Design of a Closely-Spaced, Multiple-Element Parasitic Antenna Array

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Abstract

A new design methodology for a closely-spaced, multiple-element parasitic antenna array is proposed. The design is based on the identified dominant surface wave mechanism. Optimum surface wave phase velocity is first determined for a fixed length array, and the antenna gain, radiation pattern, efficiency and input impedance are presented and optimized. Both numerical simulations and measurements are implemented.

1. Introduction

Design of a closely-spaced parasitic antenna array is of great interest in recent years for its potential application as an electrically small, super directive antenna. O'Donnell and Yaghjian proposed a two-element parasitic array design optimized using the genetic algorithm (GA) [1], in which the spacing between the driving element and the parasitic element is $0.115\lambda_0$ (λ_0 is the free space wavelength). Bayraktar *et al.* presented a compact, three-element stochastic Yagi-Uda array design using the particle swarm optimization algorithm (PSO) [2]. The spacing between their reflector and driver, and driver and director are $0.11\lambda_0$ and $0.036\lambda_0$ respectively. Lim and Ling utilized GA to design a two-element, electrically small, reconfigurable Yagi antenna for HF skywave applications [3] and they successfully reduced the element spacing to $0.02\lambda_0$. Arceo and Balanis reported a three-element, enhanced bandwidth Yagi antenna with inter-element spacing set at $0.053\lambda_0$ [4]. In all the above examples, the spacings between array elements are much smaller than that of a conventional Yagi-Uda antenna which inter-element spacing ranges from $0.15\lambda_0$ to $0.4\lambda_0$.

One common challenge needs to be addressed in the above designs is the strong mutual coupling between array elements due to the reduced spacing. Such strong coupling can result in several undesirable effects including, but not limited to, low radiation resistance, poor radiation efficiency, bad input impedance matching, and narrow frequency bandwidth. Global optimization algorithms (e.g., GA or PSO) were introduced to make performance trade-offs; however, implementations of these algorithms are so computationally intensive that the number of array elements is restricted to two or three. Further increase in the number of elements will lead to rapid increase in computational resources. In addition, limited physical insights can be gained from these brute-force optimization results.

In this paper, we focus on developing an intuitive method to design a closely-spaced, multiple-element parasitic antenna array. The design idea is based on our previous study of wave propagation in a closely-spaced parasitic array consisting of finite-height metal wires [5]. A surface wave propagating along the top of the wires was found to be the dominant propagation mechanism, and the phase velocity of the surface wave was extracted and correlated with array geometrical parameters. Motivated by this finding, we can turn the problem of designing a multiple-element, closely-spaced parasitic antenna into the design of a surface wave antenna, where conventional surface wave antenna design methodology can be used to optimize antenna gain. Different from traditional surface wave antenna design which mainly focuses on maximizing the antenna gain, input impedance and radiation efficiency also need to be optimized for closely-spaced surface wave antenna array.

2. Methodology

A 1-D closely-spaced, multiple-element parasitic array is shown in Figure 1. Each array element is a copper wire of height h and radius r. The spacing between the elements is a, and the array size is L along the y dimension. All wires are located on a perfect electric conductor (PEC) ground. A voltage source is placed at the bottom of the left-most element. Given the array setup, a strong surface wave can be excited and guided along the structure in multiple frequency bands [5], which motivates us to explore the idea of a surface wave antenna design. Conventional surface

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wave antenna design requires the phase velocity of the wave to be carefully chosen so maximum gain can be achieved for a given array size L [6]. For our array setup the surface wave phase velocity is strongly dependent upon the wire height and spacing, but is weakly dependent upon the wire radius. Therefore, we first simulate the antenna gain for different wire heights and spacings, in the hope of identifying the optimum phase velocity which provides the maximum gain. The array size and wire radius are set at L=0.5λ_o and r=0.001λ_o. Numerical Electromagnetics Code is used for the simulation.

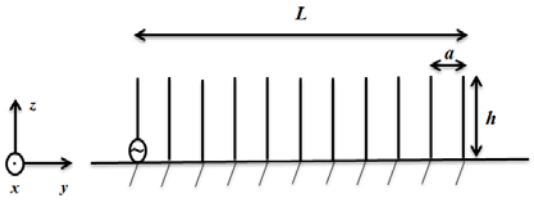

Figure 1. 1-D closely-spaced, multi-element parasitic array setup

Figure 2(a) plots the simulated antenna gain on a decibel scale versus normalized spacing and height. It can be observed that for any given spacing a, there exists a unique wire height h, the pairing of which gives the maximum gain. For example, the pair of (a=0.01λ_o, h=0.192λ_o) results in the maximum gain of 12.23dB. As the spacing becomes larger, the wire height has to be increased accordingly to maintain the peak gain value, leading to the maximum gain curve (in dark red color) in the plot. Our previous study indicates that by increasing inter-element spacing the surface wave phase velocity will be reduced; conversely, increasing wire height will result in larger phase velocity. Therefore we expect the phase velocity to stay the same along the maximum gain curve due to the cancelling effects of two geometrical changes. To verify this we extract the wave phase velocity for different optimum combinations of (a, h) using the ESPRIT algorithm. The extraction process has been presented in detail in [5] and will not be repeated here. The extracted phase velocity is plotted versus spacing in Figure 2(b), where the blue line is the mean value. The result is as expected and indeed there exists an optimum phase velocity (0.67c_0, c_0 is the speed of light) for this fixed size array (L = 0.5λ_0), which leads to the maximum gain.

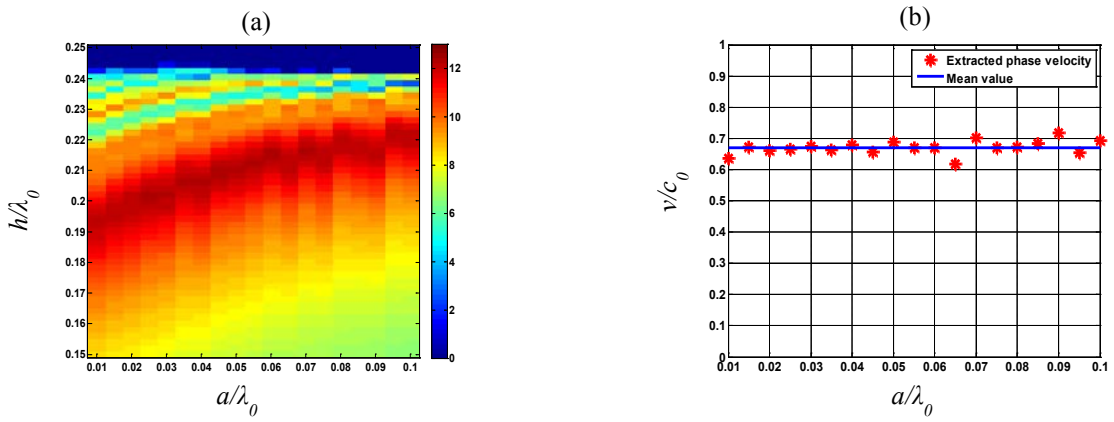

Figure 2. (a) Simulated gain for different wire spacing and height (b) Extracted optimum phase velocity

Next we investigate whether different optimum combinations of a and h lead to similar antenna performances in radiation pattern, efficiency and input impedance. Figure 3(a) shows the simulated radiation patterns in the azimuth plane for various spacings. The heights of array elements are determined corresponding to the maximum gain curve in Figure 2(a). The vertical axis is the gain on a dB scale and horizontal axis is the angle ϕ in degrees. It can be observed that radiation patterns for different optimum (a, h) are almost identical to each other, and the gain achieves maximum value at ϕ=90^o in all cases. The front to back ratio (F/B) slightly decreases as the spacing becomes larger (F/B =13.91dB for a=0.01λ_o and F/B =11.73dB for a=0.09λ_o). Figure 3(b) plots the antenna radiation efficiency against spacing a. The efficiency decreases from 98% to 93% as the spacing drops from 0.1λ_o to 0.01λ_o, which can be contributed to stronger coupling at closer spacing. But overall the efficiency is reasonably high, and closed-spacing appears to have minimum effects on the radiation efficiency in our case.

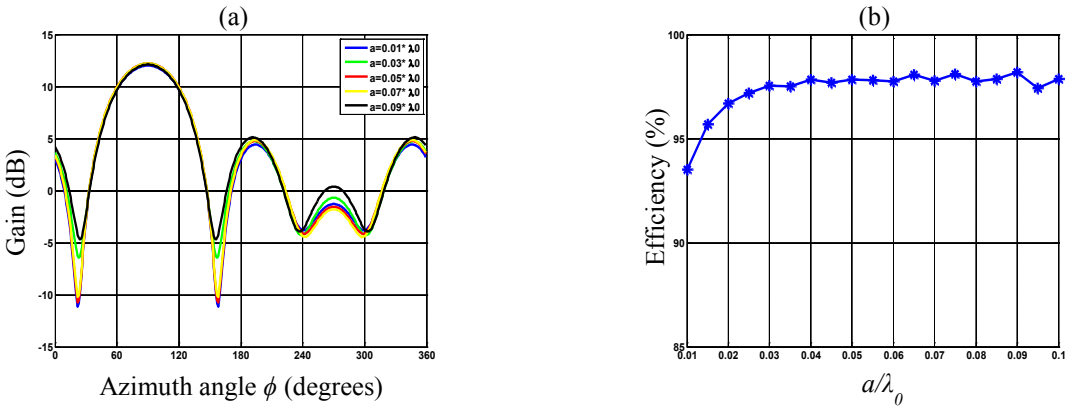

Figure 3. (a) Far field radiation patterns (b) Efficiency for optimum combinations of (a, h)

Figure 4 depicts the antenna input impedance versus spacing, in which the blue line is the input resistance and the red line is the input reactance. As the spacing becomes larger, the resistance increases while the reactance is less capacitive. However, it is challenging to match this surface wave antenna to a 50 Ohm transmission line even at a=0.1λ_o, where the input impedance is equal to 11.99-j36.56 Ohm. The capacitance needs to be tuned out and the resistance needs to be boosted up, which we will discuss next in Section 3.

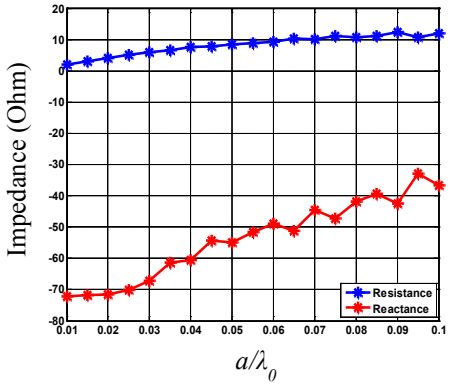

Figure 4. Input Impedance for optimum combinations of (a, h)

3. Simulation and Measurement

Following the idea presented in Section 2, we design, simulate and measure a 1-D closely-spaced surface wave antenna array at frequency 1.5GHz. The array size L and wire radius r are set at 0.5λ_0 and 0.0025λ_0. We select the wire height h and spacing a to be 0.204λ_0 and 0.05λ_0 so a uniform surface wave with optimum phase velocity 0.67c_0 can be supported along the array. The simulated input impedance for this uniform height, equal spacing array is 6.53-j61.31Ohm at 1.5GHz, which results in poor impedance matching. To improve matching, we first adjust the height of the feeding element h_f from 0.204λ_0 to 0.238λ_0 to tune out the input reactance, and then apply the folding technique [6] to boost up the resistance to 54.52Ohm.

A measurement prototype is next fabricated using 18 Gauge copper wires and placed on a 3*0.8m^2 steel plate, as shown in Figure 5. A vector network analyzer (Agilent Technologies PNA-L Network Analyzer N5230C) is used to measure both reflection coefficients and gain. Figures 6 plot both simulation and measurement results. In Figure 6 (a), the simulated reflection coefficients of the antenna reach the minimum value at 1.5GHz while the measured resonant frequency shifts to 1.535GHz. The difference can be contributed to the finite size of the ground plane. The simulated and measured 10dB bandwidths are 50MHz and 45MHz, respectively. Figure 6 (b) plots the surface wave antenna gain against frequency. The simulation and measurement show a similar trend within the frequency band. The maximum simulated antenna gain is 12.56dB at 1.5GHz and the peak measured gain is 16.29dB at 1.55GHz. More fluctuations can be observed in the measurement data due to the finite ground plane and the multipath effects.

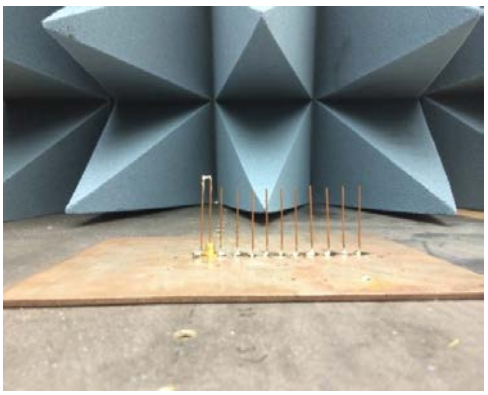

Figure 5. A 10-element closely-spaced surface wave antenna prototype

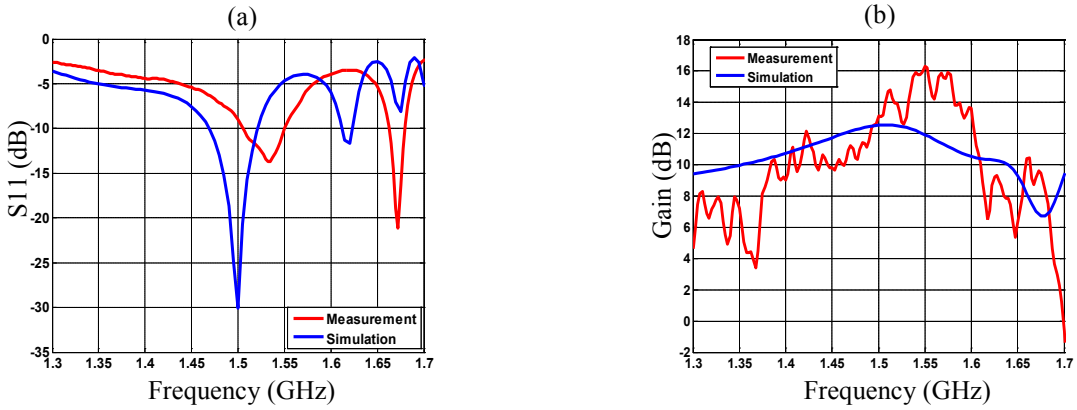

Figure 6. Comparison between simulation and measurement: (a) Reflection coefficient (b) Gain

4. Conclusion

In this paper, a 1-D closely-spaced, multi-element parasitic array has been designed based on the surface wave propagation mechanism. It was shown that for a fixed length antenna array, there exists an optimum surface wave phase velocity which results in the maximum gain. The desired phase velocity can be achieved by carefully selecting the wire height and spacing. The antenna radiation pattern, efficiency, and impedance were also examined. It was shown that the input impedance requires to be boosted up using the folding technique. A full surface wave antenna array design with inter-element spacing of $0.05\lambda_0$ was implemented and the simulation results were similar to the measurements. For future work, we plan to use electrically small elements such as meander line, cylindrical helix, and spherical helix to substitute the wire and achieve a more compact array design. We will also apply the surface wave antenna design idea to a 2-D closely-spaced parasitic array structure.

5. References

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