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Printed Decoupled Dual-Antenna Array On-Package for Small Wirelessly-powered Battery-less Device

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Abstract—A printed compact antenna array for small wirelessly powered device operating at 900MHz is proposed. The prototype is developed by printing antenna pattern on a 0.1 mm thick flexible substrate and folding the printed sheet into a rectangular volume measuring 33 mm by 56 mm by 12 mm. The edge-to-edge distance between array elements is only 0.078λ . An isolation structure is added to minimize the coupling between the elements. Measurement results show a -27 dB minimum coupling between the elements, which yields significant gain improvement up to 3.6 dB and radiation efficiency improvement up to 28 % over the design without isolation structure. When integrated with rectifier circuits, the proposed design also demonstrates superior performance by generating more DC power. The results have shown the proposed work to be a feasible solution of implementing antenna array for small device to enhance of RF power receiving capability with high compactness.

Index Terms—RF energy harvesting, isolation enhancement, antenna on package, rectenna array

I. INTRODUCTION

Low power-consumption battery-less devices powered by far-field wireless power have evolved from simple UHF RFID tags to multi-functional devices like wireless sensor sensor[1][2]. Such devices are gaining wide research interest because of their potential to be deployed for long-term sensing in various applications, such as embedded sensor for infrastructure health monitoring and medical application. Thus light-weight and small size are usually required for the ease of deployment.

For such device, antenna usually occupies significant space and is miniaturized at the cost of efficiency and bandwidth. To efficiently utilize the small space available, antenna on-package has been proposed to explore the 3D space around the device so that the internal space is freed up to house the electronic circuits [3][4]. But with single small antenna, the power received was limited, which limits the communication range of the device from the transmitter/reader.

Rectenna array has been shown to be effective to enhance the power receiving capability by using multiple antennas. Various designs were proposed for different applications[5] but are usually too bulky to be integrated into a small device. Hence the

motivation of this work is to come out with a feasible solution of antenna array implementation to enhance power receiving capability and yet maintain small size at the same time.

The proposed antenna array consists of two monopoles operating at 900MHz. The size of the package is 12 mm by 56 mm by 35 mm ($0.1\lambda \times 0.17\lambda \times 0.04\lambda$) with the largest dimension only 0.2λ . Each array element is fed through inductive coupling by planar loop on PCB. The prototype is fabricated by printing silver ink on a 0.1 mm thick PET sheet using screen printing, folded into rectangular case and fixed on 1.6mm FR4 PCB with normal glue.

Compact antenna array usually suffers from efficiency degradation because of inter-coupling effect between array elements when antennas get too close[6]. In this work, the edge-to-edge distance between array elements is only 0.078λ . So an isolation structure is introduced to reduce the inter-coupling [7]. To investigate the impact of the isolation structure, a reference design without isolation structure is also designed and fabricated. Measurement results show that the introduction of isolation structure reduces level of coupling markedly, which significantly improves the gain and radiation efficiency of array element. Then the RF receiving capability of the array was evaluated with the array connected to rectifier circuits. The results also show that the proposed design can supply more DC power to the load with compact volume.

This letter is organized as follows: Section II elaborates the design of the array. Section III discusses the design of isolation structure. The radiation performance of the two designs is presented in Section IV. And finally, Section V concludes the letter.

II. ANTENNA ARRAY DESIGN

A. Design of Array

As presented in Fig. 1(a), the array is constructed by positioning two 3D meandered monopoles symmetrically on either side of the folded ground. Each monopole is fed through inductive coupling by planar loop on PCB. To de-couple the two elements, an isolation structure is inserted in between as shown in Fig. 1(b). Fig. 1(c) and Fig. 1(d) show the planar design of the proposed design and reference design without the isolation structure.

Since the input impedance of RF-DC rectifier circuit is typically capacitive [8], using planar loop to feed the monopole makes the input impedance of antenna inductive and easily tunable—the input impedance can be tuned by varying the dimension of the loop and distance between loop and antenna[9]. Fig. 1(e) shows the design of feeding loops on PCB.

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Since this work focuses on the design of antenna array, the dimension of the loop is conveniently specified and can always be tuned to match to a specific rectifier circuit.

B. Input Impedance

The input impedance of antenna array was measured using method proposed in [10] with two differential probes and 4-port Vector Network Analyzer (VNA). Then the input impedance is calculated from the measured S-parameters. Fig. 2 shows the measured and simulated input impedance of each port of the proposed design. The measured result agrees well with simulation in general. A slight discrepancy between port 1 and port 2 is noted for measurement result, which could be due to the imperfect symmetry during the fabrication. But the errors are too small to affect any conclusions drawn in this letter.

III. DESIGN OF ISOLATION COMPONENT

A. Calculation of Coupling

The input impedance of each port of array is highly inductive (Fig. 2). When connecting to measurement instrument with 50Ω port impedance, most power is reflected and hence S_{21} (S_{12}) obtained is quite low which does not reflect the level of coupling between the two ports when both ports are matched to loads connected (rectifier circuits) in actual case. In this work, this very level of coupling is calculated from the S matrix of the array.

As shown in Fig. 3, the antenna array is represented by 2-port network in the middle. Γ_1 and Γ_2 are the reflection coefficients of the loads 1 and 2. Γ_{in} and Γ_{out} are the reflection coefficient looking into port 1 and port 2 of the array. Assuming Port 1 is connected to source, the level of coupling can be expressed by the ratio between power consumed by load 2 (P_2) and the power that goes into port 1 (P_{in}):

$$\frac{P_2}{P_{in}} = \frac{|S_{21}|^2(1-|\Gamma_2|^2)}{(1-|\Gamma_{in}|^2)|1-S_{22}\Gamma_2|^2} \quad (1)$$

The level of coupling of interest (denoted as CPL) is when port 1 and port 2 are simultaneously matched, i.e. $\Gamma_1 = \Gamma_{in}^*$ and $\Gamma_2 = \Gamma_{out}^*$. The problem is then reduced to finding Γ_1 and Γ_2 to achieve conjugate matching for both ports, and solving procedure is readily available in textbook[11]. With Γ_1 and Γ_2 known, CPL can be calculated using equation (1).

To verify the theory, the reference design was simulated for two cases: both ports directly connected to 50Ω and both ports simultaneously matched at 900MHz. CPL was calculated for the first case and compared with S_{21} from both cases, as shown in Fig. 4. It can be seen that S_{21} curve of the first case is much lower than S_{21} curve of the second case. But CPL curve agrees well with S_{21} of the second case at 900 MHz where both ports are well matched as presented by minimum of S_{11}/S_{22} curve. Thus the calculation of CPL provides an efficient way to predict level of coupling, when both ports are conjugate matched, from the S matrix of the array without going through the trouble of constructing the actual matching network.

B. Design of Isolation Structure

To design the isolation structure as shown in Fig. 1(b), a parametric study was carried out. It turned out the width of the structure L_{iso} and the length of the end section L_{end} are the most efficient parameters to tune the structure to achieve optimum CPL performance. Fig. 5 shows the CPL for different L_{iso}/L_{end} combinations. The plot shows the shift of minimum point of CPL curve is more sensitive to the change of L_{iso} than it is to that of L_{end} . And the combination $L_{iso}/L_{end} = 20.4 \text{ mm}/6 \text{ mm}$ is the optimum combination because it produces the lowest CPL at 900 MHz.

Fig. 6 shows the CPL curves calculated from measurement result of proposed design and reference design. It can be seen that the coupling between the elements is significant when the array elements are 0.078λ apart, which is as high as -6dB. But with isolation component, CPL is brought down to below -12dB. At 903MHz, CPL of the proposed design reaches a minimum value of -27dB, which is 17dB lower than that of the reference design at that frequency.

IV. RADIATION MEASUREMENT

A. Radiation Pattern and efficiency

The radiation pattern of the array was measured in anechoic chamber and the radiation efficiency was obtained by pattern integration. In order to connect the array to the measurement instrument with 50Ω port impedance, a balun and matching-network was developed and attached to each port, as illustrated in Fig. 7.

Fig. 8 shows the measured radiation pattern at 900MHz. The pattern is plotted in terms of gain, and the loss in balun and matching network has been compensated. The radiation pattern in E plane of both designs roughly retains the “donut” shape of monopole and the radiation pattern of proposed design is tilted due to the influence of the isolation structure. The radiation pattern of proposed design is apparently larger in both E plane and H plane. It is because the proposed design can achieve higher radiation efficiency. As shown in Fig. 9, the radiation efficiency for each port of proposed design is significantly higher, which leads to higher maximum gain. To the contrary, the reference design is quite inefficient and the maximum gain is also low due to the significant level of inter-coupling. Significant gain improvement up to 3.6dB and radiation efficiency improvement up to 28% over the reference design has been achieved with the insertion of isolation structure in proposed design. For proposed design at 900MHz, the radiation efficiency for Port 1 and port 2 are 48% and 50% respectively, which corresponds to maximum gain of 0.4dBi and 0.3dBi.

B. Integration with rectifier circuits

To investigate the array's power receiving capability as a whole, the antenna array was integrated with rectifier circuits and DC load. There are different topologies of combining antenna element and rectifier circuit [12]. In this work, each array element is intended to connect with one rectifier circuit and the DC output is then combined either in parallel or series as illustrated in Fig. 10. The rectifier circuit used is 2-stage modified Dickson charge-pumps [8] developed using discrete

components. The DC output of the two rectifier circuits were connected to 500 k Ω resistor. Both parallel and serial connections were investigated.

The Times-7 A6031 circularly polarized antenna with 4dBi gain at bore sight was used as transmitter. The distance between the transmitter and the array was 1.5m and the transmitted power was 26 dBm. The array was rotated along three axial planes and the DC voltage over the resistor was measured and the DC power was calculated and presented in Fig. 11. The results show both case of parallel and series connection, DC power generated by the proposed design is higher than that of the reference design in most directions. The result has proved that it is feasible to implement the de-coupled antenna array for small device to receive more power.

V. CONCLUSION

This letter has presented a space-efficient design of a two-element antenna array on-package for RF power receiving for small battery-less device. The overall size of package is $0.1\lambda \times 0.17\lambda \times 0.04\lambda$ at operating frequency. The edge-to-edge distance between the array elements is only 0.078λ . An isolation structure is designed to reduce the coupling between array elements. Measurement result has shown that a minimum coupling of -27 dB has been achieved.

The impact of coupling reduction has been demonstrated by comparison of measurement results. The results show that significant improvement in radiation efficiency and gain of array element has been achieved for the proposed design over the reference design. The RF receiving capabilities of the arrays have also been evaluated with the antenna array integrated with rectifier circuits. The results also show that the proposed design was capable of supplying more DC power than the reference design in most directions, in both series and parallel connection.

This letter has demonstrated a feasible solution of implementing compact antenna array on-package to enhance RF energy harvesting capability if the two array elements can be properly de-coupled. The design can be easily tuned to work at different UHF bands and migrated to any other fabrication technology, such as 3D printing technology.

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Fig. 1 Design of 2-element antenna array, all dimensions are in mm. (a) Reference design on PCB (b) Proposed design with isolation structure (c) Planar design of reference array. (d) Planar design of proposed array (e) Feeding loop on PCB.

Fig. 2 Measured input impedance vs. simulation of proposed design.

Fig. 3 2-port network model of antenna array.

Fig. 4 Comparison of CPL, S_{21} , and S_{11} curves of different cases. Fig. 5 CPL for different combination of L_{iso}/L_{end} . Dimensions in mm.

Fig. 6 CPL calculated from measurement result.

Fig. 7 Schematic illustration of antenna array with matching network and balun attached to interface with the measurement instrument

Fig. 10 Schematic of array connected with rectifier circuits and 500kOhm load connected at the DC output load. Solid line shows serial connection and dashed line shows parallel connection.

Fig.8 Radiation pattern of proposed design and reference design. (a) E plane radiation (b) H plane

Fig. 9 Plots of maximum gain vs. frequency. Proposed design is compared with the reference design. The passive ports are matched.

Fig. 11 Measured DC power. Curves on the left side shows the result for parallel connection and curves on the right side shows the series connection.