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A Reconfigurable Electrically-Small Antenna Operating in the 'DC' Mode

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Abstract—**In this paper, an explanation of the design of an electronically tunable electrically-small antenna, operating in the 'DC' mode is presented. Although this antenna has a narrow instantaneous bandwidth, electronic tuning allows a large band to be covered whilst maintaining the same good narrow-band operational characteristics. Evaluation of the antenna's performance is provided by practical results which consider: 3-D radiation patterns, efficiencies and non-linearities.**

I. INTRODUCTION

The growth in the utilisation of the spectrum through current and future protocols has been coupled with the ever-decreasing size of the terminal. Consequently, a greater demand is placed upon the RF and antenna designers to produce an efficient RF front-end, small enough to fit inside the terminal, yet capable of working across these platforms.

Due to this size reduction, the antenna element utilised on the terminal will, by definition, have to be subject to a size reduction. However, by reducing the element's size, its input bandwidth will also reduce [1].

Traditionally, passive antenna structures have been considered for use in handsets, and have been made to work across a wide range of protocols either by being wideband [2, 3] or multi-mode [4]. Although these structures would appear to satisfy the need for providing an acceptable input response at the desired frequencies, there are several drawbacks with this approach: the majority of the methods used to generate a wide-band or multi-mode response involve increasing the physical size of the element e.g. [2–4]; since the structure is, by definition, passive there is no control of the modes generated by the antenna (hence patterns produced may vary considerably with frequency); a wide instantaneous input-bandwidth increases the need for filtering in the RF front-end.

The element proposed in this paper in an electrically-small antenna that has a radiation pattern similar to that of a wire monopole. Being electrically-small it is inherently narrowband, but has the advantage of being tuneable which allows some degree of control over the modes excited within the antenna. It is envisaged that separate Transmit (TX) and Receive (RX) elements could be used together with each being tuned independently. This tuning capability also allows the antenna to be continuously optimised to counteract environment affects that seek to detune its match with the RF front-end, thus improving system performance by several orders of magnitude relative to a passive element. Evaluation of the antennas characteristics (input response, radiation patterns, polarisation, gain, directivity and efficiency) presented in this paper will show that, across most of the tuning range of the antenna, its characteristics remain almost unchanged. Consideration is also given to non-linear components generated by using the varactor diode.

II. THE PASSIVE ELEMENT

The introduction of a shorting pin in a patch antenna has been reported to introduce an additional mode, well below the naturally resonant first-order mode of that antenna [5]. Operation in this mode has been shown to produce patterns similar to that of a wire monopole [ibid]. The electric field distribution for this mode is uniform about the whole edge of the antenna aperture, which is tantamount to a DC current path. In this paper this is referred to as the 'DC' mode.

In a similar way for an annular ring antenna, the inclusion of a shorting pin can also introduce a 'DC' mode below the modes that are naturally present. The naturally present modes in an annular slot are given from the solutions of the modified Bessel functions [6], but the resonant frequency of this 'DC' mode is a function of the size of the shorting pin, the annular slot and substrate characteristics.

Here a passive annular slot, identical to that described in [7], was fabricated on RT Duroid 5880, Figure 1. The input response, measured on an Agilent 8722ES VNA, suggested that excitation occurred at 2.03GHz with a -10dB (return-loss) bandwidth of 10MHz. Full 3-D pattern measurement and analysis showed that the radiation patterns produced from this mode in the annular slot were identical to that of a vertically-mounted wire monopole. This confirmed that this was the 'DC' mode. The most striking difference between these two different elements' characteristics is the much smaller -10dB bandwidth of the annular slot; 10MHz as opposed to >150MHz [7].

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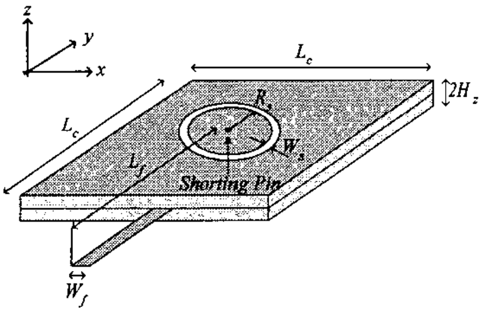


Fig. 1. Layout of Annular Slot

III. THE ACTIVE ELEMENT

Although in its 'DC' mode the annular slot's bandwidth is relatively small, it is perfectly sufficient for operation in a single channel of most current and future mobile standards, such as GSM [8], UTMS [9] and Bluetooth [10], but is insufficient to cover the entire bandwidth of any of the platforms. Therefore tuning must be considered.

A. *Varactor Diode Tuning*

A method for electronically reconfiguring a narrowband patch antenna so that its input response could cover an entire operational bandwidth (30%) was first reported by [11]. Here a similar technique is now applied to the annular slot.

In order to provide a large tuning range using a varactor diode, a large capacitance-to-voltage, $\frac{C}{V}$, ratio is required together with small parasitic affects. The Alpha Industries SMV1763-079 Hyperabrupt Junction varactor diode was used with a $\frac{C}{V}$ ratio of 1.44pF/V [12].

The varactor was connected in a reverse biased configuration between the shorting pin and ground in Figure 1, and provision for a DC bias was made. The tuning circuitry was enclosed in a small RF can of brass shim at the back of the element.

B. *Experimental Results*

Using this configuration, the input response, 3-D radiation patterns, gain, directivity, efficiency and non-linearities were measured across a range of bias voltages of the varactor.

1) Input Response: The input response, $|S_{11}|$, was measured as the reverse bias voltage, V_b was varied between 0v and 15v, Figure 2.

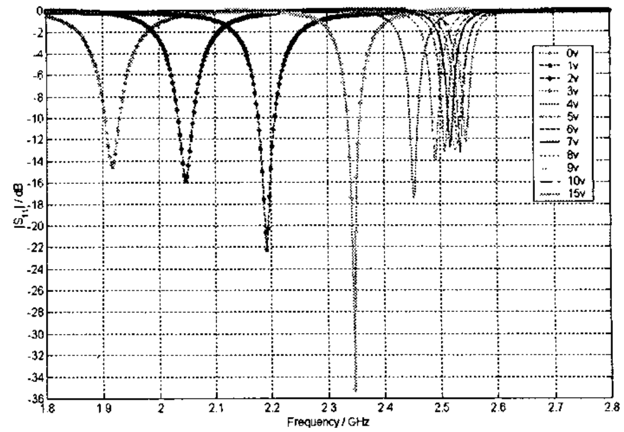


Fig. 2. Variation in Input Response with Reverse Bias Voltage

From these measurements the tuning range of the antenna is approximately 630MHz; from 1.920GHz with V_b=0v to 2.550GHz with V_b=15v, i.e 28% about 2.235GHz. As can be seen from Figure 2 the antenna remains well matched across this range, with $|S_{11}|$ <-10dB. However, the -10dB bandwidth does change slightly with bias voltage; at low bias voltages (V_b <2v) it is around 25MHz, whilst at high bias voltages (V_b >5v) it drops to around 10MHz.

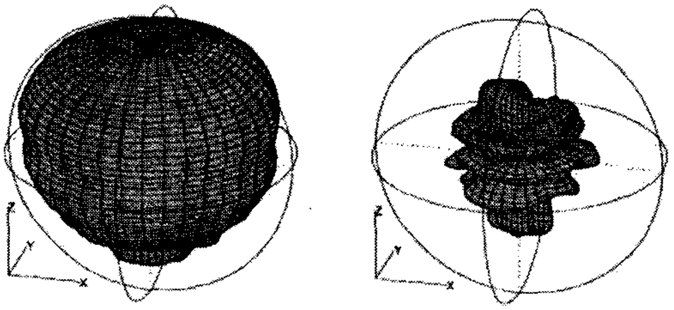
At low bias voltages the varactor is operating in its non-linear region, which has the largest change in C with respect to V [13]. It therefore follows that the largest change in the antenna's resonant frequency should be observed in this region. Referring to Figure 2 this is indeed the case. Since the varactor's losses are greater in its non-linear region it follows that the antenna's losses will be greater in this region too. This can be seen as accounting for the apparent widening of the bandwidth at low values of V_b in Figure 2.

2) Radiation Patterns: The annular slot was mounted on a circular ground plane of radius 150mm, oriented in the x-y (ϕ plane), Figure 1, and full 3-D radiation patterns measured in an anechoic chamber. Pattern measurements were performed at the same values of V_b as in the previous section.

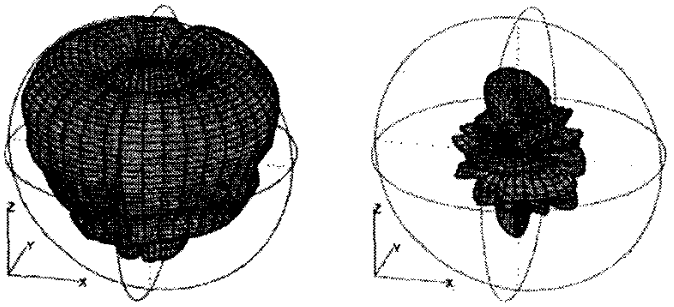
Example co- and cross-polarisation radiation patterns are shown: Figure 3(a) for V_b=0v (1.920GHz), Figure 3(b) for V_b=2v (2.195GHz) and Figure 3(c) for V_b=5v (2.495GHz) respectively. All patterns produced a null in the z-direction, with a slight variation in the beamwidth of this null being noted as V_b was increased. For all the measured radiation patterns, the level of co-polarisation excitation was always greater than 97.5%

Considering these patterns, it is clearly evident that 'DC' mode may be excited over the tuning range of the element. Comparing these patterns to those from either a wide-band [3], or indeed multi-mode element [4] shows that this tuning technique allows much more control over the radiation patterns than is the case with a passive element.

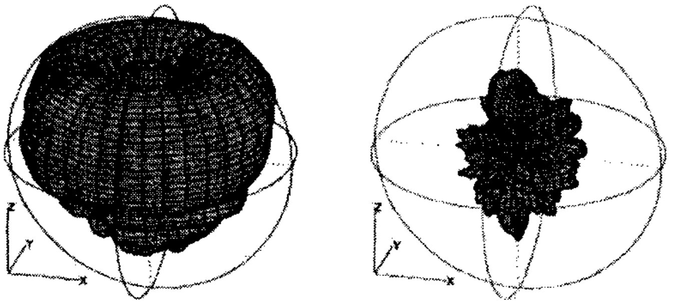
3) Directivity, Gain and Efficiency: Using the techniques outlined in [14] the directivity, gain and efficiency of the tuneable element was measured at various values of V_b. Figure 4 shows the variation in gain and directivity with bias voltage and



(a) V_b=0v Co- and Cross-polar 1.920GHz



(b) V_b=2v Co- and Cross-polar 2.195GHz



(c) V_b=5v Co- and Cross-polar 2.495GHz

Fig. 3. 3-D Radiation Patterns for Different Values of V_b. dB scale, -40dB at centre

Figure 5 shows the variation in efficiency with bias voltage.

From the radiation patterns in Figure 3, it is clear that there is little change in the overall shape of the beam as V_b is varied. It is therefore reasonable that the directivity would remain fairly constant across this range, which from Figure 4 is indeed the case.

For low V_b the gain is small and the efficiency is only 27%. As V_b is increased the gain and efficiency increases steadily, flattening out at around 2.5dBi and 45% respectively above 5v Figure 4.

Comparing the results of the gain measurements with those of the input response, it is clear that in the varactor's non-linear region, where the greatest tuning range is exhibited, the lowest gain, and hence lowest efficiency is observed. Conversely, in the varactor's linear region where the tuning range is small, the gain and efficiency are relatively constant.

The efficiency of the annular slot may be described by Equation 1:

$$\eta = \frac{P_R}{P_R + P_{FN} + P_{VD} + P_C + P_D} \tag{1}$$

Where P_R, P_{FN}, P_{VD}, P_C and P_D is the power dissipated as radiation, feed-network , varactor diode, copper and dielec-

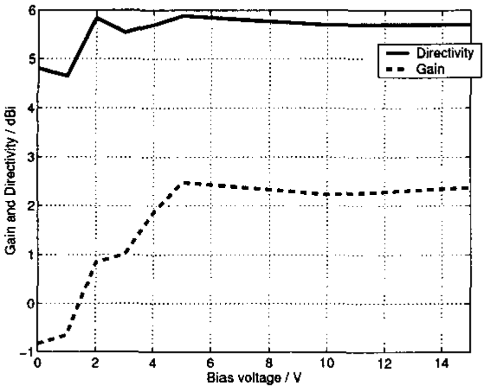


Fig. 4. Variation in Gain and Directivity Reverse Bias Voltage

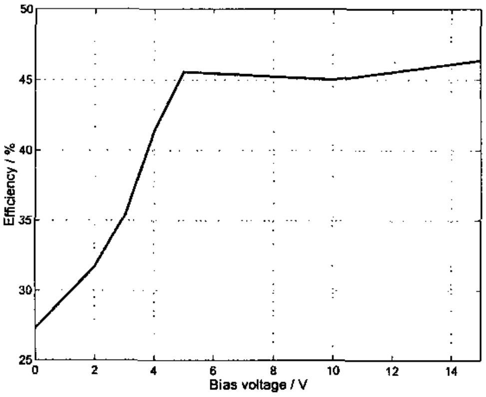


Fig. 5. Variation in Efficiency with Reverse Bias Voltage

tric losses respectively. Previous work [14] has suggested that P_C is approximately 0.03dB and, for RT Duroid 5880, P_D is approximately 1dB. Measurement of the insertion loss, L_i, of the feed network suggests that P_{FN} is approximately 1dB. P_{VD} is dependent upon V_b; measurements suggest that V_b ranges from about 2.8dB at 0v to 1.4dB at 5v.

For copper P_C is fixed, but by utilising a less lossy dielectric, such as air, P_D and P_{FN} may both be reduced and by employing a less lossy tuning mechanism, such as Micro-Electro-Mechanical-deviceS (MEMS), P_{VD} may also be reduced too. Referring to Equation 1, these changes will all increase the efficiency.

C. Measurement of Non-Linearities

The varactor diode used for tuning the slot is a non-linear device and will generate additional undesirable products that will be present in the output spectrum, the magnitude of which is dependent upon the input power level. Some of these products may be filtered out, others may not and will thus present a problem. The products which fall into this category are Third Order Intermodulation Products (IMD) and Harmonics Distortion.

For each mobile standard there are specifications on the amount of IMD and harmonic products which may be produced in- and out-of-band. For the harmonic case this is specified as both a TX and RX quantity, whilst for IMD a maximum level is only specified for TX [8–10]. The worst-case values are taken as the threshold; for IMD this is -50dBc [8] whilst for harmonics this is -30dBm [8].

A two-tone test was used to determine IMD as a function of V_b for a variety of typical power levels referenced to the Power Amplifier (PA); -20dBm to +20dBm, when the slot was used as TX. This was generated using a pair of signal generators with an offset of 10MHz feeding into a phase-matched splitter.

Figure 6 shows the results from this experiment. IMD products under 0dBm were in the noise floor over the entire range of V_b, and to aid clarity have been omitted from the graph. It can be seen that when V_b <1.5v all power levels produce unacceptable levels of IMD. Increasing V_b to 2v results in only +20dB producing too much IMD, whilst increasing V_b >3v causes the IMD requirement to be met for all power levels. Therefore, by limiting V_b such that it's always >3v the IMD requirement will be satisfied, however this has the consequence that the tuning range is limited to 148MHz (2.347-2.495GHz).

Second ($2f$) and third ($3f$) harmonic distortion was measured as a function of V_b for a variety of typical output power levels referenced to the PA; -20dBm to +20dBm, when the slot was used as TX and RX. The distance between the TX/RX was kept to 200mm.

Figure 7 shows the results from this experiment when the slot is used as TX. $2f$ and $3f$ for -20dBm, and $3f$ for -10dB were in the noise floor over the entire range of V_b, and have been omitted from Figure 7. As can be seen the harmonics produced are just below the threshold level of -30dBm over the entire range of V_b. However, for V_b <2v some caution does need to be exercised at the higher power levels (>+10dBm) since the margin between the measurements and the threshold is very small and could easily be breached by, say, spurious power fluctuations at the PA.

Like the results from Gain and Efficiency, these non-linearity measurements suggest that in the non-linear region of the varactor (V_b <3v), the products generated may be problematic for most platforms. However outside this region (V_b >3v) these products are tolerable, and thus the tuneable annular slot's use in a system is certainly not precluded.

It is envisaged that with the development of MEMS technology, less lossy tuning devices will become available. Provided that these devices also yield high $\frac{C}{V}$ a hybrid combination of MEMS/varactor based tuning could provide a more efficient

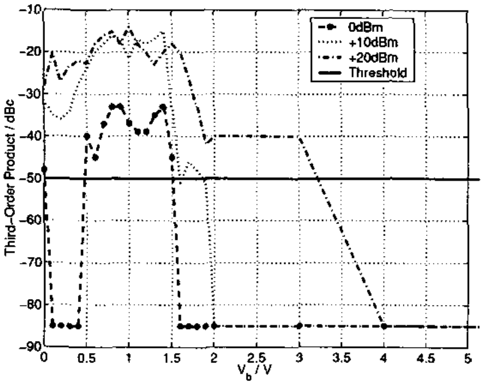


Fig. 6. Variation in IMD with Bias Voltage (TX)

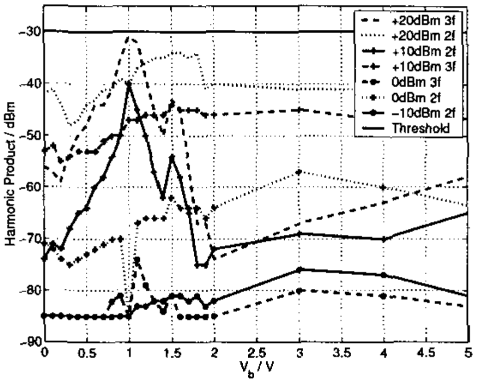


Fig. 7. Variation in Second and Third Harmonics with Bias Voltage (RX)

and linear course/fine tuning arrangement.

IV. CONCLUSIONS

By shunting a hyperabrupt junction varactor diode across the aperture of an electrically-small, narrowband annular slot antenna operating in its 'DC' mode, its resonant frequency was able to be tuned across a range of 620MHz (1.920 to 2.550GHz, i.e. 28%).

It was shown that across this range it was possible to control the mode of excitation, (hence the radiation patterns) and the directivity remained fairly constant at around 5.5dBi. However, in the varactor's non-linear region both gain and efficiency were low, and at high power levels unacceptable IMD was produced. Operating the varactor more in its linear region helped to counter these effects, and hence good operation; efficiency greater than 45% and non-linearities well within specified limits for power levels up to +20dBm may be achieved across a 100MHz band.

By manufacturing the antenna on a less lossy dielectric, such as air, and utilising MEMS technology for tuning, it will be possible to tune over a larger range with better antenna characteristics (i.e. higher gain, efficiency, and lower non-linearities) being realised.

For simplicity the work presented here considered the tuneable antenna's performance in isolation of the RF-front end. However, not only will the varactor produce non-linearities, but the PA in the RF front-end will as well, and as such future work will consider the system's linearities as a whole.

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