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Enhancing the Efficiency of Compact Patch Antennas Composed of Split Ring Resonators by Using Lumped Capacitors

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Abstract—A new type of small patch antenna with low profile and enhanced radiation efficiency is proposed in this letter. The antenna is realized with a double layer of low permittivity material (polypropylene, $\epsilon_r = 2.2$). The lower layer is used for the feeding of the antenna, and split ring resonators (SRRs) are printed on top of the upper layer acting as radiating elements. The compactness is provided by shorting the rings to the ground plane with two metal pins. Although this antenna presented initially a dual band of operation, it has been demonstrated how the use of a lumped capacitor in the inner ring can increase the total radiation efficiency of the antenna performing a single band response. Therefore, when the two original operation frequency bands coincide, a manufactured prototype of the antenna demonstrated a measured radiation efficiency of 73% that can be provided at the operation frequency of 1.29 GHz.

Index Terms—Microstrip patch antennas, radiation efficiency, electrically small antennas, split ring resonators, lumped capacitor.

I. INTRODUCTION

THE development of wireless communications has risen the need of low profile antennas with good radiation characteristics to be built inside mobile phones and wireless devices of new generation. Microstrip patch antennas are typically used for this purpose as they are realized in printed technology and they can be mounted directly in the circuit board [1]–[3]. On the other hand, their radiation efficiency is affected by the high permittivity materials often used to obtain compact sizes and multifrequency performance [1], [4], [5].

In the last years, split ring resonators (SRRs) have been used in antennas and microwaves components for several applications [6]–[8]. SRRs are well known in metamaterials, since they can provide negative permeability which can create a stop band response at the resonant frequency [9], [10], and also produce new bands of operation [6], [11], [12]. In [13] a compact patch antenna is presented where the SRRs

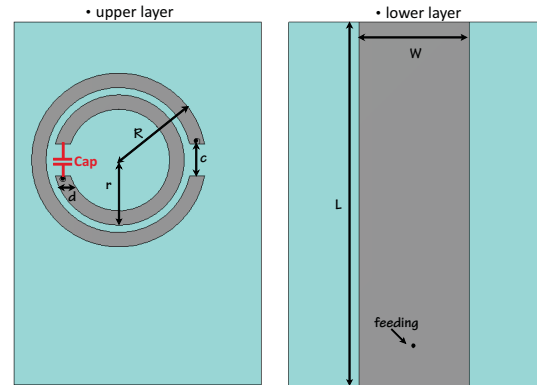
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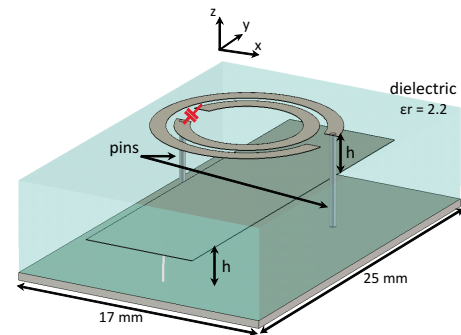
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(a) Top view.



(b) 3D view.

Fig. 1. Top and 3D view of the proposed patch antenna with SRRs.

are used to create a dual band response. Finally, in [14] numerical results show how the frequency bands of the SRRs patch antenna can be moved by adding a lumped capacitor in the gap of the inner ring. The same approach is used in this paper to create a single band patch antenna with higher radiation efficiency, for which an experimental validation is also provided. The idea of merging the two bands is similar to what has been used for decades in stacked patch antennas to increase bandwidth [2], [15] but here for the first time the focus is in the increase of the radiation efficiency.

II. ANTENNA DESIGN

The proposed geometry, including the lumped capacitor in the gap of the inner ring, is presented in Fig. 1. The antenna has two layers, both of thickness $h = 3$ mm. The lower layer is used to provide the feeding through a line of length $L = 25$ mm

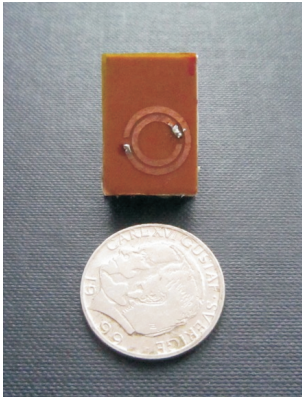


Fig. 2. Manufactured prototype.

and width $W = 7.3\text{mm}$ on a polypropylene dielectric with permittivity $\epsilon_r = 2.2$. This line is fed with a standard SMA coaxial connector. The radiating elements are two concentric SRRs with oppositely facing gaps which are printed on the upper layer with the same substrate material and thickness as the lower one. They are short-circuited to the ground plane by two metal pins attached to an end of each ring near its gap as shown in Fig. 1. The dimensions of the rings are chosen as follows: inner and outer ring radius $r = 4.5\text{mm}$ and $R = 6\text{mm}$, respectively, gap $c = 1.4\text{mm}$ and ring width $d = 1\text{mm}$. The dielectric has been chosen with a low permittivity in order to not affect the radiation efficiency, otherwise reduced when using materials with higher permittivity. On the other hand, in order to provide a compact design, the two pins connected to the end of each ring and short circuited to the ground plane behave as inductances, similarly to PIFAs [13].

The prototype, firstly considered without capacitance, is shown in Fig. 2 and in Fig. 3 measurement and simulation results of the S_{11} are presented. Simulations were carried out with the commercial software *CST Microwave Studio* [16]. Simulated and measurement results agree well, showing the double band response due to the two SRRs. The radiation efficiency for this antenna has been measured in a reverberation chamber [17] and it is shown in Fig. 4. The total radiation efficiency (green solid curve) includes the mismatch factor, whereas the radiation efficiency (blue dashed curve) is the antenna efficiency without loss contribution due to the mismatch. The total efficiency at the center of the lower frequency band at 1.26 GHz is about 45 % and in this case the radiation efficiency and total efficiency almost coincide at this operation frequency since the antenna is well matched. At the upper band center frequency (2.08GHz), the efficiency is around 80 % if the reflection losses are not taken into account.

III. EFFECT OF LUMPED CAPACITORS

By adding a capacitor in between the gap of the inner ring, as shown in Fig. 1, the upper frequency band (which is defined by the inner ring) shifts down until, for a certain value of the capacitance, it meets the lower band thus becoming a single band antenna. The resulting efficiency will be larger for this “single-band” antenna, compared to the dual band case, since it will be an effective contribution from both rings to the

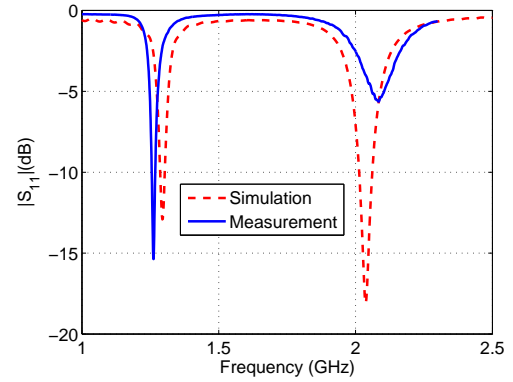


Fig. 3. Measurement and simulation reflection coefficients.

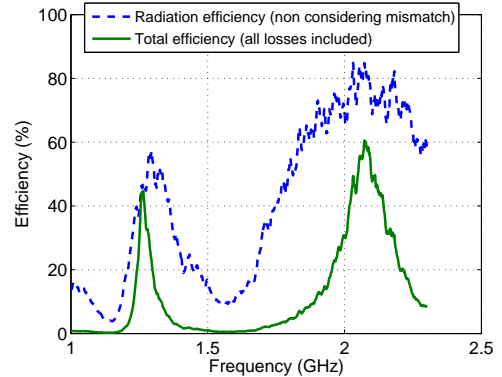


Fig. 4. Measured radiation efficiency and total radiation efficiency (including mismatch factor).

radiation. The reason for the increase of radiation efficiency with the use of the lumped capacitor may be two-pronged conveyed as a qualitative argumentation and a somewhat quantitative explanation. Qualitatively first, by using lumped capacitors to shift the upper band down towards the lower one and thereby merging them, we obtain two resonances at the same frequency. In a more mathematical (quantitative) way, the equivalent circuit model of the antenna is represented as a parallel resonant circuit comprising two RLC resonators in parallel, each pertaining to one of the two rings, as shown in [13] and represented in Fig. 5. It is also first acknowledged that the Q-factor is inversely related to the radiation efficiency, which can be conceived intuitively by the mere definition of the Q-factor. Then from the well-known expression of the Q-factor of a parallel resonant circuit: $Q = \omega_o RC$ where ω_o is the resonant frequency, raising the capacitance in the gap of the inner ring, that is responsible for the higher band, leads to a higher Q of that upper band, thus a reduced efficiency. But at the same time, although the Q of the outer (larger) ring (Q_1) on its own remains unchanged (no lumped capacitor added to it), the effective (total) $Q_{tot} = Q_1 \parallel Q_2$ of the two resonant circuits in parallel is predominated by the smaller of the two individual Q values if their difference is large, which is that of the upper band. Hence, although the Q_2 of the upper band increases with the inclusion of the capacitor, it is still much smaller than the individual Q_1 of the outer ring. As such, when

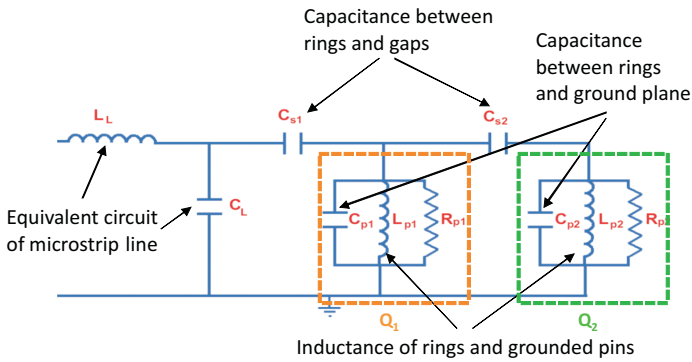


Fig. 5. Circuit model of the antenna.

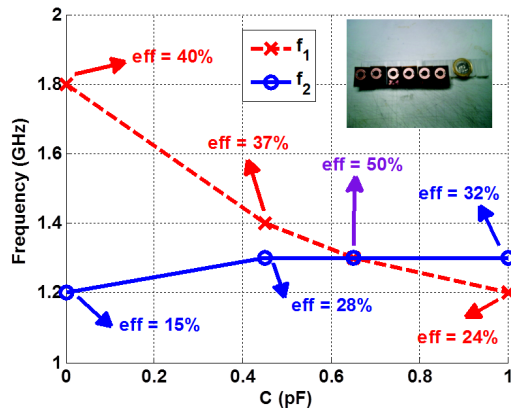


Fig. 6. Measured operation frequencies when a capacitor is placed in the gap of the inner ring. For each measurement, it is also indicated the radiation efficiency $R = 6.1\text{mm}$, $r = 4.6\text{mm}$, $c = 2.2\text{mm}$, $d = 1\text{mm}$, $h = 2\text{mm}$ and $\epsilon_r = 2.7$.

the two bands merge, although the efficiency of the upper band falls, that of the lower band increases from its original value before the merging due to the effective fall in the overall Q at that common frequency. This effect is shown in Fig. 6, for the antenna (with $R = 6.1\text{mm}$, $r = 4.6\text{mm}$, $c = 2.2\text{mm}$, $d = 1\text{mm}$, $h = 2\text{mm}$ and $\epsilon_r = 2.7$) based on such resonance-merging for efficiency improvement. Here, the lower band f_2 (due to the outer ring) is fixed while the upper frequency f_1 (caused by the inner ring) is shifted towards it. The increase in the efficiency at f_2 is more than three times (15% to 50%). Therefore, by merging two resonances, an increment of the radiation efficiency of the low frequency band can be achieved.

Coming back to the antenna whose dimensions were specified in Section II, in Fig. 7, the normalized electric field for both cases (with and without capacitor) is illustrated at the lower frequency of operation at the z -plane immediately over the rings. In this figure, it is demonstrated how the inner ring contributes more actively to the radiation when the capacitor is introduced.

In order to validate this approach, a lumped capacitor was added in the gap of the inner conductor. A capacitance of 0.82 pF was found to be enough in order to obtain the single band response. Fig. 8 shows the measured S_{11} (blue solid curve) and in Fig. 9 the radiation efficiency measured in a reverberation

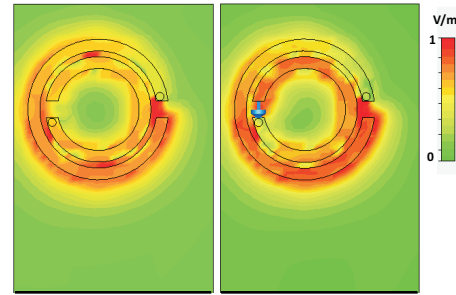


Fig. 7. Simulated electric field distribution for the antenna with and without capacitor of 0.82 pF (right and left respectively) at the lower frequency of operation.

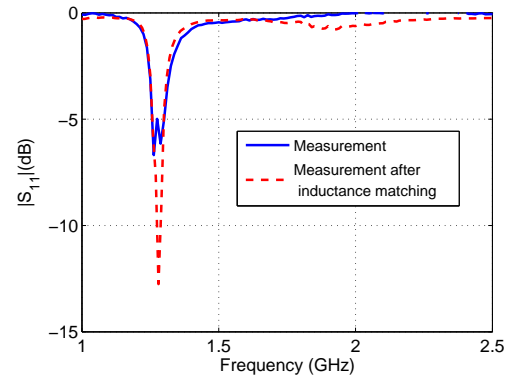


Fig. 8. Measured reflection coefficient when a lumped capacitor of 0.82 pF is added in the inner ring; before and after series inductance matching.

chamber is presented (blue dashed curve). The antenna is not completely matched at the operation frequency and this can be seen from both the measured S_{11} and total efficiency. However, this mismatch factor can be easily corrected with a series inductance as Fig. 8 shows (red dashed curve), having a maximum total radiation efficiency of 73% at the operation frequency of 1.29 GHz as finally Fig. 9 presents (red dash-dotted curve). The bandwidth of operation of the antenna (in terms of matching) is approximately 2%, in which the radiation efficiency is higher than 70%. These curves were obtained applying to the measurements a simulated model of the series inductance placed between the feeding (SMA connector) and the subsequent circuitry, just to show that the antenna matching can be easily achieved. This matching, that we call for simplicity “inductance matching” (because of the inclusion of a lumped series inductor to the circuit) can be realized in practice by using an external matching network, e.g., stubs or lumped inductors. In addition, it has also been verified by simulations that further miniaturization can be achieved by shortening the long side of the structure along the feedline (Fig. 1) to obtain a squarer, even more compact antenna without any adverse effects on the matching and efficiency performance. The size along the breadth is however limited by the outer ring.

Finally, the antenna radiation pattern has been measured and it is shown in Fig. 10. As expected the radiation pattern is quite isotropic. It is also similar to the (lower/upper) band of the PIFA studied in [13], with a null in the broadside direction

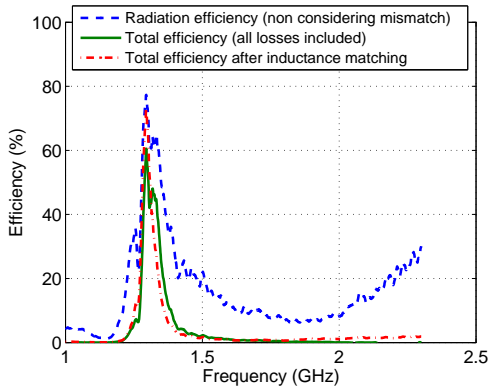


Fig. 9. Measured radiation efficiency and total radiation efficiency (including mismatch factor) for the prototype with capacitor; before and after series inductance matching.

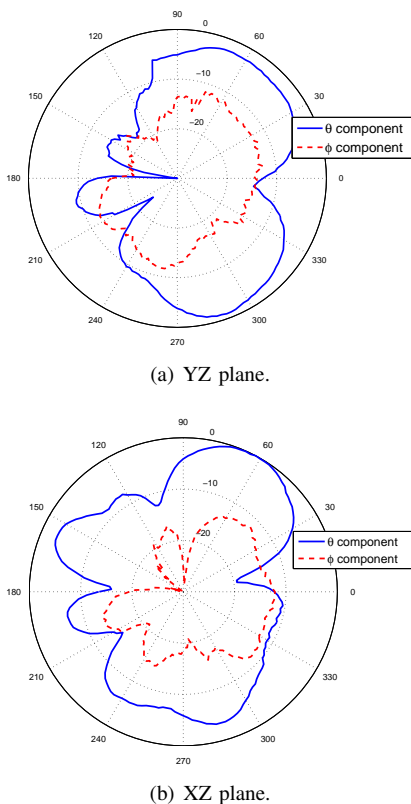


Fig. 10. Measured radiation pattern in the two main planes.

due the geometry of the antenna.

IV. CONCLUSION

A compact microstrip patch antenna with high radiation efficiency has been presented in this paper. First, a dual band antenna with SRRs was designed and measured, showing two operation frequency bands at 1.26 GHz and 2.08 GHz, created by the outer and inner rings, respectively. The measured radiation efficiency for this first prototype was found to be 45% (for the lower frequency) and about 80% (for the upper frequency, not including mismatch). Measurement results showed how the same antenna can perform better, when the two bands meet together at 1.29 GHz, by adding a capacitor of 0.82 pF. In

this case the measured radiation efficiency was found to be about 73 % covering both requirements for compactness and good radiation characteristics typically difficult to acquire at the same time for small antennas. The total size of the designed antenna including the ground plane was $0.073\lambda_0$ by $0.1\lambda_0$. Finally, it was also verified by simulations that the size of the antenna can be further reduced by shortening its length without compromising the matching and efficiency.

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