Effects of Mutual Coupling in Tapered Slot Array (TSA)

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Abstract

Based on the relation between the active reflection coefficient (ARC) and mutual coupling, a generic method to compute the mutual coupling between elements in a big array was developed. The developed method was then employed to different types of TSA arrays and the effects of mutual coupling between TSA elements on the active impedance matching in TSA arrays were investigated.

Introduction

Broadband arrays require small element spacing over a broad frequency band to achieve the desired scan capabilities. Previous research has focused on the development of small broadband elements to meet the demand of broadband arrays. However, mutual coupling between elements in a tightly spaced array can change the bandwidth of the single isolated element. Recently, there is an increasing trend in broadband array design to utilize the strong coupling among elements to shift down the centre frequency and at the same time broaden the impedance bandwidth of the array 1.

The coupling between TSA array elements was identified as being essential to the operation of elements in arrays over bandwidths that are larger than those found for the individual isolated elements. The electromagnetic performance of an array antenna is influenced significantly by the strong mutual interaction between the array elements. Therefore the knowledge of mutual coupling effects is essential in the design of array elements. However, how to accurately predict the mutual coupling in a big array in a retractable way is not yet established. A theoretical formulation for arrays with strong mutual coupling between elements is difficult to analyze since these interactions are typically a near-field phenomenon. The full element-by-element analysis of a large finite array is either excessively time consuming or impossible due to the computer memory required. Some effective numerical methods have been developed to calculate the mutual coupling between elements 2-3, but those methods are designed for specific elements such as dipole or patch antennas which are not applicable to other types of elements. In 4, a modal-based method for mutual coupling in a multilayered patch array has been described and mutual impedances were derived from the Floquet impedances.

Inspired by this work, a generic analytical based method to compute the mutual coupling between elements in a big array was developed. The Active Reflection Coefficients (ARC) of a unit cell at different scan angles are first calculated using commercial software. Based on the relation between ARC and mutual coupling, the mutual coupling coefficients can be extracted from Fourier decomposition of the simulated ARC. This method was proven to be more efficient and practical than the full modal method since only a unit cell is modelled. Effects of mutual coupling between TSA elements on the active impedance matching in tapered slot arrays were investigated.

Fourier Decomposition of the Active Reflection Coefficients

Using multi-port network analysis technique, the ARC of the centre element of a planar array as shown in Figure 1 can be expressed in terms of mutual coupling [5]:

$$\Gamma(\theta,\phi)=\sum_{m=1}^{M}\sum_{n=1}^{N}S_{mn}e^{-jk_0md_x\sin\theta\cos\phi}e^{-jk_0nd_y\sin\theta\sin\phi}. \quad (1)$$

Where θ and ϕ are the elevation and azimuth angles of the scan direction. S_{mn} is the coupling coefficient between element situated at mn and centre element. Substitute $u = k_0 d_x \sin\theta\cos\phi$ and $v = k_0 d_y \sin\theta\sin\phi$ into Eq. (1), we can rewrite Eq. (1) as:

$$\Gamma(u,v)=\sum_{m=1}^{M}\sum_{n=1}^{N}S_{mn}e^{-jmu}e^{-jnv}. \quad (2)$$

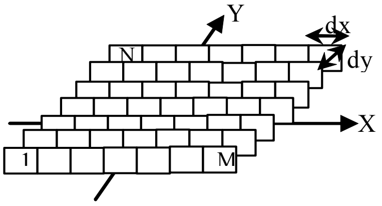


Figure 1 Parameter definition of a planar array structure

For a rectangular lattice structure, the right–hand side of Eq. (2) is the two-dimensional Fourier series representation of $\Gamma(u,v)$. Using the orthogonality of the exponential function in the domain [-π π], the S_{mn} can be determined by Fourier decomposition of the $\Gamma(u,v)$ according to:

$$S_{mn}=\frac{1}{4\pi^2}\int_{-\pi}^{\pi}du\exp(jmu)\int_{-\pi}^{\pi}dv\exp(jnv)\Gamma(u,v) \quad (3)$$

Similarly, the mutual coupling in a 1-D array can be calculated according to:

$$S_{m1}=\frac{1}{2\pi}\int_{-\pi}^{\pi}du\exp(jmu)\Gamma(u) \quad (4)$$

where $u = k_0 d \sin\theta$.

The above equations establish the relation between the active reflection coefficient and the mutual coupling between the elements in array environments. The mutual coupling coefficients between elements in an array can be found from Eqs. (3) and (4).

Mutual coupling in TSA arrays

The TSA element is characterized by strong mutual coupling. However, accurate prediction of the mutual coupling in a large TSA array is not well studied. In this section, the mutual coupling analysis technique outlined in the preceding section was implemented and applied to the stripline-fed tapered slot antenna (TSA) array. Given the broadband wide scan array requirement of 4~18GHz, the TSA element with a width of 8.3mm was studied.

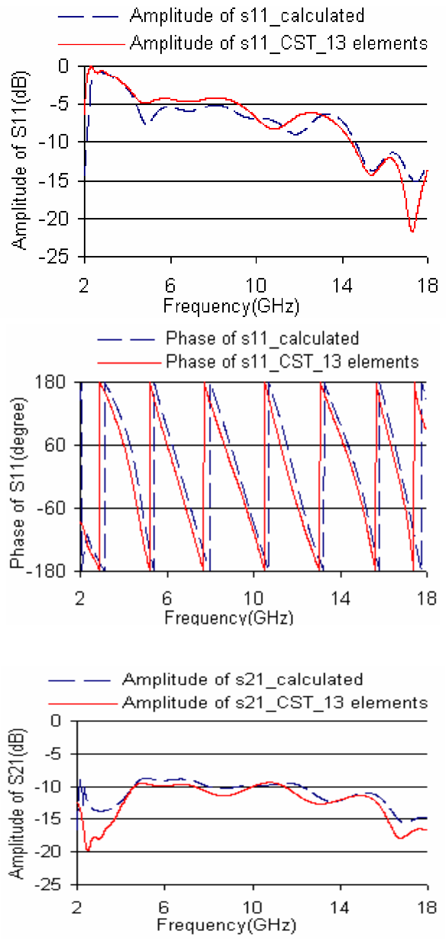
Linear TSA arrays

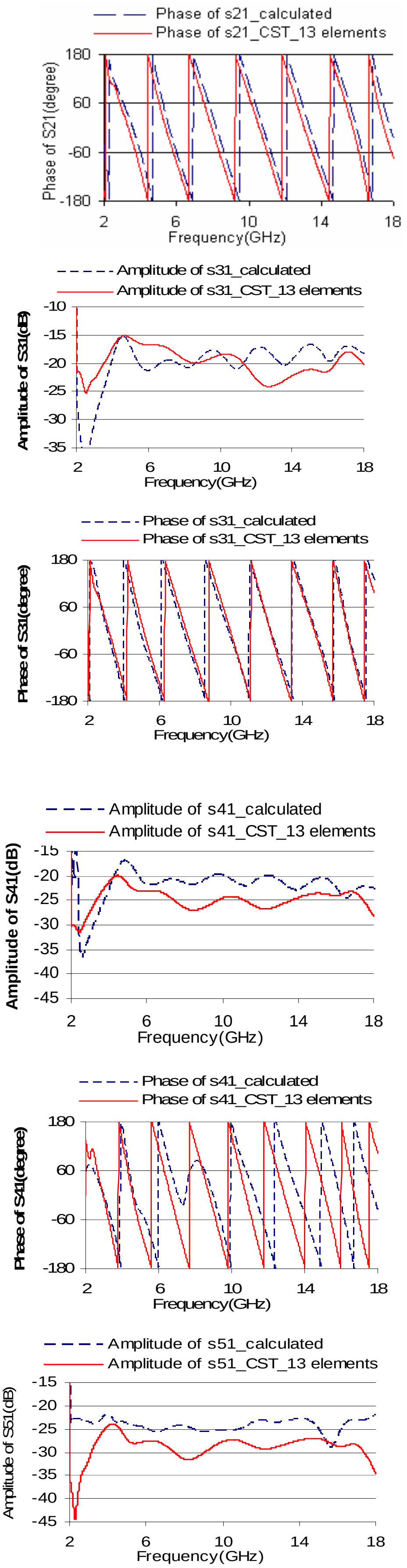
The TSA array was first modeled as an element in a uniformly excited E-plane infinite array using CST Microwave Studio. The ARCs with phase shift from [0 π] were simulated with an interval Δu of 9°. Only half space was simulated due to the symmetry of the ARC. Eq. (4) was used to compute the self and mutual coupling for the TSA elements in an infinite array environment. To validate and compare the calculated S-parameters, the S-parameters between centre element and other elements in a 13-element array were obtained directly using a full array model with the centre element excited and all the other elements passive matched. A larger array size would have been preferred but due to the memory requirement, only a small array with 13 elements was simulated. The number index of the 13-element array is shown in Figure 2.

The calculated amplitudes and phases of S-parameters in an infinite array and simulated S-parameters in a 13-element array are plotted in Figure 3 using dash line and solid line respectively. Good agreement between the calculated and simulated S11 and S21 is observed while a significant difference between the calculated and simulated Sm1 (m=3…7) is found. This is expected since the mutual coupling of central elements S11 and S21 in the finite array is less affected by the edge effects, thus can be approximated by the value of the element in an infinite array environment. But the S31 to S71 in the 13-element array are affected by the truncation effects and should be different from the values in an infinite array.

7	6	5	4	3	2	1 centre element	8…13

Figure 2 The element index of the 13-element array





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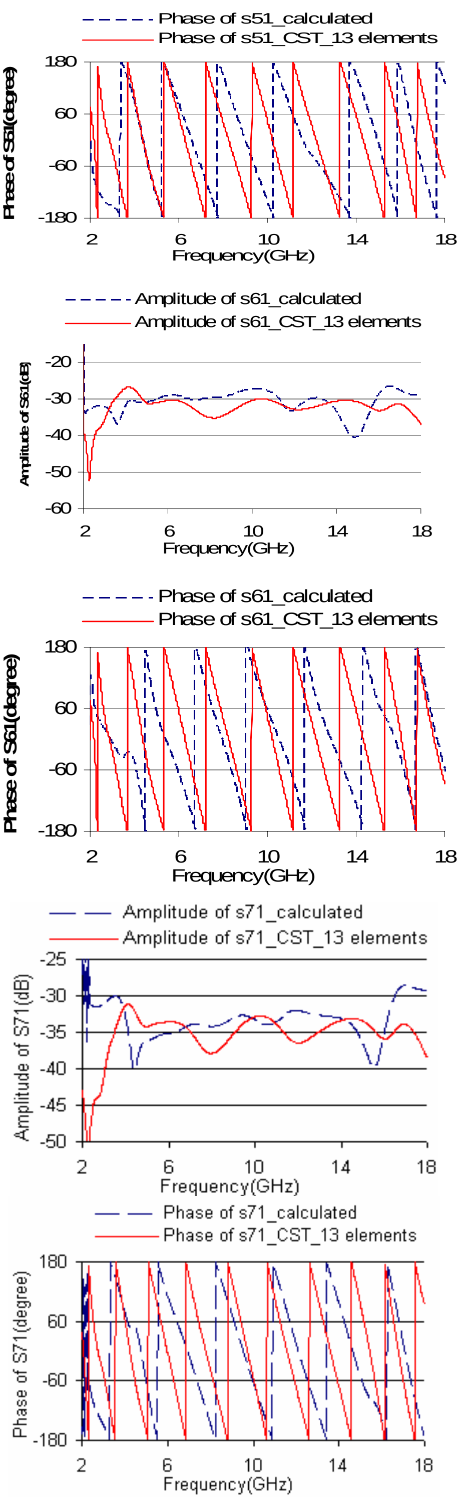


Figure 3 Amplitudes and phases of S-parameters versus frequency of the TSA in linear arrays ------ Calculated results based on our method, —— Simulated results for a 13-element array

The calculated mutual coupling between individual element and central element in an infinite linear array has been plotted as a function of frequency and element index on a contour plot in Figure 4. The mutual coupling levels between the closely-spaced elements are very strong, especially for the first 3 elements. In addition, the mutual coupling levels do not vary significantly with frequency.

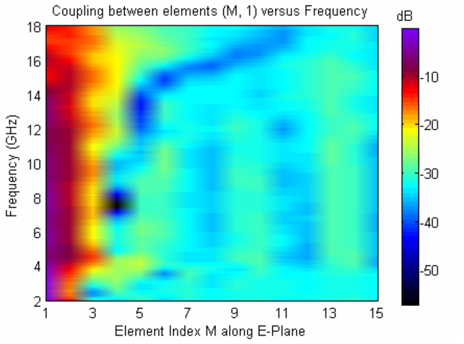


Figure 4 The mutual coupling between individual element and central element in an infinite linear array from 2-18GHz

Planar TSA arrays

The same TSA element was simulated in a planar infinite array with phase shifts along E-plane and H-plane from (0, π) with an interval of 9°. Eq. 3 was used to compute the self and mutual coupling for the TSA elements in an infinite array environment. Since the full modeling of a big planar array or even a medium planar array is prohibitive in terms of computational time and memory requirement, no full modeling of a finite planar array was conducted to validate the calculated results. To this end, the ARC at broadside of the infinite TSA array was reversely calculated based on Eq. 2 from the calculated S-parameters. The ARC at broadside including 29×29 elements coupling contribution was calculated and compared with the directly simulated ARC for a unit cell from CST and the results are plotted in Figure 5. Both the amplitude and phase of the calculated ARC agree very well with the simulated result.

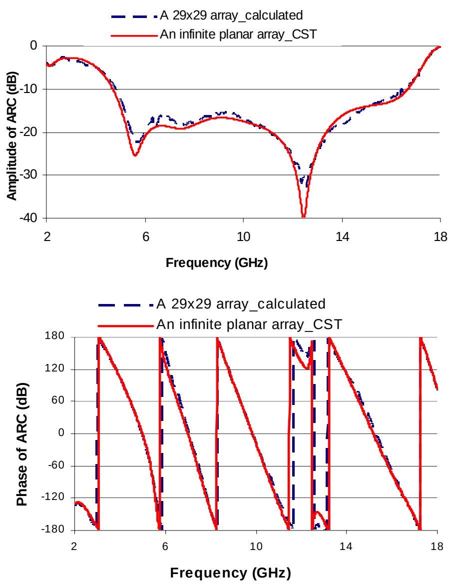
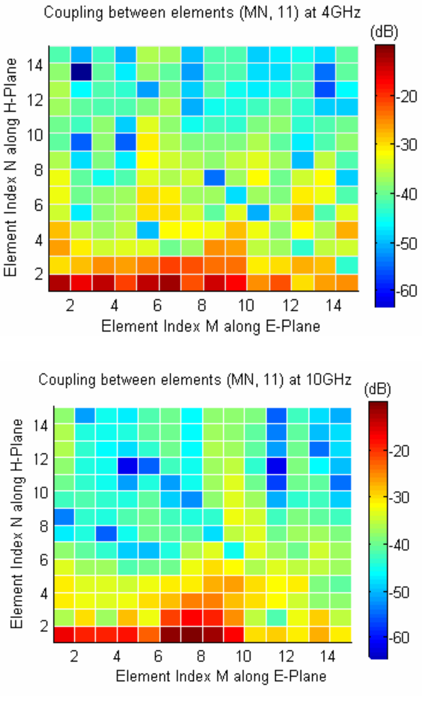


Figure 5 Broadside ARC of the planar array calculated from mutual coupling of 29x29 elements and compared with the directly simulated result

The calculated mutual coupling between individual element (up to 15 elements from central element) and central element in an infinite planar array has been plotted as a function of element index along E-plane and H-plane at different frequencies in Figure 6. Much stronger coupling is presented along E-plane than along H-plane.



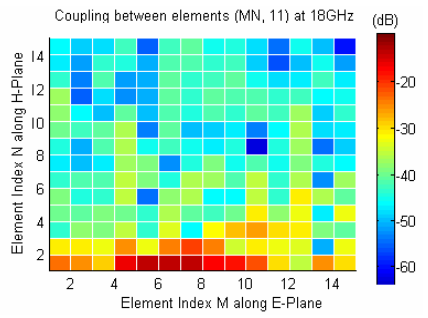


Figure 6 Calculated mutual coupling in a planar array at 4GHz, 10GHz and 18GHz

Comparison of mutual effects in linear and planar arrays

To gain some insight into the effects of mutual coupling on the Active reflection coefficients in an array, comparison and investigation into the common and difference between the linear TSA array and planar TSA array were conducted in this section. The simulated ARCs of the infinite planar and linear TSA arrays at broadside are plotted in Figure 7. The linear array presents a better impedance matching compared to the planar array, particularly at higher end of frequency band.

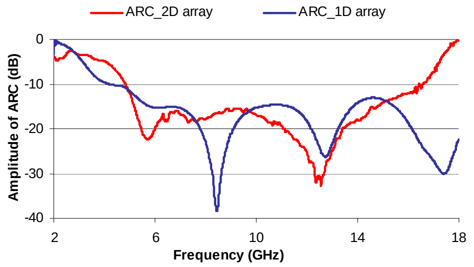


Figure 7 Comparison of ARCs in planar and linear TSA arrays

To further investigate the effects of mutual coupling between elements in an array, the ARCs of the planar array at broadside were synthesized with the calculated S_{mn} based on Eq. 2 with different number of rows (along E-plane) accounted for. The M was kept unchanged as 29 while N was set as 1, 3, 5, 7, 9 respectively. The calculated ARCs are plotted in Figure 8 together with the ARCs of the infinite planar array. The ARC calculated with N=3 at higher end of frequency band is getting close to the ARC of the infinite array. So the ARC of the planar array at higher end of frequency band is mainly decided by the central 3 rows. The contribution of mutual coupling from remote rows can be neglected at higher end of frequency band. However there are still big gap between the ARC with N=3 and infinite array at lower and middle band, so more rows were included in the calculation. The ARC calculated with increasing N gradually converges to the ARC of the infinite array. And the ARC calculated with N =9 is very close to the ARC of the infinite array.

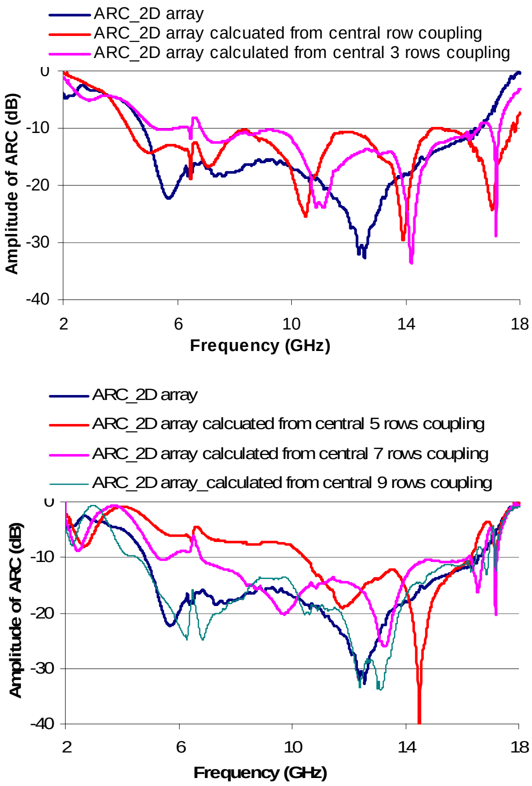


Figure 8 Broadside ARCs calculated from mutual coupling with varied number of rows (along E-plane) included

Conclusions

A generic analytical based method to compute the mutual coupling between elements in a big array was developed. The work has demonstrated that the method is effective and accurate to predict mutual coupling between elements in a strongly-coupled array. In principle, this method is applicable to any type of elements in a large array where the edge effects can be ignored and avoid the prohibitive requirements in modelling a big array using full-wave methods. Extensive examination of the coupling effects of the chosen element design has shown that a model with 14 elements at both sides of the centre element is enough to accurately account for the mutual coupling effects on ARC in an infinite TSA array. And the ARC of the planar TSA array at higher end of the frequency band is mainly decided by the central 3 rows. The mutual coupling of remote rows away from the central row will improve the ARC in the lower and middle frequency band of the planar TSA array.

References

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