Loop-Loaded Printed Dipole Array Design for a Dual-Band Radar Application

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Abstract—A loop-loaded printed dipole (LLPD) antenna array is introduced for a dual-band radar array operation at 3.0/5.5 GHz bands. A pair of loops is placed on or underneath the dipole aperture, providing dual-band operation without deteriorating the gain performance. It is numerically demonstrated that the proposed arrays offer almost 15% impedance bandwidths at designated frequencies. The full-wave analyses of the LLPD designs have been carried out using CST Microwave Studio, and cross-comparisons are provided using Ansoft HFSS.

I. INTRODUCTION

Multi-functionality plays a major role in radar applications [1] where size, weight, power consumption and cost are the main limiting factors in designing integrated transceiver circuitry. In this perspective, electronically reconfigurable printed antennas and artificial substrates were previously considered to achieve dual-band array operations [2-4]. In particular, printed dipole elements have been preferred in conformal arrays due to their low-profile and easy fabrication. Specifically, loaded dipole elements have recently been introduced for dual-frequency applications [5, 6]. In this study, we propose a novel loop-loaded printed dipole (LLPD) array design aiming for a dual-band (3.0/5.5 GHz) radar application. The LLPD array consists of dipoles loaded with rectangular loop elements placed below or on the aperture. The latter design would be preferred for a practical feeding realization. The loops provide inductive loading and allow for a secondary band (5.5 GHz) without deteriorating radiation performance of the array. From the application point of view, the proposed design can be considered to achieve dual-band array operations [2].

In this paper, we present the corresponding simulation results. We note that the full-wave analysis of the proposed designs have been carried out using CST Microwave Studio, which utilizes the time-domain finite-integration method. Also, cross-comparisons are provided using Ansoft HFSS employing the frequency-domain finite-element method. In the paper, we present the corresponding simulation results.

II. LLPD DESIGNS

We first consider an LLPD design (LLPD-1) where loop elements placed below the dipole aperture. Then, an alternative LLPD design (LLPD-2) is introduced to better accommodate practical feed structure within the cavity. In the latter design, the loops are located on the dipole aperture. Subsequently, the array performance of the LLPD-2 design is presented.

A. LLPD-1 Design

The proposed single element LLPD-1 configuration is depicted in Fig. 1. As shown, a center-fed dipole on the aperture is placed over two symmetrically-placed rectangular loops, where the dipole and the loops are separated by a thin substrate (Rogers RT/duroid 5880) with a thickness of \( h_2=0.75 \) mm, \( \varepsilon_r=2.2 \), and \( \tan\delta=0.0009 \). The structure is placed over a vacuum-filled cavity with a height of \( h=1.5 \) cm. It is important to note that the size and the location of the loops with respect to the dipole play a crucial role in occurrence of a higher frequency band. Also, the cavity height is critical for a smooth radiation pattern as well as impedance matching in the upper band. We note that ideal probe-feeds are employed as the excitation of the dipole designs presented in this paper. In a practical realization, coaxial-feed elements will be considered in the designs. Exact coaxial-feed modeling has also been modeled and preliminary results demonstrate similar performances as that of the probe modeling, which will be discussed at the conference. Since the coaxial-feed modeling almost simulates unbalanced behavior of the practical feed over the frequency band of interest, there seems to be no need for an additional balun/feed structure.

The return loss characteristics of the LLPD-1 design with and without the loops are displayed in Fig. 2. Those simulation results were obtained using CST Microwave Studio. As can be seen in Fig. 2, while the metal-backed dipole operates around 2.8 GHz, the inclusion of the loops result in two operational bands at 3.0 GHz and 5.5 GHz, where 12% and 14% impedance bandwidths are observed, respectively, where \(|S_{11}|<-10\) dB criterion with 50 Ohm system impedance is considered.

In Fig. 3, we display the corresponding input impedance characteristics of the LLPD-1 obtained using the CST and HFSS simulators. As seen, the simulation results agree with each other fairly well except for a slight frequency shift and small differences at impedance levels. The discrepancies are mainly due to different solution methods as well as different boundary conditions and meshing schemes employed in each simulator.

In addition, the LLPD-1 design offers broadside patterns with directive gain of almost 9 dB over the frequency bands of interest (3/5.5 GHz). It is important to note that the inclusion of the loops do not have any adverse effect on the patterns. We also remark that the computed total efficiency...
(radiation efficiency × mismatch losses) of the antenna is better than 95% at the designated frequency bands.

We remark that in all designs considered in the paper, ideal probe-feeds are employed at the centers of the dipoles. In a practical implementation, vertically placed coaxial feeds are projected to use within the cavity. Since the loops in the LLPD–1 design will be very close to the path of the feed-to-dipole, there will be possible physical contact and inevitable parasitic interaction between the loops and the feed structure. In an array environment, this expected interference may even cause more serious problems. To avoid such a phenomenon, we have considered an alternative design, namely LLPD–2, where the loop elements are placed on the dipole aperture. Note that the LLPD designs with coaxial feed structures will be presented at the conference.

Fig. 1 LLPD–1 configuration: $L_1=66$, $W_1=36$, $L_2=43$, $W_2=3.5$, $S_1=16$, $S_2=12.4$, $k=2$, $h_1=15$, $h_2=0.75$ (all in mm), $\varepsilon_r=2.2$

Fig. 2 Return loss characteristics of the LLPD–1 design with and without the loops

B. LLPD–2 Design

The proposed single-element LLPD–2 configuration is depicted in Fig. 4. Unlike the LLPD–1 design, the loops are now located at the dipole aperture to avoid direct interaction with the feeding structure in a practical implementation. In this new design, there are concentric loop elements to achieve better impedance matching in the upper frequency band. While the loops provide inductive loading, a capacitive effect occurs by means of the interaction between the dipole element and the loops. Note that the separation between the loops and the dipole element is only 0.3 mm.

Fig. 5 displays the return loss characteristic of the LLPD–2 design obtained via the CST and the HFSS, where similar return loss characteristics are achieved for both simulators with slight discrepancies. As seen, the dual-band operation occurs around 3.0 GHz and 5.5 GHz with 13% and 14% impedance bandwidths, respectively. The VSWR characteristics of the LLPD–2 design is also shown in Fig. 6 where the VSWR < 2 at the respective bands.

In addition, the corresponding radiation patterns of the LLPD–2 design are shown in Fig. 7. Similarly, the LLPD–2 design offers a broadside radiation with a directive gain better than 8.3 dBi and the computed total efficiency of 96% at both frequency bands.
Fig. 4 LLPD–2 configuration: $T_1=11$ mm, $T_2=7.4$ mm; all other parameters are same as of the LLPD–1 design (see Fig. 1).

Fig. 5 Return loss characteristics of the LLPD–2 design: CST vs. HFSS solutions.

Fig. 6 VSWR characteristics of the LLPD–2 design.

Fig. 7 Radiation patterns of the LLPD–2 design at the designated frequencies.

C. LLPD–2 Array Design

We now consider an array version of the LLPD–2 design introduced above. By optimizing element spacing within the array, 2×2 and 3×3 array configurations were designed. The proposed 3×3 array configuration and the corresponding return loss characteristics are displayed in Fig. 8 and Fig. 9, respectively. As seen, the CST and HFSS results agree quite well in the lower frequency band (3 GHz), but they have small differences in the upper band (5.5 GHz). Also, there are some discrepancies observed in the return loss characteristics of the array elements, particularly in the upper band. Considering the location of the elements in the array (Fig. 8), the inner array elements (1–3) result in higher return loss levels as compared to the outer elements (4–9), which may be due to adverse mutual coupling effects. More importantly, the proposed design offers dual-band array performance.

The corresponding realized gain (IEEE gain × mismatch losses) characteristics of the 2×2 and 3×3 LLPD–2 arrays are displayed in Fig. 10. As shown, the realized gain for the 3×3 array is observed in the range of 13.5–18.3 dB (almost 3 dB above that of the 2×2 array) over the whole band of 3.0–6.0 GHz. The corresponding radiation patterns are also displayed in Fig. 11. As observed, the patterns demonstrate better directivity profile in the upper frequency band, which also reflects into the realized gain as can be seen in Fig. 10. Also, the array provides grating-lobe-free patterns since the array elements are arranged so that the element spacing < $\lambda$ over the whole frequency band. In addition, the maximum side-lobe level is $-11$ dB for the 3×3 array. Also note that the computed radiation efficiency for both LLPD–2 arrays is better than 98% at the frequency bands of interest.

Fig. 8 The 3×3 LLPD–2 array configuration: $D_1=50$ mm, $D_2=36$ mm.
In the paper, we have introduced a novel loop-loaded printed dipole array achieving a dual-band performance. The analyses of the designs were carried out using CST Microwave Studio and the CST simulations were supported by the HFSS results. It has been numerically demonstrated that the proposed LLPD designs allow for almost 15% impedance bandwidths at the designated frequency bands (3.0/5.5 GHz) with high directive gains. In particular, the 3x3 array provides 16 dB realized gain on the average over the 3.0–6.0 GHz band. We note that in the proposed designs the dipole elements have been fed by ideal probe feeds. In practice, coaxial feed structures will be employed within the cavity. The corresponding preliminary results promise similar array performances. Moreover, additional loadings to the loop elements offer tunable array operation, which will be discussed at the conference along with the coaxial-feeding analysis. The fabrication and measurements of the single-element LLPD design is in progress and the array implementation will follow.

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