A Simple Approach for Reducing Mutual Coupling in Two Closely Spaced Metamaterial-Inspired Monopole Antennas

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Abstract—A simple approach for reducing the mutual coupling in two closely spaced electrically small antennas (ESAs) is proposed based on the general idea of field cancellation. The antenna array consists of two metamaterial-inspired small printed monopole antennas. The mutual coupling is reduced by self-cancellation of the induced common ground and near-field currents, without introducing additional structures. A fabricated prototype of a two-element array with an edge-to-edge separation of \( \frac{\lambda_0}{30.6} \) (or center-to-center separation of \( \frac{\lambda_0}{13.6} \)) yields a measured mutual coupling of \( |S_{11}| \) better than \(-18\) dB across the impedance band of \( 1.7\text{GHz} \), which is significantly better than the \(-9\) dB level of the original array.

Index Terms—Antenna arrays, electrically small antennas (ESAs), metamaterials, mutual coupling, printed monopole.

I. INTRODUCTION

THE development of next-generation wireless communication systems requires broadband and multiband devices for faster data transfers. Meanwhile, there is a trend toward the miniaturization of handheld devices. These conflicting requirements must be met using low-cost solutions that simultaneously maintain a high radiation efficiency. Transmission-line metamaterials (TL-MTM) provide a conceptual route for implementing small resonant antennas. Typically, TL-MTM antennas suffer from narrow bandwidths. Recently, [1] addressed the bandwidth problem by proposing a two-arm TL-MTM antenna resonating at closely spaced frequencies. Furthermore, a compact triband monopole antenna with single-cell metamaterial loading was demonstrated in [2] and [3] for WiFi and WiMAX applications, whereas a dual-band metamaterial antenna was proposed in [4] for WiFi applications.

Another TL-MTM type of a dual-band electrically small antenna (ESA), fabricated on an FR4 board with thickness of 1.6 mm, has been recently reported in [5]. This antenna is based on the planar coplanar waveguide (CPW) monopole topology, but with a single-cell metamaterial loading, as shown in Fig. 1(a). The antenna comprises a two-arm fork-like monopole with a thin-strip inductor loaded on top of the monopole and an interdigital capacitor loaded on the right-side arm. This type of loading creates a second resonance covering the lower WiFi band of 2.40–2.48 GHz, in addition to the monopole resonance over the 5.15–5.80 GHz upper WiFi band. At the lower WiFi band, the antenna no longer acts as a regular monopole along the vertical direction, but rather as a slot along the horizontal direction. The proposed loading forces the current to wrap around the slot perimeter and induce an E-field distribution along the horizontal direction within the slot, both contributing to the slot-mode radiation. The monopole element has dimensions of \( 8.5 \times 5.7 \) mm\(^2\) (or \( \lambda_0/14.4 \times \lambda_0/21.4 \) at 2.45 GHz). A dual-band performance can be clearly seen from the HFSS simulation shown in Fig. 1(b).

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radiation efficiencies are above 60% and 90% at the lower and higher WiFi bands, respectively. This design is single-layered and via-free and can therefore be easily fabricated at a low cost.

Multiple-input–multiple-output (MIMO) communication systems require good isolation between antenna elements. It is challenging to design a closely spaced antenna system with good isolation [6]. Recently, in [7], a suspended neutralization strip that is physically connected to the antenna elements was inserted for improving isolation, and in [8], a coupling element located between adjacent antennas was introduced to create an additional coupling path. The idea behind these two methods is to use additional conducting strips to cancel out the existing mutual coupling.

In this letter, we describe a simple technique to reduce the mutual coupling between two closely spaced antennas having the previously described topology shown in Fig. 1. This is important for MIMO applications in handheld units. Some preliminary simulation results have been reported in [9].

II. PROPOSED MUTUAL COUPLING REDUCTION TECHNIQUE

A simple approach is proposed to enhance the isolation for a closely spaced antenna array that consists of two antennas of the kind shown in Fig. 1(a). This approach exploits the general idea of field cancellation, but without the aid of any additional conducting strips, which in turn simplifies the design and fabrication process.

A. Two Major Sources Contributing to Mutual Coupling

Before introducing the isolation-enhanced design, it is worthwhile to examine the contribution of mutual coupling from different sources. As shown in Fig. 2, the two antennas of Fig. 1 are placed symmetrically along the central axis of the array and separated by an edge-to-edge distance of 4 mm or λ₀/30.6 at 2.45 GHz and a center-to-center distance of 9.7 mm or λ₀/12.6 at the same frequency. The current distribution at the lower WiFi band (2.40–2.48 GHz) is sketched using HFSS and is shown in Fig. 2(a). The induced currents at Antenna B, when Antenna A is fed with a sinusoidal current, are mainly due to: 1) the near-field coupling from Antenna A; and 2) the common-ground current shared with Antenna A. Since the antennas are very close to each other, these induced currents due to mechanisms 1) and 2) on Antenna B are approximately in phase. Moreover, as can be seen from Fig. 2(b), first, |S₁₁| and |S₂₂| are identical due to symmetry and second, the antenna array exhibits a simulated mutual coupling of |S₂₁| worse than -10 dB across the frequency range from 2.45 to 2.54 GHz, with the peak mutual coupling of -8.8 dB occurring at the resonance of S₁₁ (f = 2.49 GHz).

B. Mutual Coupling Reduction Exploiting Field Cancellation

The idea of reducing the mutual coupling between the two antennas shown in Fig. 2(a) is to make the contributions to mutual coupling from the above-mentioned induced currents cancel each other. This can be achieved by simply flipping Antenna B along the central axis of its CPW feedline as shown in Fig. 3(a). When this is done, the induced ground currents retain their original phase, but the induced near-field currents reverse their phase. This is due to the asymmetric loading capacitor. At the lower WiFi band, the loading capacitor results in circular currents along the loop that is composed of the two-arm fork-like monopole and the loading inductor above it [5]. Since the currents on the CPW feedline flow into/out of the arm with the least impedance (that is, the arm that does not contain the interdigital capacitor), the induced near-field currents and the induced common-ground currents are contradiirectional on the central conductor of the CPW feedline. This leads to a very low mutual coupling, as can be verified from the simulation shown in Fig. 3(b) (|S₂₁| = -24.9 dB at 2.46 GHz, the resonant frequency of S₁₁). It should be noted that this method is not applicable for the isolation enhancement at the higher WiFi band (5.15–5.80 GHz). At that band, the loading capacitor becomes electrically shorted, and the inductor becomes an open, leaving the in-phase currents, instead of the circular currents, flowing on the two arms.

C. Final Design

It should also be noticed from Fig. 3(b) that the resonant frequency of Antenna B is shifted by 70 MHz toward the lower frequency from the resonant frequency of Antenna A. This is because the antenna array is now asymmetric along its central
Fig. 3. A closely-spaced antenna array composed of two small antennas. Antenna B is flipped along the central axis of its CPW feedline as compared to Fig. 2(a). (a) Current distribution at lower WiFi band. (b) Simulated S-parameters.

axis, and the performance of each small antenna is sensitive to the corresponding size of its left and right CPW ground plane. The resonance of Antenna B can be fine-tuned using the offset length $\Delta L$ as shown in Fig. 4(a), until its resonance is aligned with that of Antenna A when $\Delta L = 0.5$ mm. In Fig. 4(b), the simulated mutual coupling is better than $-14.8$ dB across the band of $|S_{11}| < -10$ dB from 2.40 to 2.50 GHz. The mutual coupling at the resonance of $S_{11}$ is $-17.6$ dB, which is significantly better than the corresponding $-8.8$ dB level of the original array shown in Fig. 2. The HFSS simulated current distribution is shown in Fig. 5, where contradirectional currents on the central conductor of the CPW feedline of Antenna B can be clearly seen.

III. EXPERIMENTAL RESULTS

The design of a closely spaced antenna array composed of two small antennas with the proposed isolation enhancement scheme shown in Fig. 4(a) was fabricated and tested. The fabricated prototype is shown in Fig. 6(a), and the measured S-parameters are shown in Fig. 6(b). The two-element antenna array exhibits a measured impedance bandwidth of 110 MHz from 2.47 to 2.58 GHz for $|S_{11}| < -10$ dB, and a bandwidth of 70 MHz from 2.47 to 2.54 GHz for $|S_{22}| < -10$ dB. The resonant frequencies of $S_{11}$ and $S_{22}$ are shifted by about 70 MHz toward the higher frequency, and there is a 35-MHz offset between the resonances of $S_{11}$ and $S_{22}$. These discrepancies between the simulated and the measured results are likely due to a variation of the dielectric constant of the FR4 substrate and also due to a slightly nonuniform milling of the interdigital capacitors and strip inductors on the antennas. The measured mutual coupling of $S_{23}$ is better than $-18.2$ dB across the band of
Fig. 6. The final design of a closely spaced antenna array composed of two small antennas with isolation enhancements. (a) The fabricated prototype. (b) The measured $S$-parameters.

$|S_{11}| \leq -10$ dB with a mutual coupling of $-22.7$ dB at the resonant frequency of $S_{11}$ ($f = 2.53$ GHz). This is in line with the observation from the simulated results shown in Figs. 3(b) and 4(b).

IV. CONCLUSION

A simple technique has been proposed to reduce the mutual coupling between two MTM-inspired electrically small monopole antennas that are closely spaced. This technique relies on the self-cancellation of the induced common-ground and near-field currents and does not require any additional structures, which in turn simplifies the design process and reduces the fabrication cost. The theoretical performance is verified by full-wave simulations and experimental data. We have shown that for two small antennas sized $\lambda_0/1.4 \times \lambda_0/21.4$ and spaced edge-to-edge $\lambda_0/30.6$ or center-to-center $\lambda_0/13.6$, the peak mutual coupling (within the $|S_{11}| < -10$ dB band) is reduced from $-8.8$ dB of the original array to $-14.8$ dB in HFSS simulation and $-18.2$ dB in measurement for the mutual-coupling reduced array. These attributes make the proposed antenna well suited for emerging multiantenna wireless applications.

REFERENCES