Research Article

Backward Surface Wave Propagation and Radiation along a One-Dimensional Folded Cylindrical Helix Array

Bin Xu and Yang Li

Department of Electrical and Computer Engineering, Baylor University, Waco, TX 76798, USA

Correspondence should be addressed to Bin Xu; bin_xu@baylor.edu

Received 28 April 2015; Accepted 30 July 2015

Academic Editor: Diego Masotti

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Wave propagation along a closely spaced folded cylindrical helix (FCH) array is investigated for the purpose of designing compact array for energy transport and antenna radiation. It is found that the height of this surface wave guiding structure can be decreased from $0.24\lambda_0$ to $0.06\lambda_0$ by replacing the monopole element with the FCH. Both the propagation constant and the mode distribution of the dominant wave mechanism are extracted by ESPRIT algorithm, which indicates that a backward propagating surface wave is supported by the array structure. A compact backfire FCH antenna array is designed and measured based on the identified dominant wave mechanism.

1. Introduction

Wave propagation and radiation along a one-dimensional metal wire array has long been of interest since the invention of the Yagi-Uda antenna [1]. With carefully selected monopole wire height (0.2 to $0.25\lambda_0$, with λ_0 being the free space wavelength) and spacing (0.2 to $0.35\lambda_0$), a surface wave with an optimum phase velocity can be supported by the structure and can be radiated in the end-fire direction [2]. More recently, there is an emerging interest in minimizing the size of the array for two important applications: electromagnetic (EM) energy transport and compact antenna array design. It was found in [3] that the transmission loss of EM energy along a 1D metal rod array is smaller than $1.5 \text{ dB}/\lambda_0$, which can be attributed to the strong coupling between closely spaced rods ($0.054\lambda_0$). For the second application, a closely spaced, multiple-element parasitic antenna array was designed and implemented, with its interelement spacing being as small as $0.02\lambda_0$ [4].

In spite of the above success in reducing the spacing between wires, there still remains a challenge to minimize the height of each array element. It was found that the height of metal wire should be close to a quarter-wavelength to ensure the dominant surface wave is strongly excited. One idea to minimize the element size is to substitute the metal wire with electrically small elements such as a folded

spherical helix (FSH) [5] or a folded cylindrical helix (FCH) [6], the size of which can be as small as $0.06\lambda_0$. The effects of mutual coupling between two closely spaced FSHs or FCHs have been studied recently for wireless power transfer applications [7, 8]. However, wave propagation along a 1D closely spaced array with electrically small element is not well understood and still needs to be investigated. Previously we have simulated surface wave propagation along a 1D FCH array and compared the results with that of a 1D metal cut wire array [9]. In this paper, we extend our study to simulate and measure surface wave propagation and radiation along a 1D closely spaced FCH array.

The paper is organized as follows: in Section 2, a 21-element FCH array is first designed and fabricated. Broadband transmission data and near electric field distributions are simulated and measured along the array. In Section 3, the dominant propagation mechanism and its associated propagation characteristics, such as propagation constant and mode distribution, are extracted using a super resolution estimation algorithm. A parametric study is performed to figure out correlation between the propagation constant and array geometrical parameters. In Section 4, a compact backfire parasitic antenna array is designed based on the identified dominant wave mechanism. Both simulation and measurement results are presented. Section 5 concludes the paper.

FIGURE 1: 1D folded cylindrical helix array setup: (a) simulation and (b) measurement.

FIGURE 2: Simulated and measured reflection coefficients.

2. Wave Propagation along a 1D FCH Array

First, a single 4-arm FCH element centered at 400 MHz is designed by using formulas provided in [6]. The helix radius R , height H , and number of turns are 0.0317 m, 0.047 m, and 1, respectively. The height of the folded helix corresponds to $0.063\lambda_0$, which is much shorter than that of a quarter-wavelength monopole antenna. Next, 21 identical elements are placed along a straight line in the y -axis to form the FCH array. The interelement spacing S is equal to 0.08 m, corresponding to $0.11\lambda_0$ at 400 MHz. Figures 1(a) and 1(b) show the simulation and measurement setup of the FCH array. While a finite sized metal ground plane is used in the measurement, an infinitely large perfect electric conductor (PEC) ground is assumed in the simulation to save computational time. A voltage source is placed at the bottom of the left-most element and a field probe is moved in between parasitic elements to sample the near electric fields at the ground plane level for different frequencies. Numerical software FEKO [10] is used for simulation and

a vector network analyzer (Agilent PNL N5230C) is applied for measurement.

Figure 2 compares the simulated and measured reflection coefficients S_{11} of the source antenna. They exhibit similar trend and both are significantly different from the sharp resonance behavior of a single FCH antenna, as presented in [6]. This is due to the strong coupling between closely spaced helices. The resonance band in the measurement shifts downward by approximately 20 MHz comparing to the simulation data, which can be attributed to manufacturing errors.

Figures 3(a) and 3(b) show the normalized transmission data for both simulations and measurements on a dB scale. The antenna mismatches have been removed by normalizing $|S_{21}|^2$ to $1 - |S_{11}|^2$ and $1 - |S_{22}|^2$. The horizontal axis represents the frequency from 300 MHz to 500 MHz with an interval of 2.5 MHz, and the vertical axis represents the distance between transmitting and receiving antennas along the y -axis from 0.4 m to 1.6 m with a spacing of 0.08 m. As shown in Figure 3(a), the receiving field strengths are much stronger

FIGURE 3: Normalized transmission coefficients: (a) simulation and (b) measurement.

FIGURE 4: Simulated near field distribution in the y - z plane at 390 MHz: (a) E_y and (b) E_z .

between 355 MHz and 415 MHz, and within the pass band wave propagation exhibits negligible decay along the y -axis. Outside of this pass band, field strengths are much weaker and attenuate much faster. The measurement results in Figure 3(b) show good agreement with simulation results, except the pass band shifts downward by approximately 20 MHz, similar to the above observation for Figure 2.

To further reveal the wave propagation along the FCH array, we simulate the near field distributions in the y - z plane at a sample frequency of 390 MHz. Figure 4 plots the normalized near electric field components E_y and E_z on a dB scale. The horizontal axis represents the distance along the y -axis from 0.4 to 1.6 m with a 0.08 m interval. The vertical axis represents height in the z direction from 0 to 0.2 m with an interval of 0.002 m. In Figure 4(a), a standing wave pattern

can be clearly observed along the y direction, implying the interference between $+y$ and $-y$ traveling waves due to the finite size of the array. Along the z direction, the magnitude of E_y peaks at the height of the helix and decays rapidly away from the interface between the FCH and the air. A similar interference pattern can be observed in Figure 4(b) for the E_z component, except its strength is much weaker than E_y .

3. Extraction of Dominant Wave Mechanism Using ESPRIT

To better understand how wave propagates along the 1D FCH array, we extract the dominant wave mode and its associated propagation characteristics from the above transmission and near field data. First we model the transmission

FIGURE 5: Comparison between original data with fitted results by ESPRIT: (a) simulated magnitude at 390 MHz; (b) simulated unwrapped phase at 390 MHz; (c) measured magnitude at 370 MHz; (d) measured unwrapped phase at 370 MHz.

data as a summation of different wave modes, each with a unique propagation constant β_m , attenuation constant α_m , and magnitude c_m , which can then be extracted using ESPRIT algorithm. ESPRIT is a super resolution spectrum estimation algorithm which was originally developed for estimation of sinusoid signals in noise [11]. More recently, it has been successfully applied to both wave propagation and antenna radiation problems [12]. The extraction process has been explained in detail in [4] and will not be repeated here. Consider the following:

$$S_{21} \cong \sum_{m=1}^M c_m e^{-j\beta_m y - \alpha_m y}. \quad (1)$$

As an example, Figures 5(a) and 5(b) plot the ESPRIT fitted magnitude and phase curves at 390 MHz by adding the first two dominant terms. The results show excellent agreement with the original simulated transmission data, and the propagation constants of the two dominant terms are found to be $-2.236k_0$ and $2.236k_0$ (k_0 is the free space wave number), implying the superposition of incident and reflected components of a single slow wave mode. It is found that the dominant mode is a backward traveling surface wave for the following two reasons: first, the amplitude of the mode with a propagation constant $\beta = -2.236k_0$ is stronger than other modes extracted from the ESPRIT; second, the unwrapped phase increases as distance y increases,

FIGURE 6: Normalized electric field mode distributions at 390 MHz: (a) E_y and (b) E_z .

FIGURE 7: Extracted phase constants of simulation and measurement against frequency.

as shown in Figure 5(b), implying that the dominant mode is a backward traveling wave. The ESPRIT algorithm is also applied to the measured transmission data at 370 MHz and the comparison between original and fitted data is shown in Figures 5(c) and 5(d). We intentionally shift the frequency downward by 20 MHz to make a fair comparison between simulation and measurement, as stated in Section 2. Table 1 shows the propagation constants of the dominant backward surface wave, and the results are very similar between simulation and measurement.

Furthermore, we extract the mode distribution of the dominant surface wave from the simulated near electric field data in Figures 6(a) and 6(b). Figures 6(a) and 6(b) plot

TABLE 1: Propagation parameters of the dominant mode.

Dominant mode	β_m/k_0	α_m/k_0
Simulation (390 MHz)	-2.236	0.0089
Measurement (370 MHz)	-2.4485	0.1584

the extracted E_y and E_z mode distributions versus height z at 390 MHz. It can be seen that the magnitude of E_y peaks around the height of the FCH element (0.047 m) and decays exponentially away from the interface, a typical characteristic of surface wave propagation. The E_z distribution is more complicated below the interface between the FCH and the air

FIGURE 8: Parametric study on array geometry parameters: (a) radius; (b) height; (c) spacing.

FIGURE 9: 1D compact, closely spaced backfire antenna array.

FIGURE 10: Simulated and measured antenna reflection coefficients.

FIGURE 11: Simulated and measured antenna gain.

but is similar to E_y above the FCH height. We also map out the frequency dispersion behavior of the backward traveling surface wave and show the results in Figure 7. It is seen that, except for the 20 MHz frequency shift along the horizontal axis, the values of β increase as frequency increases for both simulations and measurements.

Finally, a parametric study is conducted to correlate the propagation constant with array geometrical parameters. The first parameter we examined is the radius R . Both the height and the spacing between elements are fixed. Figure 8(a) shows that β increases as R increases. The second varying parameter is the height H of the helix, as shown in Figure 8(b). The phase constant varies slightly since the total length of the helix does not change much. Finally, in

Figure 8(c) we explored the effect of spacing and it was found that by increasing the interval of the adjacent element from 0.07 m to 0.1 m the propagation constant drops from $-1.83k_0$ to $-2.49k_0$ due to the variation of coupling between array elements. It is concluded that by carefully selecting a combination of radius R , height H , and spacing S we can achieve a desired propagation constant β for a fixed length FCH array. This observation is rather important for the surface wave antenna design, as will be explained in the next section.

4. Backfire Surface Wave Antenna Design

In this section, a compact 1D, closely spaced parasitic antenna array centered at 400 MHz is designed based on the above identified dominant surface wave mechanism. The total length of the array is assumed to be $0.5\lambda_0$. Given this fixed array size, the propagation constant of the surface wave has to be carefully determined to maximize the directivity of the array, which is similar to the 1D metal wire antenna array design [4]. The optimum phase constant β_{opt} for this half-wavelength array is found to be $-1.98k_0$. Then the radius R , height H , and spacing S are selected to be 0.03115 m, 0.049 m, and 0.104 m to achieve this β_{opt} . Other combinations of array geometrical parameters can also result in this optimum propagation constant, as discussed in the previous parametric study. Figure 9 plots the final array design setup, which consists of four FCH elements. The height of the source antenna is tuned to be 0.042 m to match the input impedance to 50 ohms at the center frequency.

Figure 10 shows the antenna reflection coefficients versus frequency. The center resonance frequencies are found to be 400 MHz and 386 MHz for simulation and measurement. The -10 dB bandwidths are both 3 MHz. Figure 11 compares the simulated and measured gain in the backward end-fire direction ($\theta = 90^\circ$, $\phi = 270^\circ$). The maximum gain values are 10.99 dBi for simulation and 10.33 dBi for measurement. Finally, Figure 12 plots the simulated antenna array radiation patterns in both the azimuth plane (i.e., xy plane) and the elevation plane (i.e., yz plane) at the center frequency, which clearly shows the backward radiation pattern. The simulated front-to-back ratio is found to be 9.4 dB, while in measurement it is 12.8 dB.

To provide more physical insights into our FCH array operation, we compare its interelement phase delay with the well-known Hansen-Woodyard end-fire array condition [13]. Given the extracted propagation constant ($-1.98k_0$) and spacing ($0.138\lambda_0$), the phase delay θ_0 between adjacent FCH elements is found to be

$$\theta_0 = \beta_{\text{opt}}d = -1.98k_0 \times 0.138\lambda_0 = -1.72 \text{ rad.} \quad (2)$$

According to the Hansen-Woodyard end-fire array condition, the theoretical optimum phase delay θ_{HW} between adjacent array elements should be close to

$$\begin{aligned} \theta_{\text{HW}} &= -\left(k_0d + \frac{\pi}{N}\right) = -\left(\frac{2\pi fd}{c} + \frac{\pi}{N}\right) \\ &= -1.6525 \text{ rad,} \end{aligned} \quad (3)$$

TABLE 2: Comparison between our antenna and other small antenna arrays in the literatures.

Reference	Number of elements	Spacing	Height	Gain	F/B	BW
Our antenna	4	$0.138\lambda_0$	$0.06\lambda_0$	10.3 dBi	12.8 dB	0.75%
[14]	3	$0.11\lambda_0$	$0.275\lambda_0$	7.14 dBi	8.6 dB	2.28%
[15]	3	$0.06\lambda_0$	$0.092\lambda_0$	8.5 dBi	7 dB	2.7%
[16]	3	$0.09\lambda_0$	$0.1\lambda_0$	8.43 dBi	6.63 dB	1.2%
[17]	3	$0.053\lambda_0$	$0.21\lambda_0$	9.9 dBi	n/a	12.44%

FIGURE 12: Simulated radiation patterns at 400 MHz: (a) azimuth plane and (b) elevation plane.

where c is speed of light and N is number of elements. It can be seen that the phase delay of our FCH array θ_0 is close to that of Hansen-Woodyard end-fire condition θ_{HW} , resulting in its maximum radiation in the $-y$ direction.

Finally, we compare our FCH antenna array performance with other small antenna arrays in the literatures [14–17]. The comparison is shown in Table 2. It can be clearly seen that our FCH array exhibits the lowest height, highest gain, and best front-to-back (F/B) ratio among all antennas. The tradeoffs we made include one more element and slightly larger spacing. The -10 dB input bandwidth of our antenna is the smallest, which can be attributed to the lowest height of the FCH element.

5. Conclusion

In this paper, surface wave propagation and radiation along a 1D FCH array is investigated from both simulation and measurement perspectives. It is found that a *backward* traveling surface wave can be supported by this structure. The propagation characteristics of this dominant wave mechanism are extracted and discussed. Furthermore, a backfire surface wave antenna is designed and implemented based on the identified wave mechanism. The study presented in this paper opens a new door for low-profile parasitic surface wave antenna array design. For future work, we will expand the study to array structures with other electrically small elements such as the folded spherical helix or the meander line. We will also look into the possibility of applying the FCH antenna array for wireless power transfer.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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