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Low-profile Slot Antenna integrated with a thin polymer non-metallic battery

Michael Woods, John C. Batchelor

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Michael Woods

School of Physical Sciences and Engineering
University of Kent
Canterbury, UK
maw44@kent.ac.uk

Dr. John Batchelor

School of Engineering
University of Kent
Canterbury, UK
j.c.batchelor@kent.ac.uk

Abstract— In this study, a low-profile slot antenna was designed with the purpose of having the ability to be integrated into the structure of a layered non-metallic polymer battery. Using a set of previous published parameters for the slot antenna, the structure was modified in the CST Microwave Studio package in order to suit the needs of a battery substrate. A second slotted ground plane was attached beneath the antenna. The composite substrate and ground planes replicates the layered structure of a plastic planar battery, with the intention of reducing the size of the slots on the bottom plane which also acts as a battery terminal. The effect of the slot size and tan δ value of the substrate on the radiation patterns was also investigated.

Keywords—antenna, battery, polymer, non-metallic

I. INTRODUCTION

Antennas and batteries are two widely used components in the field of wireless electronics, with some of the more well-known applications being in mobile devices [1],[2],[3] and sensors [4]. Several issues however arise when using these two components together. Both a battery and an antenna are often seen as relatively bulky components meaning they are challenging to fit within compact device envelopes. Furthermore, it is well known that antennas are subject to mismatch and dramatic efficiency reduction in the presence of proximal metal planes. Conventionally, batteries are wrapped in a hermetic metal seal, meaning there must be a separation from the antenna(s) to avoid degradation in efficiency.

We are proposing the idea of a fully integrated battery-antenna system. The design will be extremely thin and lightweight, while aiming to maintain acceptable antenna input match and radiation efficiency. With this integrated design, we have considered low-profile applications which include sensors, home monitoring systems and lightweight portable radio for use in the military. There is also interest in using thin integrated antenna-batteries for security purposes.

A typical modern lithium ion battery consists of a negative electrode (anode) and positive electrode (cathode) separated by an electrolyte solution, which allows the transfer of lithium ions between the two electrodes [5]. Either side of these electrodes is a metallic current collector.

A key feature for this new design is that the new battery must be non-metallic (no metal seal or metallic current collectors). Therefore, the replacement material must be highly conductive for the battery to maintain its performance. We propose using conducting polymers for this purpose. Various polymers have been used in batteries previously, and have demonstrated good conductivity values. The first conducting polymer was discovered by Shirakawa in 1977 in polyacetylene [6]. Still today regarded as one of the most conductive of all polymers in its doped form, values of up to 10^5 S/cm have even been reported [7]. Other commonly used polymer electrolytes include polyaniline which has demonstrated high conductivity values of as much as 58 S/cm for a pellet synthesised with H_3PO_4 and up to 500 S/cm for stretched polyaniline films in the stretching direction [8]. PEDOT:PSS, a copolymer, has shown values of over 3000 S/cm when treated with sulphuric acid [9]. With some polymer electrolytes showing conductivities close to that of metals, they are a very good alternative for a non-metallic battery.

The antenna design is based on a planar layered battery design to use for our integrated antenna, similar to that used by Nagatomo [10]. Fig. 1 shows the battery design proposed in this case.
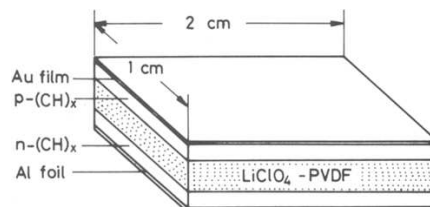

Fig. 1: Planar solid state plastic battery design proposed by Nagatomo [10].

We treat the polymer films and electrolyte as the antenna substrate, while the metallic films of the battery would essentially be the conducting layers containing a slot antenna.

II. METHODOLOGY AND RESULTS

A. Starting structure

The CST (Computer Simulation Technology) Microwave Studio package transient solver was used to perform all of the simulations in this study. As the aim was to simulate a wideband antenna, the starting structure was based on a CPW-fed slot dipole by Nithisopa [11] which was developed to function on a substrate structure close to the battery design proposed by Nagatomo. The slot antenna consisted of two asymmetric slots cut into an upper plane of metal. The thickness of the substrate was 1.575mm, with a relative dielectric constant (ε_r) of 2.2. The ground plane was 0.018mm thick. The slots used for the feed (W1) and the gap between the two feed slots (W2) were 0.5mm and 2.4mm respectively. The length of the CPW feed line (H3) was 23mm. The left slot had a height (H1) and width (L1) of 4.1mm and 33.8mm. The right slot had a height (H2) and width (L2) of 7.8mm and 43.8mm. Fig. 2 shows the dimensions and S_{11} results for this design:
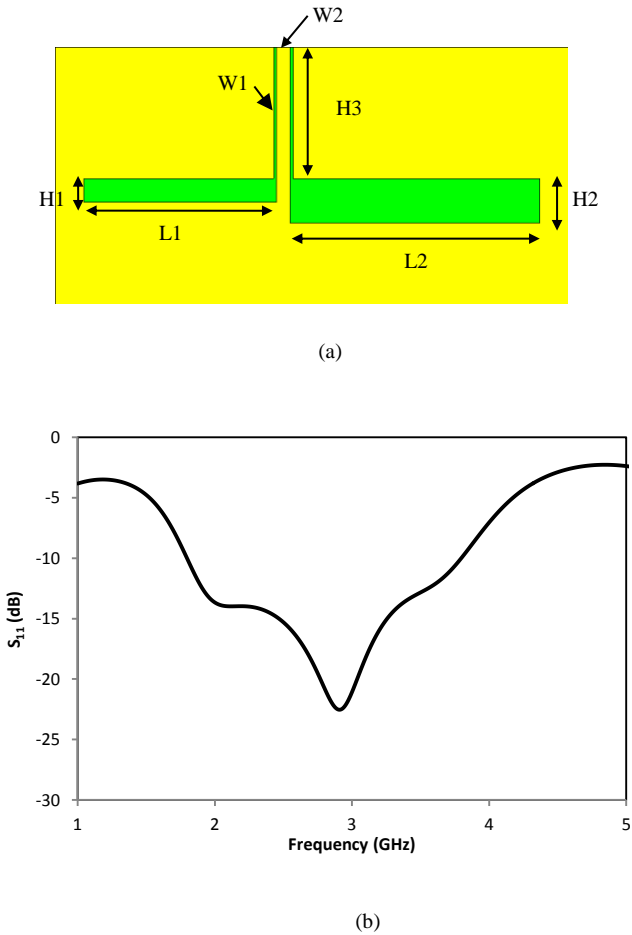
The -10dB fractional bandwidth was calculated to be about 70% and the antenna simulated total efficiency was -0.38dB with a gain of 5.7dBi.

B. New structure

To create a low profile structure with low surface area, the dipole length was reduced. End caps were added to each slot. For the left slot, the cap had a height (H4) of 18.1mm and a width (W3) of 7mm. The cap at the end of the right slot was of height (H5) 18mm and width (W4) 24mm. These values were obtained via a parameter sweep on CST to select the optimum bandwidth. The modified structure showed an improvement in bandwidth of 85% and a total efficiency of -0.47dB was observed along with a gain of 5.4dB, which compares well with the original structure. It should be noted that our modified designs use the original frequency range chosen by that of Nithisopa, purely due to the fact that there is no specific application in mind at this stage. Fig. 3 shows the dimensions and S_{11} results for the end loaded design.

(a)

(b)

Fig. 2: (a) Initial dimensions for CPW-fed slot antenna and (b) Simulated S_{11}. Ground conductivity = 5.8 x 10^7 S/m.
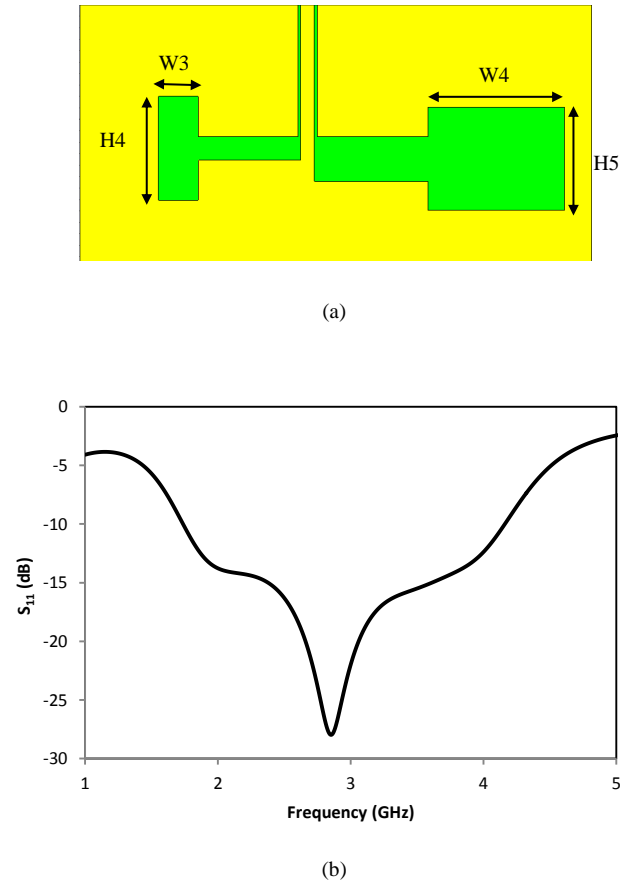

(a)

(b)

Fig. 3: (a) Modified slot antenna with end caps and (b) Simulated S_{11}. Ground conductivity = 5.8 x 10^7 S/m.

C. Conductivity

Conducting polymer conductivities are lower than bulk copper which was used in the original design. To assess the effect of reducing conductivity, a parameter sweep was performed in order to see the effect that conductivity of the ground plane had upon the bandwidth of the structure. In this case, the parameter "n" was defined as 5.8×10^n S/m. It was observed that the antenna maintained bandwidth for conductivities down to that of 5.8×10^2 S/m whilst lower values resulted in a significant loss of bandwidth. The lowest conductivity value for the conducting plane at which the bandwidth was maintained is closer to conductivity values quoted for several polymer electrolytes, such as polyaniline (10×10^2 S/m in some cases [12]).

D. Lower ground plane

The next stage of the investigation required the addition of a second ground plane, representing the lower battery terminal. This lower ground plane was added progressively as illustrated in Fig. 4. The intention was to cover as much of the base as possible with conductor, while retaining a good bandwidth. We wished to find the minimum rectangular slot size for the ground plane that gave sufficient efficiency and bandwidth, as opposed to designing a more complex slot configuration that would perhaps yield better results at the expense of design time.

The process began by inserting a conducting layer of 0.018mm thickness in stages from the lower edge of the bottom layer. Once again, a parameter sweep was conducted, with the width of the metal layer referred to as "g" being the varying factor.

(a) Fractional Bandwidth = 95%   Efficiency = -5.074 dB

(b) Fractional Bandwidth = 87%   Efficiency = -5.088 dB

(c) Fractional Bandwidth = 93%   Efficiency = -5.199 dB

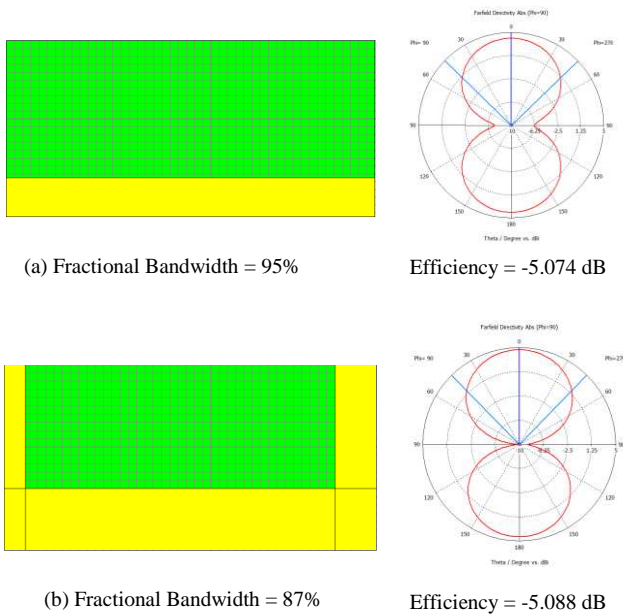(d) Fractional Bandwidth = 86%   Efficiency = -4.588 dB

Fig. 4: a-d showing addition of second ground plane to the modified antenna structure.

The metal was inserted in stages with one sheet added at a time, to gain a better insight into how the bandwidth would change with each parameter. As a greater amount of the surface was covered and enclosed with the conducting film, a structure closer to that of an all-plastic solid state battery was obtained. At this point, further parameter sweeps were conducted, mainly for parameters "g" and "l" to ascertain the maximum extent of lower battery terminal area before the antenna performance is lost. By keeping parameter "l" constant, parameter "g" was increased, enclosing the slots seen in the middle of the structure. TABLE I shows the effect of increasing parameter "g" upon the bandwidth of the structure, with all other parameters kept constant.

TABLE I
EFFECT OF INCREASED HEIGHT OF GROUND PLANE UPON PERCENTAGE BANDWIDTH

Width (mm)	Lower frequency (GHz)	Upper frequency (GHz)	Centre frequency (GHz)	Fractional Bandwidth
5	1.38	3.81	2.60	94%
10	1.40	3.80	2.60	93%
15	1.41	3.61	2.50	88%
20	1.35	3.72	2.50	95%
25	2.75	3.6	3.19	27%

By performing these multiple simulations, it was deduced that the slot on the bottom ground plane located directly underneath the CPW feed was necessary to avoid total

mismatch (S_{11} > -10dB). However, there was no requirement for a slot beneath the dipole to achieve an input bandwidth of 27% which could still be considered wideband. Fig. 5 shows the design in which the slot beneath the dipole is removed.
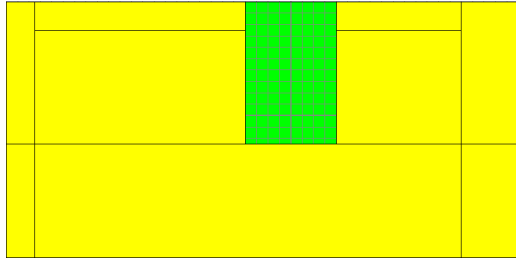

Fig. 5: Lower ground plane with slot beneath CPW feed.

E. Design modification to replicate battery parameters

The next parameter to investigate is the thickness of the substrate. In Nagatomo's proposed polyacetylene battery, the total structure thickness was about 0.4mm. Around 0.3mm of this consisted of the polyacetylene and electrolyte layers with the remaining thickness due to the metallic films deposited on the top and the bottom of the structure. Therefore, to obtain an antenna design closer to these proposed batteries, the thickness of the substrate was reduced from 1.575mm to 0.3mm. To assess whether the antenna would still function well with anode/cathode conductivity values closer to metal, in this case, we used a value of 3000S/cm, which is equivalent to that demonstrated by PEDOT:PSS. It is also necessary to know the permittivity and conductivity of the electrolyte substrate.

The ionic conductivity of the substrate in this case was taken from a study of PVDF-HFP/PMMA using lithium perchlorate as the salt, along with varying concentrations of propylene carbonate [13]. This value was of the order of 10^{-3} S/cm. Based on a study of PVDF permittivity [14], it has been calculated that ε_r is about 3 at 1MHz, which was used as an initial assumption. It was found that using these parameters, bandwidths of around 66% were achieved. With the lower ground plane, total efficiencies of around -3.7dB with gains of around 1.7dB were obtained.

F. Radiation patterns

The radiation patterns for the antenna were simulated for the design with the lower ground plane as shown in Fig.4(d). The effect of changing the width of the centre slot beneath the dipole upon the far fields was observed for two frequencies in the S_{11} matched bandwidth. In particular, TABLE II shows the gain and efficiency results for this analysis.

TABLE II
EFFECT OF SLOT WIDTH UPON ANTENNA GAIN AT THE FREQUENCIES 2.3GHZ AND 3.4GHZ

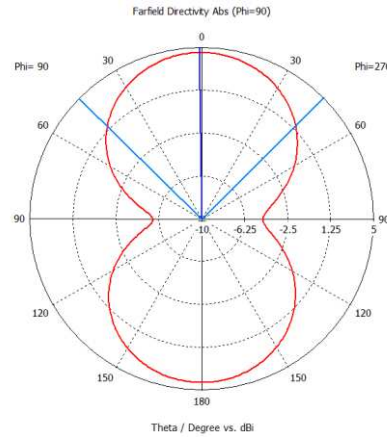| Width of slot (mm)	Antenna gain (dBi) at 2.3GHz	Total efficiency (dB) at 2.3GHz	Antenna gain (dBi) at 3.4GHz	Total efficiency (dB) at 3.4GHz
16	2.3	-2.9	4.1	-1.9
11	2.3	-2.9	4.2	-1.8
6	1.5	-3.7	4.2	-2.0
1	0.2	-4.8	2.6	-3.3

Fig. 6: Radiation pattern for the slot width of 1mm at 2.3GHz

The variation in antenna gain with substrate loss was also of interest owing to the high frequency loss of the electrolyte material. A study was performed by increasing the tan δ value for the antenna substrate and observing the changes in the far field patterns at two frequencies within the S_{11} bandwidth. In this case, the lower ground plane slot width beneath the dipole was kept constant at 1mm. TABLE III shows the change in gain as a result of the substrate loss.

TABLE III
EFFECT OF SUBSTRATE LOSS UPON ANTENNA GAIN AT THE FREQUENCIES 2.6GHZ AND 3.7GHZ

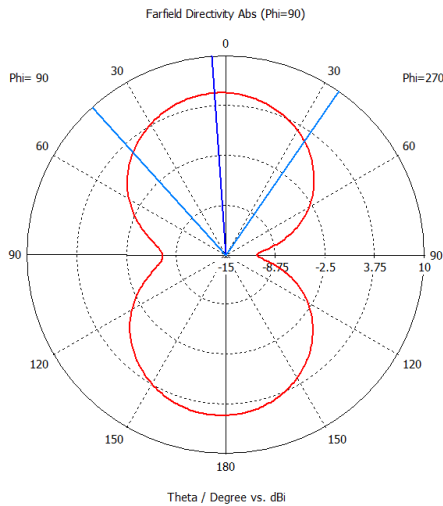| Tan δ	Antenna gain (dB) at 2.6GHz	Efficiency (dB) at 2.6 GHz	Antenna gain (dB) at 3.7GHz	Efficiency (dB) at 3.7GHz
0.0009	3.3	-2.2	3.0	-2.7
0.009	3.2	-2.3	3.0	-2.7
0.09	2.6	-2.9	2.7	-3.1
0.9	-1.8	-7.3	-3.0	-8.8

Fig. 7: Radiation pattern for the loss tangent of 0.09 at 3.7GHz

III. Conclusion

Simulation has indicated the possibility to create a fully integrated battery-antenna system in the microwave band, based on polymer battery material properties taken from the literature. By creating a structure that is wideband and shows reasonable gain and efficiency results even with relatively lossy substrates, close to that of a planar polymer battery, an antenna with reasonable efficiency can be designed.

Research into conducting polymers shows that we can still achieve high conductivities, which are not far off that of metals. This shows promise in terms of creating a non-metallic battery. Results showed that the antenna could maintain its performance down to a value of 5.8×10^2 S/m, which covers a range of polymer electrolytes that possess conductivities around this value and higher.

By adding a second ground plane to the bottom of the structure, we were able to see how the antenna performed with two current collectors. Once again, good bandwidth values were obtained with slots cut into the bottom current collector. It was observed that the slot beneath the feed was necessary for the antenna to function, but a large proportion of the slot below the dipole could be taken away.

To simulate conditions as close as possible to an actual polymer battery, the substrate thickness was set to 0.3mm and given an ionic conductivity value of 10^{-3} S/cm. The relative permittivity of the electrolyte substrate was assumed to be 3. Good bandwidth and reasonable gain was obtained with values of 66% and 1.7dB respectively.

The far field dependence on the width of the lower ground plane slot was assessed as well as the loss tangent (tan δ) value of the substrate. The trend for slot width showed that as it was reduced, the gain and total efficiency decreased as would be expected. Similarly, as the loss tangent was increased, a reduction in both gain and total efficiency occurred, with a drastic reduction in performance shown at a tan δ value of 0.9.

IV. Acknowledgment

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