A novel co-located cross-polarized two-loop PCB antenna in the ISM 2.4 GHz band

B. Elnour, D. Erricolo

University of Illinois at Chicago, Department of ECE, Chicago, IL 60607-7053

Email: belnou2@uic.edu, erricolo@ece.uic.edu

Abstract—This paper outlines the design of a co-located cross-polarized two-loop antenna for the ISM 2.4 GHz band. This antenna may be of interest to radar applications in the problem of finding the direction of arrival of a signal and in wireless applications that exploit polarization diversity. This antenna is an initial result towards the design of an electromagnetic vector sensor.

Index Terms—Antenna diversity, Antenna measurements, Direction of arrival estimation, Polarization,

I. INTRODUCTION

This paper examines the design of a dual polarized antenna obtained by co-locating two electric loops built on two orthogonal printed circuit boards (PCB). Previous literature related to orthogonal collocated loops is limited and recent contributions include [1], [2].

This antenna represents the initial results of research to obtain an electromagnetic vector sensor (EMVS), i.e. an antenna that measures all the six components of the electromagnetic field at one location. EMVS are important in sensing applications; in fact, analytical results [3], [4] show that EMVS should outperform scalar array antennas in the accuracy of the Direction of Arrival (DoA) estimation in radar systems application of the target echo, in interference suppression of wide band undesired sources, and null steering by making use of all available electromagnetic information [5].

While this antenna stems as part of a research work focused on a radar application, this dual polarized antenna should be of interest to communications applications because it enables the use of polarization diversity. In fact, classically, communications systems relied on one polarization per frequency per physical communication channel. To increase the communication channel capacity, one possible approach is taking advantage of polarization diversity by associating the same physical communication channel to two orthogonal polarization states [6], thus doubling the communication channel capacity [7], [8].

Recent research results show that in a scattering rich environment, there are up to six independent degrees of freedom of the electromagnetic field that could be exploited to improve channel capacity by a factor of six compared to a single polarized antenna and a factor of three compared to a dual polarized antenna [9], [10], [11] resulting in an EMVS. In principle, an EMVS consists of three orthogonal dipoles and three orthogonal loops that are all co-located. This paper addresses the challenges of designing a co-located dual

polarized antenna consisting of two orthogonal loops, which is a step towards the realization of an EMVS.

II. ANTENNA DESIGN

The design of an electric loop is usually more challenging than the design of an electric dipole. In fact, uniform current across the loop is harder to achieve as the wavelength of the antenna becomes larger [12]. The goal is to design an electric loop with a uniform current, which makes it equivalent to a magnetic dipole.

Another important aspect in designing either the loop or the dipole is to have good match at the input of the antenna, preferably $50\ \Omega$, to comply with commercial measurements equipment and standard coaxial cables. Based on current antenna designs for practical and commercial applications, the goals are set to design the electric loop with a return loss below -10 dB, an isolation below -10 dB and radiation efficiency higher than 50%. To overcome the above practical challenges and aspects for designing an electric loop that exhibits the radiation characteristics of an electric loop, the Kandoian loop is chosen.

A. The Kandoian loop

The Kandoian loop was originally designed to overcome all the negative aspects mentioned above in order to enhance the performance and maintain the radiation characteristics of the electric loop [13]. The electric loop is of great interest in itself since it is believed to have higher resistance to noise that is electric in nature, since the electric loop is nothing but a magnetic dipole. Additionally, an electric loop is stackable, which makes it a good option for an array of stacked antennas separated with a half wavelength distance [13]. The Kandoian loop is designed by dividing the loop into four sectors where each sector is fed separately. The feed system provides uniformity of the current flowing around the loop from the contributions of the four sectors of the pie as shown in Fig. 1. The original Kandoian loop was not built using a PCB.

The antenna is intended to be matched to $50\ \Omega$ using microstrip design techniques. The loop dimensions are a function of the operating frequency where the higher the operating frequency the smaller the diameter of the loop.

The co-located cross-polarized loops antenna is constructed using two Kandoian loops. The design of a single Kandoian loop is addressed in the following section.

Fig. 1. Current distribution of a Kandoian Loop

B. Design and fabrication of a single loop

The single loop design is based on the Kandoian loop [13] and work previously developed by Konanur et al. [14] [15]. The antenna is designed to have a constant current distribution contrary to the classical large loop. The antenna is built as a two layer printed circuit board, the first layer has the structure of the loop itself. The antenna is fed using a coaxial connector attached to the second layer, which also contains the connector ground, as shown in Fig. 2 that represents the actual built single loop. The electric loop was designed using Ansoft HFSS version 10.1 simulator. The design was moved to Agilent ADS in order to generate files to fabricate and build the antenna. Using ADS, an SMA connector supply pad and ground were added to the original design, which is imported from HFSS. The antenna is also simulated in ADS with the new connector and ground pads to make sure that adding the connector and ground supply did not de-tune the antenna.

Fig. 2. Loop fabricated on a PCB

The loop simulated with HFSS has a current density fairly uniform along the surface. The loop has the following characteristics:

- The electric loop is designed and built as a 2-layer PCB board
- Substrate Material: Rogers 4003, $\epsilon_r=3.38$, Height=1.5 mm
- Board dimensions = 90 mm x 90 mm
- Optimized radius of loop = 28 mm, 2 mm wide traces

- Bottom Ground Patch = 17 mm x 17 mm, Top Ground Arms= 4 mm wide

Fig. 3. Return loss S_{11} of the single loop

In the simulation, the loop is fed an incident power of 1 W and the corresponding radiated power is 0.95 W, hence the radiation efficiency is 95%. The radiation efficiency of the measured loop is 93%, which is very close to the theoretical value. The antenna impedance is 50Ω and, at the frequency of 2.4 GHz, the return loss S_{11} of the measured loop is close to the simulated value of -25 dB, as shown in Fig.3. The antenna has a bandwidth of 100 MHz and can be operated between 2.35-2.45 GHz where the return loss is below -10 dB. The radiation efficiency in both simulated and measured cases is calculated from the knowledge of the power transmitted and power received and accounting for the path loss. In the measurements case the total received power is calculated by integrating the received power from all directions (3D) and accounting for path loss, receiving antenna losses and directivity.

This single loop was also used, as described in [5], to show the superior performance of a synthesized EMVS with respect to a linear array antenna for DoA applications.

C. Design and fabrication of two co-located loops

In order to co-locate the orthogonal loops, the design of the first loop, loop 1, was modified by the implementation of a series of slots and spaces to allow for the insertion of a second loop, loop 2, in a plane perpendicular to the first one and without affecting its performance. The antenna is reconfigurable and designed for a current existing band (ISM) band, the antenna is also re-centered around 2.4 GHz after co-locating the two loops. Loop 2 was also built on a two layer printed circuit board, with the main structure consisting of the four pies of the loop on the top level (layer 1), while the bottom level (layer 2) is the ground plane to host the SMA connector that feeds the loop. The second layer is connected to the first layer through vias that run from the first layer to the second.

Loop 2 went through a series of optimizations to achieve an acceptable return loss and isolation. The new modified loop did

Fig. 4. Co-located cross-polarized two-loop antenna

preserve the original characteristics of the single loop design, with a return loss value of -14 dB or better. Once loop 2 was successfully designed without altering the performance of the original electric loop, the two loops were co-located as shown in Figs. 4- 7. Referring to Fig. 6, the feeds of the modified antennas are slightly moved from the center position compared to the single loop feed shown in Fig. 2 to make room for co-locating the two antennas. The co-located loops have pigtail feeds, each pigtail ends in a conventional SMA connector just like for the single loop case. Modifications to the loop radius, ground patch, and feed arms were applied to optimize the antenna. After the optimization, the antenna has the following characteristics:

- The electric loop is designed and built as a 2-layer PCB board.
- Substrate Material: Rogers 4003, $\epsilon_r=3.38$, Height=1.5 mm
- Board dimensions = 90 mm x 90 mm
- Optimized radius of loop = 28.5 mm, 2 mm wide traces
- Bottom Ground Patch = 15 mm x 15 mm, Top Ground Arms= 4 mm wide

The fabricated antenna is built as a 2-layer PCB board as shown in Fig. 7, while its return loss and the isolation between the two loops are shown in Figs. 8 and 9, respectively.

Fig. 5. Detailed view of the co-located cross-polarized two-loop antenna

Fig. 6. Detailed view of the connectors. The ground plane is represented in pink and the feed is represented in gray.

Fig. 7. Co-located cross-polarized two-loop antenna

From Fig. 8, one observes that loop 1 and loop 2 have return losses below -12 dB in the interval 2.3 GHz-2.5 GHz. Hence, this interval will allow the antenna to be used in the ISM 2.4 GHz band. The operating frequency ranges of the two loops overlap in the interval 2.3 GHz-2.5 GHz. Therefore, the two crossed loop antenna may be operated as a wide-band antenna, with a bandwidth of 200 MHz in that frequency range, with an isolation of -13 dB between the two elements and with a return loss below -10 dB. For a single frequency operation this antenna should be used at 2.40 GHz, in this case the return loss at this frequency is -16 dB for both loops with an isolation of -14 dB. Finally, the agreement between the measured return loss and the simulation is not as good at higher frequency for the two crossed loop antenna as it was for the single loop antenna, as shown in Fig. 3. A possible explanation is that the feed causes a de-tuning of the antenna resulting in a wider band antenna compared to the simulation. In the case of the single loop the feed and ground were simulated in ADS to confirm performance before creating fabrication files with ADS, but in the case of the two loops it was not possible to

apply the same approach since ADS is not a 3D simulator.

Fig. 8. Simulated and measured return loss of the co-located cross-polarized two-loop antenna

III. CONCLUSIONS

A $50\ \Omega$ matched co-located cross-polarized two-loop antenna is designed for the ISM 2.4GHz band. To the best of our knowledge, this antenna is the first of its kind. The original building element, the Kandoian electric loop, was built as stated in section II-B and was used to demonstrate initial results of superiority of the use of a synthesized EMVS versus a linear antenna array in DoA applications [5]. Electric loops have better performance than electric dipoles with regards to noise and because of the compact nature of the antenna the cross polarized electric loops antenna can as well be used for wireless applications for cellular base stations, for omnidirectional reception in mobile receivers and in MIMO systems to improve the direction finding capabilities and channel capacity. Simulated and measurement results show that it can also operate as a wide-band antenna up to a bandwidth of 200 MHz.

This antenna represent a step towards the realization of three orthogonal loops that are required to achieve the design of a theoretical EMVS. However, the inial results achieved with the design of this antenna raise the issue of the challenge of maintaining isolation and resonance among its elements as a concern for the design of an EMVS.

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Fig. 9. Simulated and measured isolation of the co-located cross-polarized two-loop antenna

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