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Comparison of an Electrically-Small Planar Antenna Array with a Conventional Monopole Array

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Abstract—**A new type of linear array is proposed which utilises annular slot antennas operating in the 'DC' mode. These conformal elements are electrically-small and have wire monopole like radiation patterns.**

A thorough analysis of this array's performance is provided, with a comparison against the performance of an equivalent wire monopole array given at each stage. It is shown that overall, the characteristics of the conformal, electrically-small annular slot array are very similar to that of the wire monopole array, with only a small decrease in gain and a significant decrease in mutual coupling being reported.

I. Introduction

With the impetus to exploit the channel to its maximum potential, multi-element antenna architectures are required, either at the receiver (RX diversity), transmitter (TX diversity) or both (MIMO capacity enhancement [1]. Further link robustness can be provided via advanced coding techniques, such as space-time coding [2] and iterative decoding [3]. As well as capacity enhancing schemes, adaptive capabilities are also being researched for future generation terminals [4]. Both schemes rely upon using multiple antenna elements at the terminal. However, due to the ever-decreasing size of current and future generation mobile terminals there is less space available at the terminal for placement of suitable antenna elements.

The majority of antenna research for handset applications has focused upon methods of generating wideband elements [5–7]. Although these techniques allow instantaneous operation across a wide range of standards, their bandwidth enhancement comes at the expense of the element occupying a large volume within the handset.

To date, little research has been focused on addressing the issue of integrating antenna elements of a practical size, for the aforementioned schemes, into a handset.

This paper starts by explaining the operation of an electrically-small element suitable for use in a handset. Next, the performance of a linear array of these elements is characterised and its performance compared to an equivalent array of wire monopoles.

II. The Annular Slot Operating in the 'DC' Mode

There are four accepted ways in which an antenna may be small: electrically-small; physically-constrained; physically-small; and functionally-small [8]. Since the available volume inside a mobile terminal, is, by definition limited, any antenna used in such a situation needs to be physically small relative to the terminal. The element used here is electrically-small and has a radiation pattern identical to that of a wire monopole, yet is conformal.

The annular slot is fed by a stripline-feed. Since this is screened it reduces unwanted coupling into the antenna from the RF front-end. A shorting pin is placed in the centre of the conductor. This excites an additional mode in the input response, which is below the first-order, naturally-resonant mode. Excitation of this mode results in a uniform current distribution around the slot, similar to the case for a 'DC' current path, hence the nomenclature 'DC' mode is used.

The length of the stripline stub past the slot transition provides a means of reactive stub-matching to this mode. The overall structure is enclosed in a cavity, which is shorted out at the boundaries.

III. Single Element Design

Two identical annular slots were constructed on 1.6mm thick RT5880 (ϵ_r=2.2), designed to operate around 2GHz. A 50 Ω stripline feed was fabricated to couple into the slot. The slot had an inner radius of 9mm, and a slot width of 0.5mm. The whole structure was enclosed in a cavity of 60x60mm^2.

In the vast majority of published material on antennas, only the radiation in the principal **E** and **H** planes is presented. Although this may seem a succinct way of illustrating the radiation from the antenna, it is rather misleading since the majority of the radiation pattern is simply ignored. A more thorough way of illustrating an antenna's pattern is to consider both the 3-D co- and cross-polar radiation patterns.

For radiation pattern measurements the annular slot was mounted on a circular ground plane of radius 150mm. Figure 1 and figure 2 shows the full 3-D co- and cross polar patterns respectively for the antenna oriented in the x-y (ϕ plane).

Figure 3 shows the input response, $|S_{11}|$, of the antenna showing it to be resonant at 2.03GHz with a -10dB bandwidth of approximately 10MHz.

Pattern analysis shows that the proportion of cross-polarisation excitation using the annular slot is exceptionally

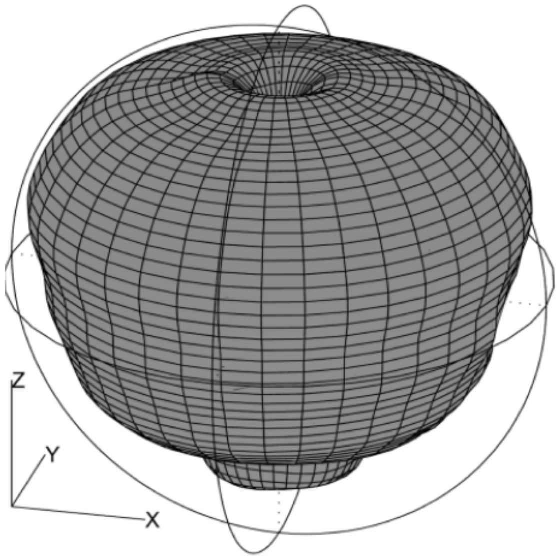

Fig. 1. Co-Polar Radiation Pattern for Annular Slot (dB Scale, -40dB at centre)

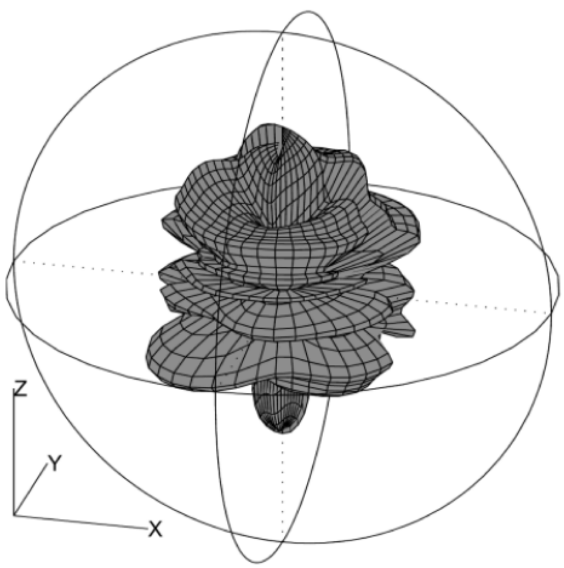

Fig. 2. Cross-Polar Radiation Pattern for Annular Slot (dB Scale, -40dB at centre)

small; 98.6% of the power is in the co-polar pattern, figure 1, whilst only 1.4% is in the cross-polarisation pattern, figure 2.

Comparison with the co-polar radiation pattern produced by a z-directed wire-monopole, shows that in terms of radiation, the patterns produced by the conformal annular-slot antenna are almost identical.

The efficiency of antennas operating in an electrically-small mode is often questioned as being potentially low [9]. However, an efficiency, η, of 73.4% $\pm$4% for the annular slot compared to a η of 93.6% $\pm$2% for an equivalent wire monopole has been reported [ibid].

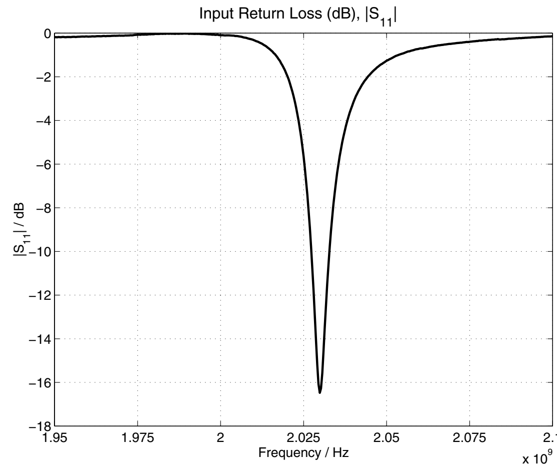

Fig. 3. Input Return Loss for the Annular Slot

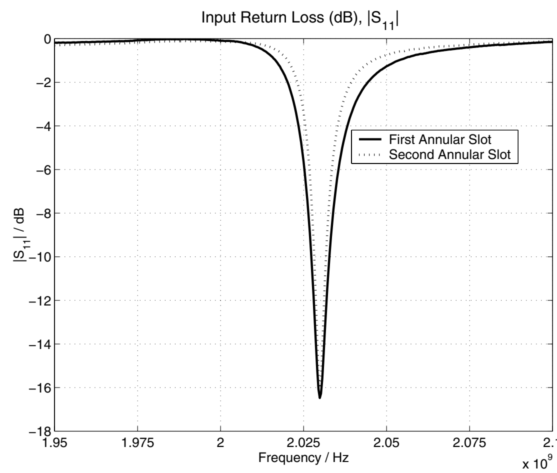

Fig. 4. Input Return Loss for Annular Slot Array Elements

IV. Array Design

In order to compare the performance of the annular slot array, a wire monopole array working at the same frequency was constructed. Monopole elements of $0.25\lambda_0$ in length at 2GHz were used. They were mounted $0.5\lambda_0$ apart on a circular ground plane of radius 150mm. The two identical annular slots were also mounted on an identical circular ground plane.

V. Array Characterisation

The two different arrays were compared by considering the following parameters: input response, 3-D radiation patterns, directivity, gain, efficiency and mutual coupling between the elements.

A. Input Response

The input responses of the individual elements were measured. Figure 4 and figure 5 show this for the and annular slot and wire monopole elements respectively.

Although both arrays are well matched at 2.03GHz, the -10dB instantaneous bandwidth for the annular slot array

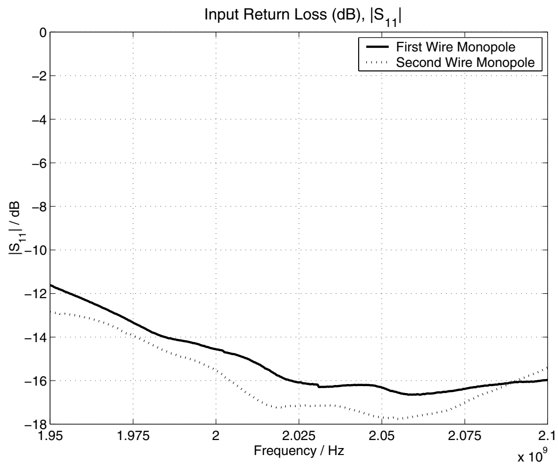

Fig. 5. Input Return Loss for Wire Monopole Array Elements

(≈ 10MHz) is less than that of the wire monopole array (>150MHz). However, although small, the instantaneous bandwidth of the annular slot array is sufficient for operation on more than one channel of most mobile standards such as GSM [10], DCS1800 [10], UMTS [11], DECT [12] and Bluetooth [13].

A simple method of tuning these elements has been developed by the authors, which would provide operation across the entire spectrum of a range of standards.

B. Radiation Pattern

Both arrays were fed using a splitter feeding into two phased-matched feeder cables, and were mounted such that the ground-plane was in the x-y (ϕ) plane, with the elements placed along the y-axis, and boresight was z-directed.

Figure 6 and figure 7 shows the full 3-D co- and cross-polarisation patterns respectively, for the annular slot array, whilst figure 8 and figure 9 shows the full 3-D co- and cross-polarisation patterns respectively, for the wire monopole array.

For the annular slot array, the radiated power was divided into 97.2% in the co- and 2.8% in the cross-polarisation excitation. Whilst, for the wire monopole array, these figures were 97.1% and 2.9% respectively. Comparison with the levels measured for the individual element, indicates that the level of co-polarisation radiation for the annular slot array is still strong, and is almost identical to that of the wire monopole array.

C. Directivity, Gain and Efficiency

Directivity, D, was measured using the technique outlined in [9]; for each measured radiation pattern, the Poynting vector is integrated over free-space and divided by the maximum level of radiation for a particular angle of (θ,ϕ).

For the annular slot array in figure 6, D was calculated to be 8.3dBi, whilst for the wire monopole array in figure 8, D was calculated to be 8.2dBi. Since the radiation patterns are almost identical, it would be reasonable to expect these two figures of D to be almost identical too.

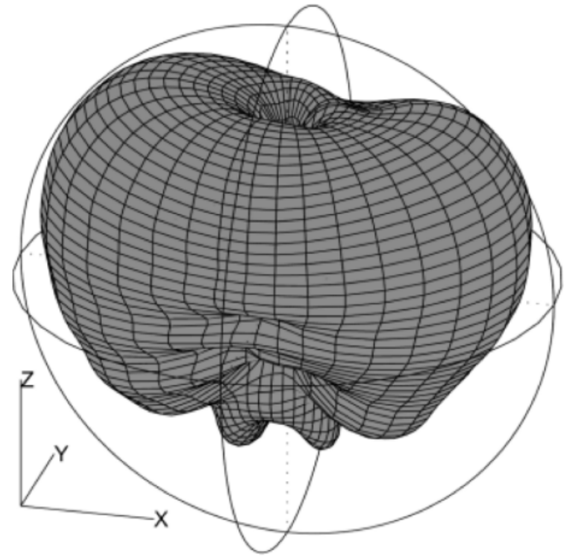

Fig. 6. Co-Polar Radiation Pattern for Annular Slot Array (dB Scale, -40dB at centre)

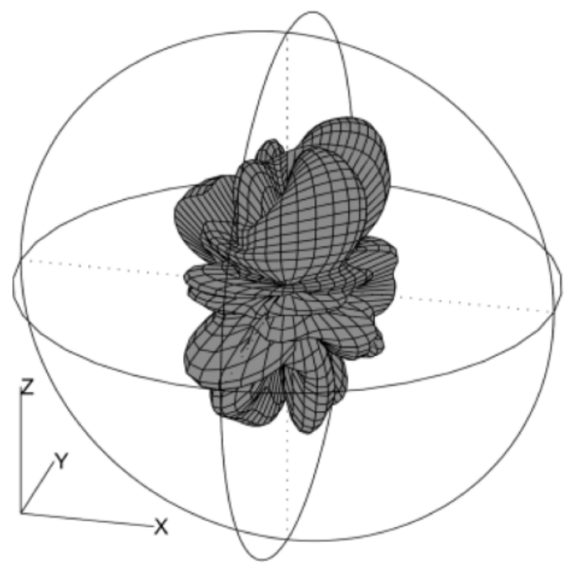

Fig. 7. Cross-Polar Radiation Pattern for Annular Slot Array (dB Scale, -40dB at centre)

Gain, G, was measured using the modified technique in [ibid]. Since this method is based upon the two-antenna approach [14], it was required that two identical arrays be built, and their input and radiation characteristics evaluated (input response and radiation patterns).

The value of gain measured had to be compensated for various mismatches and potential misalignments, which produces a 'figure of uncertainty' on the final values of G and efficiency, η [ibid]. For the annular slot array η was 71.2%±2%, whilst for the wire monopole η was 93.6%±2%.

The difference in η between the two arrays is 22.4%, which only represents about a 1.2dB drop in radiated power. Intuitively, the inclusion of a dielectric will introduce loss, and it would be reasonable for the efficiency of an antenna using a di-

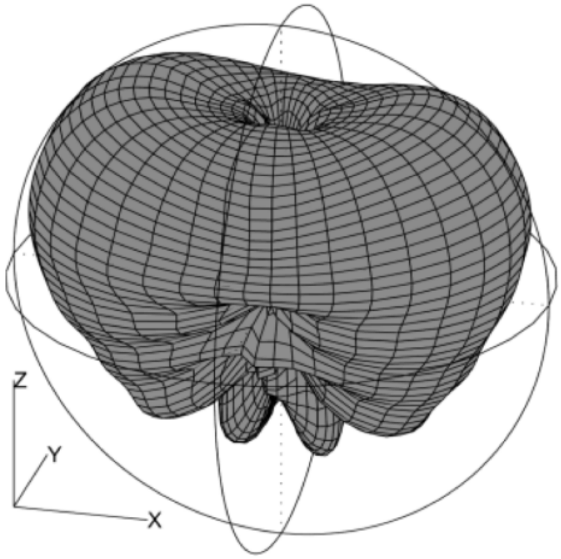

Fig. 8. Co-Polar Radiation Pattern for Wire Monopole Array Slot (dB Scale, -40dB at centre)

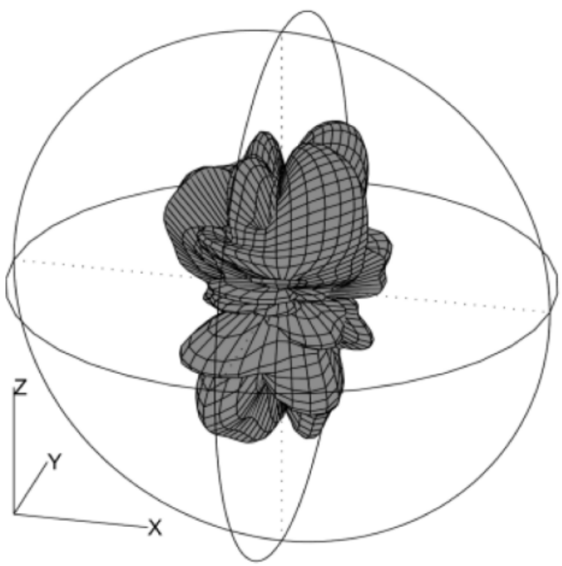

Fig. 9. Cross-Polar Radiation Pattern for Wire Monopole Array (dB Scale, -40dB at centre)

electric (i.e. the annular slot array) to be less than one which uses air (i.e. the wire monopoles array) [9].

D. Mutual Coupling

In order to investigate the variation in mutual coupling between the elements as a function of separation, the forward transmission coefficient, S_{21} was measured as the separation between the elements was varied.

Due to practical limitations, the minimum separation was limited to $0.4\lambda_0$ (how close the annular slots could be placed to one another), and the maximum to $0.7\lambda_0$ (in order to keep the elements on the aforementioned ground plane). The results from this experiment are shown in figure 10.

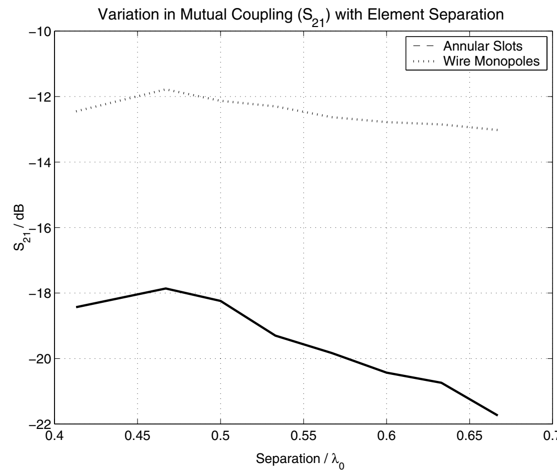

Fig. 10. Variation in Mutual Coupling with Element Separation

As can be seen from figure 10, the mutual coupling between the low-profile annular slots is, at worse, 6dB down, (for a separation of 0.47 λ_0) and at best, almost 9dB down relative to the high-profile wire monopoles (for a separation of 0.67 λ_0).

VI. Conclusions

The results presented in this paper have shown that the radiation pattern from the annular slot array is almost identical to that of the wire monopole array; the directivities only differ by 0.1dBi. The input responses indicate that the annular slot array has a much smaller instantaneous input (-10dB) bandwidth ($\approx$ 10MHz), compared to the wire monopole array (>150MHz). However, it has been suggested that this may not necessary restrict the use of such an array.

The gain of the annular slot array is 1.8dBi less than that of the wire monopole array. The efficiency of the annular slot array is also less than the wire monopole array, but in real terms this only represents a decrease of 1.2dB.

For electrically-small annular slot elements the mutual coupling is significantly less (between 6 to 9dB) than that of wire monopoles.

The analysis of these antenna arrays has looked at at input responses, radiation patters, gain, directivity, efficiency and mutual coupling which should allow for the arrays to be incorporated into an integrated RF system design. Given the size of the electrically-small planar array, it should find many applications in current and future generation mobile terminals.

Acknowledgments

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