from a microstrip based broadside LWA with reflective terminations was presented. It was deduced that the manufacturing tolerances limit the achievable improvement in SLL in reality.

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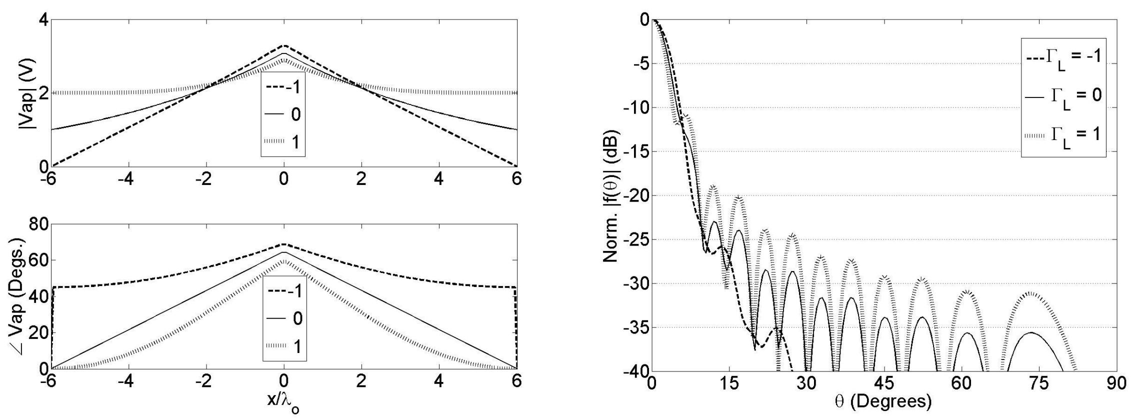
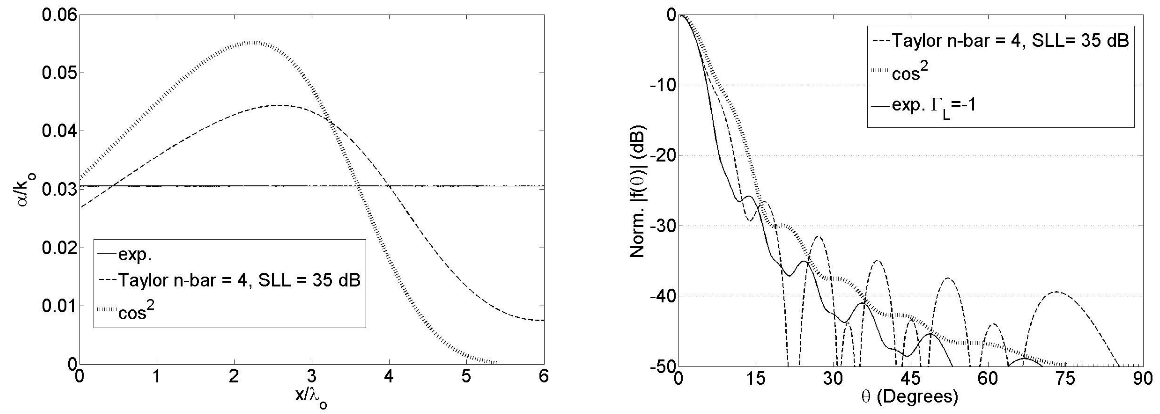


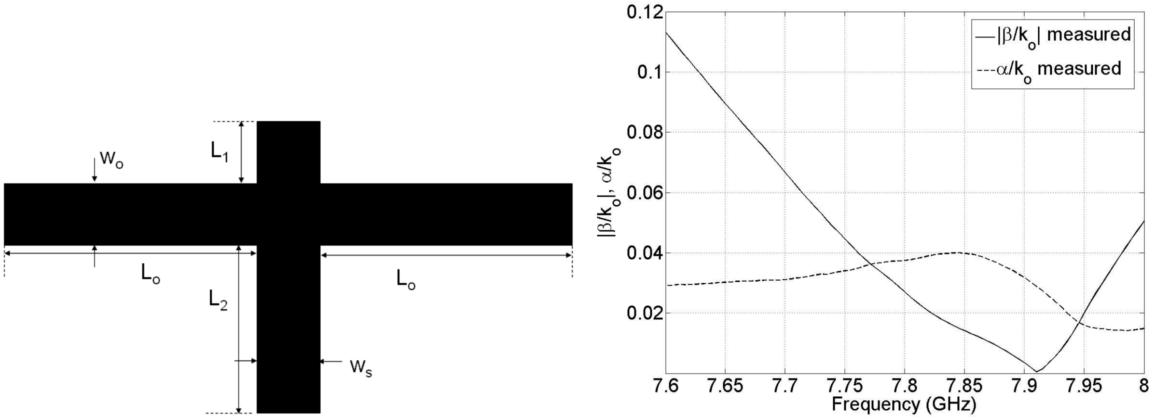
(a) (b)

Figure 1: (a) Aperture distributions and (b) normalized radiation patterns for various Γ_L



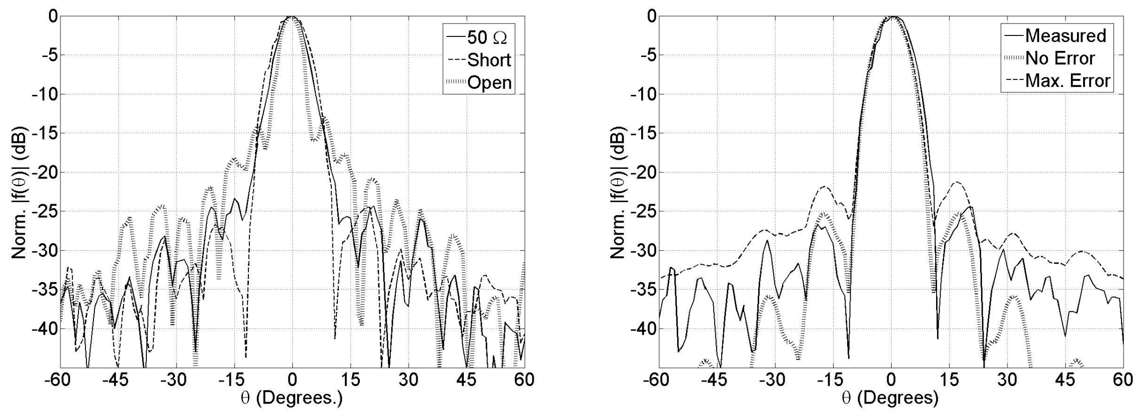
(a) (b)

Figure 2: Comparing Γ_L=-1 case with classical tapered distributions: (a) $\alpha(x)/k_o$, (b) normalized radiation patterns



(a) (b)

Figure 3: Microstrip based LWA: (a) cell dims. (mm) : W_o=W_s=1.9, $2L_o$+W_s=d=17.2 , L_1=1.8711, L_2=5.0589 on RT/Duroid 6006 with 1.27 mm thickness, (b) k_{LW}/k_o



(a) (b)

Figure 4: Radiation patterns at 3.4 m at 7.75 GHz: (a) measured, (b) short (Γ_L=-1) case measured vs. theory with random error