Designing a Linear Microstrip Array for Broadside Radiation Using the Leaky Wave Approach

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1. Introduction

The topic of designing a traveling wave linear microstrip array (TLMA) is a classical one and has been discussed in detail [1]. However, the conventional design technique treats each radiating element individually, and subsequently accounts for the mutual coupling effects as the array is designed. The possibility of designing a TLMA using the leaky wave (LW) approach was suggested in [2], though an example was not given. Using the LW approach, the mutual couplings are inherently accounted for and the radiation behaviors can be concisely described using the leaky wavenumber $k_{LW} = \beta - j\alpha$ [2].

Broadside radiation can be achieved using a symmetric (center-fed) TLMA [1] and also a symmetric leaky wave antenna (LWA) [3, 4]. In this paper, we apply some of the LW theoretical analyses presented in [3, 4] to the design of a 1-D TLMA for broadside radiation. Note that in the LW approach, the influence of the truncation effects is usually neglected since the antenna is assumed to be infinitely long [3, 4]. In contrast, the influence of the finite antenna length and the associated end terminations are considered here.

2. Design Method

From the LW perspective, the TLMA is considered to be a periodic LWA. The fundamental property of the broadside radiation from such a LWA has been described in [3] for an infinite structure. In this section, we take the approach of modeling the 1-D TLMA as a continuous TL of finite length. This is an approximate approach which is valid as long as there is only one fast spatial harmonic (β_{-1}) and that the periodic spacing is small compared to λ_o [2]. In the case of the TLMA for broadside radiation, such an approach is accurate in describing the main beam and the close in sidelobes as long as grating lobes are avoided (periodic distance $d < \lambda_o/2$).

Assuming that the radiation is proportional to the voltage on the TL and that there is one radiating aperture per period of the TLMA, the normalized aperture distribution for matched terminations is described by:

$$V_{ap}(x) = e^{-jk_{LW}|x|}, \; -L/2 \le x \le L/2 \tag{1}$$

where L is the total length of the LWA. Assuming isotropic radiating elements, the radiation pattern is:

$$f(\theta) = \int_{-L/2}^{L/2} V_{ap}(x)\, e^{jk_o x \sin\theta} dx \tag{2}$$

Strictly speaking, for a periodic LWA, x is sampled to coincide with the positions of the radiating elements and the integral sign in Eq. (2) is replaced with a summation [3]. However, for design purposes Eq. (1) and (2) may be used within the specified limitations described in the first paragraph.

The first step of the design, then, is to use Eq. (2) to determine the k_{LW} needed for the broadside radiation and the desired antenna directivity. As a starting point, one may use the beam splitting condition as derived for the infinite symmetric LWA [3], [4]. This condition states that one main beam at broadside exists for $\alpha \geq |\beta|$, with $\alpha=|\beta|$ being the point at which the beam is on the verge of splitting. Thus, the intersection point of $\alpha=|\beta|$ may then be used as the intended operating point (α_{int}) such that L can be determined and the desired pattern approximated using Eq. (1) and (2). It is a common design practice to set $L/2=0.18\ \lambda_o/\alpha_{int}$ such that ≈ 90% of the power has been radiated before reaching the matched terminations for the α_{int} value [2]. For this design we have chosen $\alpha_{int}=0.035$ and $L/2=5.14\lambda_o$. Note that Eq. (2) predicts a beam splitting condition in the $|\beta|>\alpha$ range, for practical values of L. Therefore, the $\alpha=|\beta|$ point is only a convenient point to aim for in the design.

Fig. 1 shows the isotropic directivity at $k_{LW} = -0.035 - j0.035$ with D(0)=12.3 dBi for the chosen L/2 value. Note that the LWA gain, at the end, is modified by the gain of the radiating elements as understood from the principle of pattern multiplication. However, the behavior of the main beam and the close-in sidelobes will be similar to that predicted by Eq. (1) and (2) since the radiating elements are typically chosen to have low directivity and minimal variation near broadside.

3. Design of the TLMA cell

Note that the k_{LW} is a strong function of frequency and the particulars of the LWA structure. Therefore, the next design step is to realize the desired k_{LW} with a physical structure. For the TLMA, we have chosen a series fed microstrip open stub (similar to a comb array [1]) as shown in Fig. 2 for a single cell. Standard design equations involving microstrip open stub and TL equations [1] may be used in the initial design of a single cell. Achieving small $|\beta_{-1}|$ values for the TLMA requires $d \approx \lambda_m$, where λ_m is the guided wavelength in the microstrip. The α values are influenced by the width of the stubs and the intersection point between the microstrip TL and the stub.

More accurate computation of k_{LW}, which includes the mutual coupling effects, requires a full-wave simulation such as the periodic Green's function method [3] or the method of convergence of k_{LW} with an increasing number of cells (N) [5]. The latter method is compatible with most commercial full-wave simulation package such as ADS Momentum and has been chosen for this design. It was observed that, in this case, the k_{LW} convergence was quickly achieved for N values between 8 to 11.

The simulated and measured values extracted from N=11 of the k_{LW}/k_o are plotted in Fig. 3. Note that the $\alpha=|\beta|$ points occur at roughly the same value of 0.036, but are offset in frequency at approximately 7.77 and 8.05 GHz (Δf = 3.5 %) for the measured and simulated, respectively. Therefore, we expect maximum broadside beam in the vicinity of 7.77 GHz.

4. Measured Results

The symmetric TLMA structure was manufactured using a standard etching process and then measured. The TLMA consists of 2 x 11 cells and it is center fed using an F-SMA connector with the center conductor penetrating the dielectric. The TL sections adjacent to feed point were tapered for matching to 50Ω. The two TLMA ends were connected to 50 Ω, short, and open terminations. The reflective terminations were considered since good 50 Ω loads may be expensive in some applications. To account for the reflective terminations, assuming that L is sufficiently long such that the reflected wave reaching x = 0 is negligible, Eq. (1) may be modified:

$$\begin{aligned} V_{ap}(x) &= e^{-jk_{LW}(x-L/2)} + \Gamma_L\, e^{+jk_{LW}(x-L/2)}, 0 \le x \le L/2 \\ &= e^{+jk_{LW}(x+L/2)} + \Gamma_L\, e^{-jk_{LW}(x+L/2)}, -L/2 \le x \le 0 \end{aligned} \quad (3)$$

The measured S_{11} are shown in Fig. 4. The effective broadside gain and radiation pattern were measured at 3.4 m ($0.9L^2/\lambda_o$ at 7.8 GHz) distance and are plotted in Fig 5. Note that one broadside beam exists at 7.7 GHz which is in the $|\beta|\geq\alpha$ range per Fig. 2. At 7.7 GHz, the open case exhibits a slightly narrower beamwidth but higher sidelobe levels (SLL). The short and 50 Ω cases show comparable highest SLLs and beamwidths (Fig. 2a). The short and open cases exhibit higher effective gain than the 50 Ω case for some parts of the frequency band: 7.7 - 8GHz (open) and 7.5 - 7.7 GHz (short). The steep rolloffs below ≈ 7.55 GHz are due beam splitting in the broadside beam.

5. Conclusions

The design of a TLMA using the LW approach has been presented. The frequency where the maximum beam at broadside exists, is well predicted by the measured k_{LW} values. The possibility of using reflective terminations was considered and measured results show that they can offer some advantages.

References

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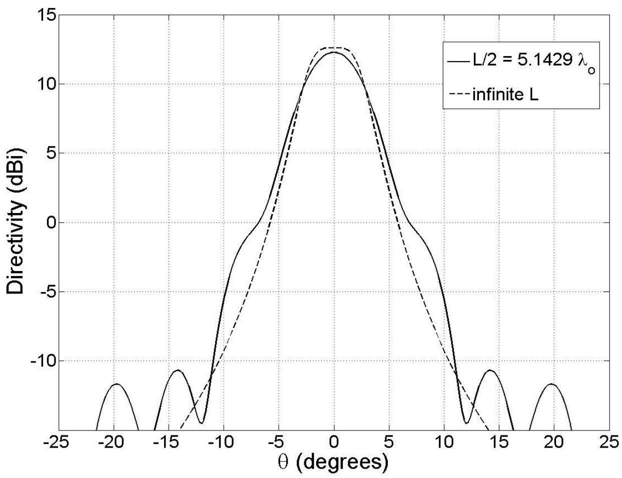


Figure 1: Directivity, D (θ) for k_{LW} = -0.035 – j0.035

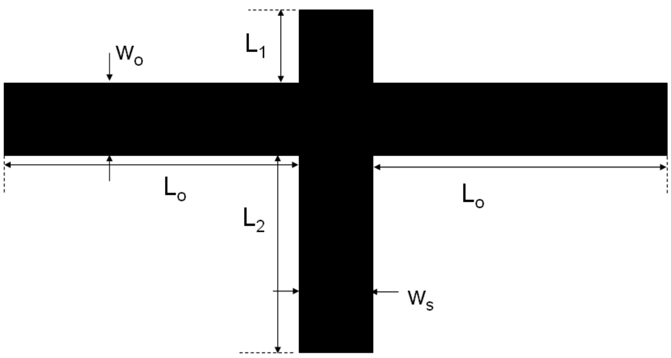


Figure 2: A single cell of the TLMA. Dims. (mm) : W_o=W_s=1.9, $2L_o$+W_s=d=17.2 , L_1=1.8711, L_2=5.0589 on RT/Duroid 6006 with 1.27 mm thickness

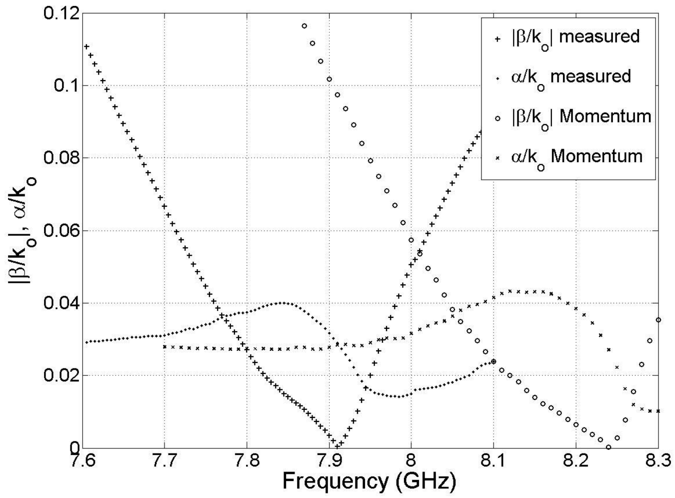


Figure 3: Normalized k_{LW} measured and simulated from 11 TLMA cells

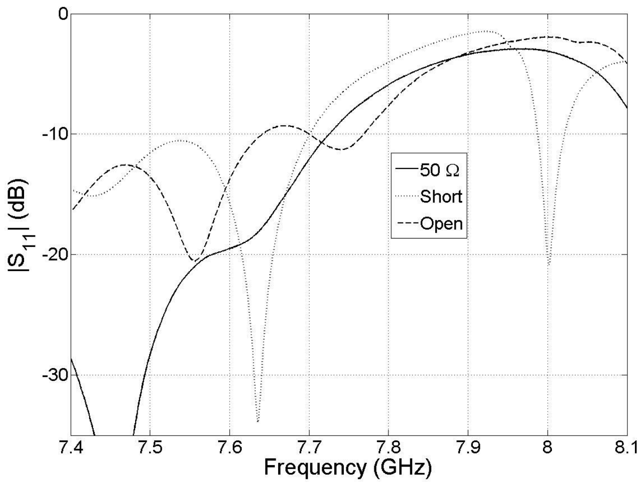
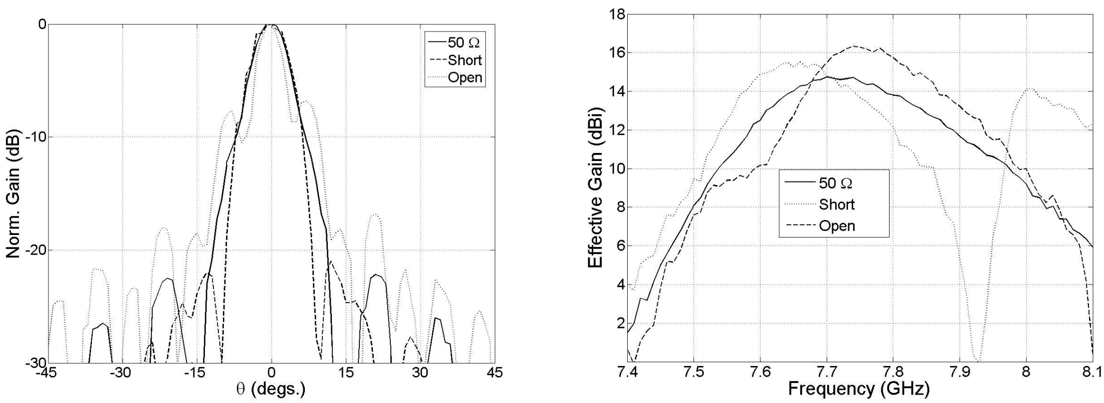


Figure 4: Measured TLMA $|S_{11}|$ with 50 Ω, short, and open terminations



(a) (b)

Figure 5: Measured antenna gains at 3.4 m: (a) Radiation pattern at 7.7 GHz
(b) Broadside effective gain