A Taper Optimization for Pattern Synthesis of Microstrip Series-Fed Patch Array Antennas

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Abstract—An EM based straight forward design and pattern synthesis technique for series fed microstrip patch array antennas is proposed. An optimization of each antenna element (λ/4-transmission line, λ/2-patch, λ/4-transmission line) of the array is performed separately. By introducing an equivalent circuit along with an EM parameter extraction method, each antenna element can be optimized for its resonance frequency and taper amplitude, so to shape the aperture distribution for the cascaded elements. It will be shown that the array design based on the multiplication of element factor and array factor fails in case of patch width tapering, due to the inconsistency of the element patterns. To overcome this problem a line width tapering is suggested which keeps the element patterns nearly constant while still providing a broad amplitude taper range. A symmetric 10 element antenna array with a Chebyshev tapering (-20dB side lobe level) operating at 5.8 GHz has been designed, compared for the two tapering methods and validated with measurement.

I. INTRODUCTION

Series fed microstrip array antennas are widely used in the field of communication and microwave sensors. Their advantages, as they are light weight, low profile and a compact and minimum line length feed network are appreciated for many years in various applications. Almost three decades ago pattern synthesis for series feed antennas was presented in [1] for traveling wave microstrip arrays. A more recent study is presented in [2] for non-uniformly spaced patches in a traveling wave configuration. Recent series fed array resonator antenna designs are found in [3] and [4] with a strong focus on the impedance bandwidth. In [3] the tapering was achieved with a constant patch width, by using a combination of recessed (inset) microstrip line feed technology and variation of width of the feeding line. All three tapering methods, patch width, recessed feeding and line width variation have been used in [4] for a design to improve the VSWR. New designs for low side lobes have been presented in [5], where the dispersion characteristic of a unit cell antenna element is exploited to achieve a cosine aperture distribution. In the same context a dual-frequency series fed patch array has been presented in [6].

This paper presents a systematic and straight forward design procedure to synthesize radiation patterns of series fed microstrip resonator array antennas according to given amplitude distribution. By using the concept of element factor and array factor it is assumed that the element factor is constant while the array factor is defined by the spatial distribution and the excitation of the elements. For the patch width tapering this concept cannot be used, since the patches change their radiation characteristic when having different width. In order to design an antenna based on the amplitude distribution we therefore need patch elements which can be tapered without affecting their radiation characteristics. With such elements, the multiplication with the array factor can be done to obtain the over all radiation behavior.

The paper is structured in the following manner. First, in II the antenna element with its corresponding equivalent circuit and the EM extraction is explained. In III we use the method described in prior paragraph to optimize five antenna elements by tapering the patch width and then tuning the line width to obtain the prescribed amplitude distribution. Based on these two approaches two symmetric ten-cell antennas are simulated and their radiation patterns are compared. Finally, in IV a prototype of the line width tapered antenna has been fabricated and the measurement results are compared with the EM simulation results.

II. ANTENNA ELEMENT:

EQUIVALENT CIRCUIT MODEL AND OPTIMIZATION

Fig. 1. Symmetric patch cell model in Empire XCcel with its amplitude setting to $a_1 = 1$ by definition. Simulation parameters are: $h_{high} = 1.7$ cm, $h_{low} = 1.67$ cm, $w_{patch} = 2$ cm, $w_{line} = 0.2$ cm on Rogers 5880 with $\varepsilon_r = 2.3$ and height $h = 1.5$ mm for a resonant frequency $f_s = 5.8$ GHz.

In Fig. 1 the antenna element is depicted with one patch and
two connection lines on either side. The distinct advantage of modeling the patch in this configuration is that the port placement is in the center of the connection line. Here, we have TEM conditions, so that the patch including the attached transmission lines can be accurately characterized for the cascading, taking into account the discontinuity and all radiation effects. In an array setup the last patch element has to be terminated with a short which transforms to an open at the patch edge. This open is not fully equivalent to an open patch edge, due to the attached line and its effect on the radiation slot. For the consistency of the elements pattern we therefore prefer to terminate this last antenna element with a via short at the end of the quarter wavelength transmission line. An equivalent T-circuit has been chosen to model the antenna element, as shown in Fig. 2. $Z_{\text{ser}}$ shows a series resonator behavior with the resonance frequency $f_{\text{ser}}$, while $Z_{12}$ show a parallel resonance behavior with the resonance frequency $f_{\text{par}}$. If both resonances are adjusted to the operating frequency, the antenna element is properly tuned which corresponds to the length of $\lambda/4$ - $\lambda/2$ - $\lambda/4$ in an ideal transmission line model. If we now cascade the antenna elements and introduce a short at the very last element we will have a constant current flowing through all the antenna elements. At resonance we simply have a series connection of all patch elements, representing an antenna amplitude distribution which goes along with $\sqrt{R}$, Fig. 3.

Fig. 2. An equivalent T-circuit to model the antenna element (including the $\lambda/4$ feed lines), shows a series and a parallel resonance behavior. In this model the series resonator represents our radiation mode. With the parallel resonator properly tuned the model can be simplified.

Fig. 3. Circuit representation for $n$-cascaded antenna elements at their resonance frequency. By varying $R_l$ an amplitude tapering is achieved.

By using the gradient optimization in Empire XCcel, $l_{\text{line}}$ and $l_{\text{patch}}$ have been adjusted for $3\{Z_{\text{ser}}\} = 0$ and $3\{1/Z_{12}\} = 0$ at the operating frequency $f = 5.8$ GHz. With a patch width of $w_{\text{patch}} = 2$ cm and a line width of $w_{\text{line}} = 0.2$ cm, we define the normalized amplitude $a_1 = 1$ for this antenna element. The optimized line length are: $l_{\text{line}} = 1.7$ cm, $l_{\text{patch}} = 1.67$ cm. To optimize an antenna element for a given amplitude value a normalization is done with $\sqrt{R_{\text{norm}}/R_l} = a_i$. For amplitude optimization (patch or line tapering) of the antenna element, we extract $R_l$ at resonances, normalize this value to obtain $a_i$. The optimization goal is then formed by the two resonance frequencies $f_{\text{ser}}$, $f_{\text{par}}$ and the amplitude $a_i$.

III. AMPLITUDE TAPERING:

PATCH WIDTH / CONNECTION LINE WIDTH

In this section the circuit based parameter extraction of $a_i$ is compared with normalized $E$-field patterns to support the proportionality: $\sqrt{|R|} \propto |E|$. For the farfield evaluation of a single antenna element a simultaneous current excitation with a $180^\circ$ phase difference at the two ports of the antenna element is needed. In simulation, we can simply force the current distribution which would establish in the array configuration. There are two different ways to modify the resistance $R$: varying the patch width or the transmission line width. As the standard approach, patch widths modification is examined first.

A. Tapering the patch width:

In Fig. 4 the normalized farfield in broadside direction is compared with the normalized resistance $\sqrt{R_{\text{norm}}}$ for three different patch width $w_{\text{patch}} = \{2, 1.6, 1.2\}$ cm. Due to the normalization at broadside, only $\Theta = 0$ can be compared and evaluated. Furthermore, $R$ is constant and the angle dependency is just for visualization convenience. The values for the normalized amplitude of $a_1 = 1$ match by definition. A deviation can be observed when the patch width becomes smaller. It can be seen that the amplitudes do not match perfectly with the resistance, in other words, the directivity changes with varied patch widths. This indicates the patch width tapering also affects the element pattern and it is not suitable to design an array antenna with a well defined pattern by using our extraction method.

B. Tapering the line width:

As a new approach, TL widths modification is examined. With the same strategy as in the previous subsection the line width modification has been examined. The normalized quantities are plotted for the three different line width $w_{\text{line}} =$
[2, 2.5, 3.5] mm. From Fig. 5, it can be seen that the amplitudes match perfectly with the resistances, in other words, the directivity does not change with varied line widths. The advantage of this approach is that the patch geometry does not change a lot, so the element factor can be assumed to be constant.

\[ a_i : 0.7, 0.55, 0.8, 0.92, 1, 1, 0.92, 0.8, 0.55, 0.7 \]

![Fig. 5. Line width tapering: Normalized E-field co-polarization patterns vs. circuit based extracted amplitudes and showing a constant element factor and supporting our parameter extraction method.](image)

C. Comparison of a 10 Element Array Antenna:

We have chosen a Chebyshev characteristic with a constant side lobe level (SLL) of -20dB to compare the two tapering methods and to demonstrate the circuit based extraction and optimization. The initial amplitude coefficients are based on Chebyshev synthesis and have been calculated with PCAAD. They have been modified by taking into account the patch element factor, so as to get a flat -20dB SLL after the multiplication of element factor and array factor. The amplitude coefficients for our design are: \( a_i = [1, 0.92, 0.8, 0.55, 0.7] \). The method described in II has been used to optimize each antenna element for the calculated amplitude \( a_i \) from the synthesis. In Fig. 6(a) the microstrip layout of the patch width tapering is depicted, where as in 6(b) the line width tapering is shown. It is evident that the line and patch length have less variation in case of the line width tapering. Due to the constant patch width, the resonance frequencies needed only a minor retuning. In case of the patch width tapering we can see a variation of the line length and of the patch length, since smaller patches have to be longer to have the same resonance. The feeding has been done in a symmetric manner, so to not disturb the field distribution on the antenna and increase the side lobe level. Finally, we can compare the farfields in the \( xz \)-plane. Fig. 7 shows the directivity pattern calculated from PCAAD. While there is a good agreement of the main lobe for both tapering strategies, they show differences in the side lobes. Especially, the first side lobe shows a deviation for the two approaches. The line-width-tapering agrees with our initial design pattern and the patch-width-tapering shows a difference of about 4dB. The reason is due to the inconstancy of the antenna element patterns when the patch width is varied.

![Fig. 6. Configurations with two different tapering methods for the given amplitude tapering. a) patch width-tapering method; b) line-width tapering method.](image)

![Fig. 7. Directivity patterns for the two different tapering methods (full wave FDTD analysis with Empire) compared with the pattern computed by PCAAD (analytical model, multiplication of element factor and array factor).](image)

IV. ANTENNA PROTOTYPE

A prototype of the antenna with line-tapering has been fabricated, measured and compared with simulation results. It was essential to feed the antenna without any modification of the antenna structure itself but keeping the SLL, which is rather sensitive even to minor changes. An empirical approach has been chosen by simply moving the coaxial port from the center along the antenna and comparing the radiation pattern with the one given in Fig. 7. Without examining this systematically, we found a very good agreement in the radiation pattern for the probe feeding at the position 11.6 mm from the center line. Since the impedance bandwidth was also good, we fabricated the antenna with a SMA connector at this position. This of course does not provide a general feeding technique, nevertheless here, it has been successfully used to feed our antenna structure without severely affecting the side lobes. Fig. 9 shows the measurement setup in the anechoic chamber. The antenna has been fabricated on a Rogers Duroid 5880 substrate material with a height of \( h = 1.5 \) mm. Only the \( xz \)-plane is measured and compared to our simulation results. Of main interest is the SLL, so that the far field measurement is not gain calibrated. In Fig. 10, we show the normalized farfield plots for the simulation and for the measurement. The agreement is reasonable and supports
V. CONCLUSIONS

A circuit based design strategy is presented which allows the accurate pattern synthesis according to a given amplitude distribution for series fed patch arrays. The patch is modeled in a symmetric environment taken into account the feed line and all other parasitic effects. Using circuit parameters extracted from EM simulations, we have optimized each antenna element for the operating frequency as well as for a given normalized amplitude. Two different tapering techniques have been compared and it turned out that the line-width-tapering has some distinct advantages over the patch-width-tapering.

For the line-width-tapering, the element factors are nearly constant and the line length and patch length can be kept almost constant as well. Since the line-width-tapering is more sensitive, fabrication tolerances might be an issue for higher frequencies.

REFERENCES