# Gain and Efficiency of Linear Slot Arrays on Thick Substrates for Millimeter-Wave Wireless Applications

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## I. Introduction

Millimeter-wave (mm-wave) systems are gradually becoming more and more attractive for wireless applications. Indeed, they become particularly appealing for wireless communications due to the wide bandwidth that they offer. At these frequencies, the physical size of antennas becomes small opening up the possibility of integrating entire printed arrays with associated T/R electronics on the same substrate for implementing advanced mm-wave front-end systems. In this framework, array techniques become very desirable for increasing the directivity of low cost printed antennas for fixed point-to-point or point-to-multipoint links [1]. This is essential for ensuring proper link margins and for mitigating multipath propagation effects. In addition, scan capabilities or/and adaptive processing array techniques can play an important role toward the realization of practical broadband mobile wireless communication systems [2].

Unfortunately, the realization of highly efficient and low-cost printed mm-wave antenna arrays still remains a challenging task. This is mainly due to the increased losses and in particular conductor and surface-wave ones. One way to reduce surface-wave losses is through the proper spacing of the antenna elements for achieving phase cancellation of the radiated surface-wave power in the substrate. This was demonstrated for a pair of printed slot antennas separated by a half guide-wavelength $\lambda_g/2$ in [3]. Recently, this concept has been extended to slot antenna arrays with elements also separated by $\lambda_g/2$ [4].

This work concerns the performance of uniform broadside linear slot arrays on thick substrates and has a twofold purpose. The first goal is to systematically examine the surface-wave efficiency with the number of slots and their inter-element spacing. The second goal concerns the optimization of the inter-element spacing for maximizing the overall *gain* for a given number of antenna elements.

## II. Theory

A general diagram for a linear printed array of N slots is shown in Fig. 1. The critical figure of merit for this work is the antenna efficiency which is defined by

$$\eta_e = \frac{P_{rad}}{P_{rad} + P_{sw} + P_{back}} \tag{1}$$

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where $P_{rad}$ is the useful radiated power, $P_{back}$ is the power that leaks at the back of the array and $P_{sw}$ denotes the surface-wave power trapped in the substrate (see Fig. 1). The calculation of the trapped surface-wave power is based upon the application of the reciprocity theorem which for a single slot is outlined in [5]. The extension to an array of slots is straightforward. In this work, only the dominant surface-wave mode TMo is accounted for and the corresponding trapped power is given by

$$P_{TM_o} = \frac{\omega\varepsilon_o\varepsilon_r}{8\pi h_{eff}}\int_0^{2\pi}(\cos\phi)^2|AF_s(\phi)|^2 d\phi \text{ where } AF_s(\phi) = \sum_{n=1}^{N} M_n e^{j(n-1)k_g d\cos\phi} . \qquad (2)$$

In equation (2), $h_{eff}$ is the effective height of the substrate for the TMo mode and $AF_s$ is the pertinent array factor. Also, $k_g = 2\pi/\lambda_g$ is the guide wavenumber for the TMo mode and $M_n$ are the excitation magnetic currents at the input terminals of each slot.

### III. Numerical Results

First shown in Fig. 2 are the efficiencies $\eta_e$ for 1,2,4,8 and 16 slots spaced by half a TMo guide wavelength (i.e. $d = 0.5\lambda_g$) apart on a substrate with $\varepsilon_r = 4.0$ and thickness equal to a quarter dielectric wavelength (i.e. $h = 0.25\lambda_d$) at the design frequency $f_o$ (see Fig. 1). The computed efficiencies account only for the dominant TMo surface-wave mode and they are plotted against the normalized frequency $fN = f/f_o$. This is a reasonable approximation given that around the design frequency, the first TE mode is only just triggered. The chosen substrate thickness leads to maximum efficiency and optimum front-to-back power density ratio at broadside (equal to $\varepsilon_r$) [3]. It is interesting to point out that the most significant improvement in efficiency takes place when going from a single slot to a pair of slots. Additional slot elements continue to increase the efficiency but at a much slower rate.

It can be noted that for a uniform linear array with N-elements (N=even), an inter-element distance of $d_n = \lambda_g n/N$, (n=1,2..,N-1) also leads to destructive interference along the array axis for the TMo parasitic mode. Therefore, it is tempting to examine what happens to the efficiency for these other inter-element spacings $d_n$. Figure 3. shows the efficiency for an 8-element linear slot array with normalized inter-element spacings $dN = d_n/\lambda_g = n/N$ (n=2,4,5,6,7), again on a substrate of dielectric constant $\varepsilon_r = 4.0$ and thickness $h = 0.25\lambda_d$ at the design frequency. As shown in Fig. 3, an overall maximum efficiency over the considered bandwidth 0.7<fN<1.4 is achieved when the inter-element spacing is $\lambda_g/2$ at the design frequency. Shorter spacings lead to somewhat reduced efficiencies but with a flatter frequency response. In this case, the reduced efficiency can be attributed to the corresponding less sharp TMo patterns. On the other hand, longer than $\lambda_g/2$ spacings again lead to a reduced efficiency which can be attributed to the manifestation of higher TMo pattern sidelobes. In addition, the frequency response of the efficiency deteriorates, especially with distances that are close to an entire guide wavelength $\lambda_g$ (i.e. dN=7/8) which signifies the onset for constructive interference for the TMo mode along the array axis. Nevertheless, the case for which the inter-element distance is larger than $\lambda_g/2$ is interesting because it corresponds to a *higher directivity and gain* for a given number of slot elements around the design frequency. This is further examined in the next paragraph.

In Figure 4, the gain of the array defined by $G = \eta_e D$ where $D$ is the array directivity is examined. As shown, for a given number of elements (N=8 here) some bandwidth can be traded for an increase of the overall gain $G$. In the case of Fig. 4, an optimum inter-element spacing seems to be dN=6/8. This leads to a gain of 13.2 dB for the 8-element array which is about 1.5dB higher than the corresponding gain with dN=0.5 at the design frequency. The corresponding improvement in directivity is even more significant: Indeed at the design frequency and with dN=6/8 the directivity is D=14.3dB which is 1.7dB higher compared to that for the standard spacing of dN=0.5. As can be inferred from Fig. 3, the corresponding efficiency remains between 71%-75% within a ±10% bandwidth about the design frequency. This still represents a hefty absolute bandwidth when operating at millimeter-wave frequencies. It should be noted that for this particular case, a spacing of dN=6/8 at fN does not lead to a grating lobe within the entire considered bandwidth of 0.7<fN<1.4. Furthermore for a series feed arrangement [4], a longer spacing alleviates the need of inserting excessive sections of a meander line between elements in order to excite them in phase.

## IV. Conclusion

A systematic study of the efficiency of uniform linear slot arrays on thick substrates has been undertaken. It was found that the efficiency can be improved drastically with an increased number of slot elements. The most significant improvement in efficiency takes place when going from one to two elements. Subsequent slots continue to increase the efficiency but at a slower rate. On a $h = 0.25\lambda_d$ thick substrate, an overall optimum efficiency is achieved when the elements are spaced half a TMo guide-wavelength apart, i.e. $d = \lambda_g/2$. However this is no longer true for the practical case in which the gain of the array is to be maximized for a given number of slot elements. In this case a judiciously selected longer distance $d > \lambda_g/2$ can lead to an improvement of the array gain and offers the potential for a simplified series feed network.

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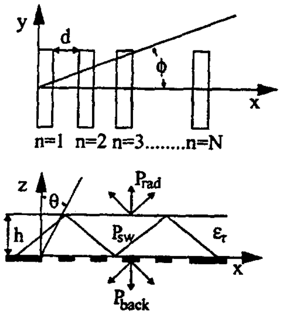

Figure 1

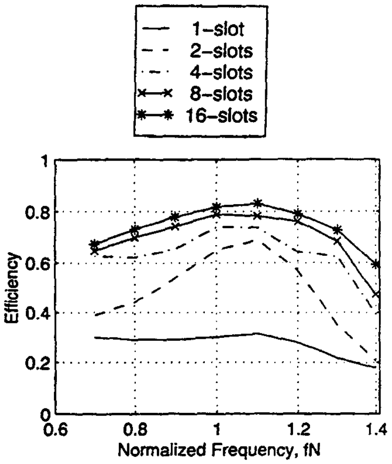

Figure 2

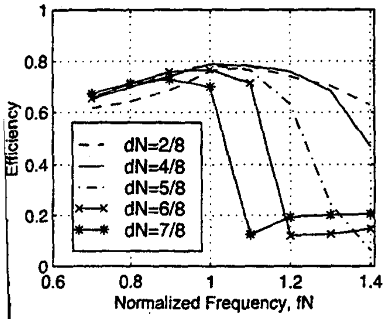

Figure 3

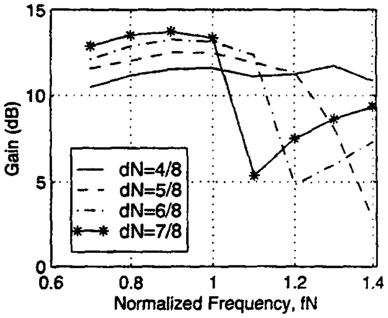

Figure 4