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Increasing the Wireless Power Transfer (WPT) Link Efficiency by High Gain Helices

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Abstract — In this study we compare helix and patch array antenna characteristics for wireless power transfer (WPT). It will be shown that the helices offer higher link efficiency for a similar beam scanning limit compared to patch antenna elements. We provide 12-by-12 element planar array results for both cases at different element spacings. The frequency band of interest is ISM 2.4-2.5GHz and we do the comparisons in this range. It is concluded that helix elements, when used as an array, offer significant improvements for wireless power link efficiency, whilst also offering a reasonable beam scanning range.

Keywords — antennas, helix, patch, phased arrays, WPT, MPT.

I. INTRODUCTION

Transferring electrical power without connected wires or cables has been sought after, for a long time. Many studies have been done to analyze transferring power through radio waves. WPT is possible in different ways. For short ranges it is viable through Inductive, capacitive and magnetodynamic coupling. Resonant inductive coupling is used for the mid-range power transmission, and for long-range purposes microwave and light wave technologies are the preferable approaches. Our study is concentrated on microwave power transmission (MPT). A MPT system includes four integral parts as power amplifier, transmit antenna, receive antenna, and rectifying circuit, which together with the antenna element is called a Rectenna. The aim is to increase the power efficiency in each section to have an efficient MPT system. Transmitter and receiver antenna characteristics can highly affect the total system efficiency. Depending on the application, different types of antennas may be used. Phased array antennas with retrodirective approach has attracted much attention in recent years [1]. For sure, the aperture size, spacing between array elements and the type and gain of the elements are important factors which each play a role in affecting the link efficiency. Brown [2] in 1974 provided useful design curves for calculating the WPT link efficiency in the near and far field ranges. Shinohara et al [3] investigated the antenna beam shape effects on the received power. In [4] a focused microstrip antenna array was proposed to increase the link efficiency. A comprehensive study of array designs for long-distance wireless power transmission has been provided in [5].

To evaluate how the arrays composed of high gain elements might increase the efficiency of WPT link, we compare the realized gain of 144-element helix and patch arrays at different inter element spacings. The maximum scan angle capability of

each array is identified by the limit at which the first appearing grating lobe magnitude is equal to the first side lobe level.

II. HELIX AND PATCH DESIGNS

Helix and patch elements are shown in Fig. 1. Fig. 1(a) depicts the helix structure and its dimensions. It has 7 turns with the vertical dimension of 19cm and aperture diameter of 4.6cm. This helix is operating in axial mode, and radiates a right hand circular polarized (RHCP) wave. In Fig. 2(b) we can see the probe-fed patch element. This patch antenna was designed on a RT-Duriod 5880 substrate with thickness of 0.254mm. The return loss of helix and patch antennas is depicted in Fig. 2.

Fig. 1. Helix (a) and patch antenna (b) dimensions.

The impedance bandwidth of helix antenna quite large, but this is not very significant for MPT, as we are only interested in radiating at a single frequency in the frequency range of 2.4-2.5GHz. The curve shows the helix S11 is lower than -10dB in the desired frequency band. From Fig. 2. We see that the designed patch antenna has a resonance at 2.47GHz with an impedance bandwidth of around 30MHz.

Fig. 2. The S11 of patch and helix antennas.

III. HELIX AND PATCH RADIATION PATTERNS

In this section, we draw a comparison between the radiation patterns of helix and patch elements. In Fig. 3. The radiation patterns of helix and patch elements are shown in one plane. As we are mostly interested in gain comparison, the pattern in another plane has not been included. It is seen that the helix element has 12.4dBi realized gain at 2.47GHz while the patch element produces a realized gain of 6.8dBi at this frequency.

Fig. 3. Radiation patterns of helix and patch antennas.

We know that the helix element here, is a traveling wave antenna with its gain dependent on the number of turns, or in other words on its length. The gain of the designed helix is 5.6dB higher than the patch element and this is enough for us to do the comparison between arrays composed of these elements in terms of WPT link efficiency. We notice from Fig. 3. that the half power beam width (HPBW) of helix and patch elements is around 30 and 90 degrees respectively. We know that the scanning ability of a phased array antenna, is dependent on the spacing between its elements which dictates appearance of grating lobes. In next section, we do a comparison about gain and scanning capabilities of the mentioned antennas.

IV. TEST RESULTS

At first, we compare the element-to-element links of patch and helix antennas. This comparison is done at the same distances ($d=100$ cm) between TX and RX antennas with transmit power of 0.5W for both cases. Fig. 4. Illustrates the patch and helix links. The Transmit and receive antennas are same in each case. The receive antennas are both loaded with 50 ohm resistors. We are interested to compare the received power by these loads. Fig. 5 depicts the received power at the terminal of helix and patch vs frequency. The simulation was done by CST [6] software. It is apparent that in the helix and patch links, the received power at 2.47GHz is 0.0104w and 0.008w respectively. It means in the helix link case, the received power is 13 times more than the patch link. This is very close to the value calculated by the Friis formula, which is 13.2. In the following section, we compare array antenna characteristics of these elements.

Fig. 4. Helix and patch links in CST.

Fig. 5. Power received by patch and helix elements.

A double helix link budget test was done in the QUB's anechoic antenna chamber at the RX to TX distance of $d=5.6$ m and $f=32.5$ GHz. Using a power meter the power level of -3.73 dBm was measured at the connector feeding the transmit antenna. Then, we used the power meter to measure the received power by the second helix antenna. The value read was -34.4 dBm which is very close to the -34.1 dBm calculated by Friis formula for antennas with 12.5 dBi gain. The picture of link test in anechoic chamber is shown in Fig. 6.

Fig. 6. Double helix antennas under test for received power.

V. HELIX AND PATCH ARRAYS, CHARACTERISTICS

In section IV, a comparison was done between helix-to-helix and patch-to-patch scenarios in terms of link efficiency. We noticed that the helix link provides 13 times better power delivery. However, when these elements are populated in an array form, they will show different characteristics rather than when isolated. This is because of the gain difference between these elements. We can divide high gain elements in 2 categories, one with large and the other with small physical aperture. In fact, in the large aperture high gain elements, the gain is directly dependent on the physical aperture size while in small aperture elements like helices or dielectric rod antennas the gain is dependent on the length, not the physical aperture. It means for smaller aperture high gain elements, it is possible to have arrays with shorter inter element spacing. Although, we should bear in mind that the array characteristics depend on the electrical aperture size too. In other words, as long as the electrical aperture of neighboring elements overlap, the array gain will not reach its maximum. The antenna electrical aperture size and directivity are dependent on each other by the following formula:

$$(1) \quad A_e = \frac{\lambda^2}{4\pi} D$$

Where A_e is the electrical aperture area, D is the directivity of array antenna and λ is wavelength. This formula shows a linear relationship between antenna directivity and electrical aperture. In fact, the larger the directivity, the larger the electrical aperture would be. Therefore, for an array of high gain elements, the inter element spacing must be large enough so the array can deliver its maximum potential gain. But, this causes the problem of grating lobes for scanned arrays. Here we intend to compare patch and helix arrays in terms of array gains and beam steering capabilities. We set the criterion for maximum scan to an angle

where the grating lobes' magnitudes are lower than the first side lobes levels (SLL). As we do not consider any amplitude taper, the first SLL would be 13.5dB lower than the main beam.

VI. GAIN AND SCAN ANGLE LIMIT COMPARISON

To compare helix (as high gain element) and patch (as low gain element) arrays, we consider a 144-element (12-by-12) planar array with different element spacings. Table. 1 includes the data about this comparison. This table shows the information about the helix array gain (HAG), helix array scan limit (HASL), patch array gain (PAG) and patch array scan limit (PASL) capabilities over different element spacings. It is apparent that in the patch array case, for spacings beyond 12cm, the grating lobe magnitude is higher than the side lobe level even in zero scan conditions. As we know for spacings higher than λ the grating lobes will appear even in zero scan or broadside radiation situation. We will assume, for a WPT transmit array, that a 20 degrees scan limit is acceptable. From this assumption, Table 1 shows that the 144 element patch array has a gain of 30.4 dBi, whereas the helix array delivers 32.5 dBi realized gain. This 2.1 dB increase in gain for the helix array equates to a 62% better link efficiency contribution for the helix array on the transmit side. This shows that the helix array would offer a very significant improvement in MPT links, requiring beam scanning capability. The better scan capabilities of the helix array compared to the patch array, is due to the narrower beamwidth patterns of the helix elements. As the grating lobe magnitude is multiplied by the high gain element pattern, the overall radiation pattern of the array produces lower grating lobe levels compared to the low gain element case which has a flatter gain value over its radiation angle.

Table.1. 144-element helix and patch arrays results.

Spacing(cm)	HAG(dBi)	HASL(deg)	PAG(dBi)	PASL(deg)
7	28.1	90	27.5	80
8	29.2	60	28.6	50
9	30.2	46	29.6	34
10	31.1	30	30.4	20
11	32	27	31	8
12	31.6	25	28	0
13	31.8	22	27.9	0
14	32.5	20	28.5	0
15	33.4	18	28.8	0
16	34.1	14	29	0

VII. CONCLUSION

A comparison has been carried out between high gain helix and patch phased array antennas, in terms of gain and scan limits. The study showed that the array antenna composed of high gain helices, delivers higher gain within the same scan limits comparing to a patch array with a similar aperture area. This means, helix elements are suitable candidates for high-efficiency moving-object MPT.

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