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Dual-band Omnidirectional Circularly Polarized Antenna

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Abstract—A dual-band omnidirectional circularly polarized antenna is proposed. The antenna comprises back-to-back microstrip patches fed by a coplanar waveguide. A very low frequency ratio of 1.182 has been achieved, which can be easily tuned by adjusting four lumped capacitors incorporated into the antenna. An analysis of the omnidirectional circular polarization mechanism as well the dual band operation is provided and confirmed by numerical and experimental data. Key parameters to tune the resonant frequencies and the axial ratio have been identified. The prototype antenna provides omnidirectional circular polarization in one plane with cross polar isolation better than 12 dB for both frequency bands.

Index Terms—Aperture coupled antennas, Circular Polarization, Microstrip antennas, Multifrequency antennas.

I. INTRODUCTION

Circularly polarised (CP) antennas have gained much attention due to their improved immunity to multipath distortion and polarization mismatch losses including those caused by Faraday rotation. These properties are desirable for satellite communications, WLAN and RFID systems. However the number of compact CP antennas with omnidirectional patterns is still very small. These antennas are needed for multi-user communication in indoor environments with many scatters (e.g. RFID or WLAN systems). In satellite communication, where one traditionally expects the beam to be directed towards the sky, the orientation of the antenna cannot be a priori determined for many applications, making omnidirectional antennas desirable. Moreover, many modern systems require dual-band operation with relatively low frequency ratios (i.e. the ratio between GPS L1 and L2 bands is 1.28; between L1 and Galileo E6, it is 1.232), which introduces additional complexity to the design.

To the best of our knowledge, there are no works in the open literature reporting dual-band omnidirectional CP antennas. The first approach to provide omnidirectional CP (for single frequency) involved an array of radiating elements, located around a common centre [1]-[4]. These solutions are somewhat large and more complex to manufacture than planar structures. Attempts to reduce the number of radiators degraded the performance, with shouldering and dipping in the radiation pattern [2], [3]. A lower profile antenna was proposed in [5], where omnidirectionality was achieved by superposition of four horizontally polarized stubs and a vertically polarized mushroom structure.

There is however very little reported work introducing omnidirectional CP behavior using planar structures. The first one employs epsilon negative material and its zeroth order resonance to replace a mushroom in [5] by a completely planar structure [6]. It exhibits good omnidirectional axial ratio (AR), however the use of five combined elements and zeroth order resonance makes it difficult to modify the antenna for dual band operation.

Another paper introduces the basic concept of using back-to-back coupled patches [7]. The AR in the plane of omnidirectionality for the planar structure is kept within a 4 dB limit and the $S_{11}$ is -11.19 dB for the CP frequency. There is however around 6 dB variation in the CP radiation pattern and no gain value reported.

Many techniques have been proposed to implement dual-frequency patch antennas for unidirectional CP, including stacked patches [8], dual-negative materials [9], slots cut in the patch [10]-[12] or complex annular ring structures [13].

From the above-mentioned patch structures, the slot loaded rectangular patch was chosen for our design due to its simplicity and relative compactness (compared to the stacked patch). Slots can be used to perturb the current distribution, shifting the higher modes down in frequency and modifying their radiation pattern to be broadband. Typically there is a slot along each radiating edge of the antenna [10], [12]. Such configuration employs a third resonant mode ($TM_{300}$), generating an unwanted $TM_{300}$ mode that needs to be suppressed. As typical CP patch antennas employ two orthogonal modes, a total of four slots would be required using this technique.

In this paper the first dual-frequency antenna with omnidirectional performance is proposed. The omnidirectional right-handed CP is achieved by employing back-to-back coupled patches. The use of a novel feed, a conducting strip connected between patches and a reduced ground plane size allows better impedance matching and reduced overall size, compared to [7]. Slots with capacitive loading provide dual-band operation, however in contrast to previous work, only two slots are used in each patch. This configuration supports $TM_{200}$ (and respectively orthogonal $TM_{020}$) mode rather than $TM_{300}$, simplifying the design.

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II. ANTENNA DESIGN

The antenna consists of two layers of substrate (Taconic™ RF 35, with $\varepsilon_r = 3.47$ and height $h = 1.54$ mm) placed between three layers of metallization. The inner metallization forms the ground plane and comprises the coplanar waveguide (CPW) feeding structure, whereas the outer ones form two patches in a back-to-back configuration. The patches are additionally connected together by a thin copper strip (see Fig. 1).

The radiators are electromagnetically-coupled to a 50 $\Omega$ CPW (with slot 1 mm wide, central strip - 4.7 mm) located along the diagonal of the patches. The end of the line is triangularly tapered to increase its impedance. The parameter $l_{CPW}$ was optimized to realize best matching (as the input resistance of the patch decreases towards its center). The use of the tapered transformer provides greater immunity to the slight difference in input impedance of the two resonant modes of the patch.

The other end of CPW transforms to a 5 mm long 50 $\Omega$ microstrip line (with the ground planes connected by vias) connected to an SMA. The substrates are cut along the footprint of the ground plane.

There are two slots cut in each patch, with a 1.5 pF lumped capacitor [14] connected across the centre. The slots are of slightly different lengths, which is one of the CP perturbation mechanisms.

The structure was manufactured using LPKF Proto Mat milling robot. The ground plane (layer B) was milled on both layers of substrate, providing better symmetry between the patches. For precise alignment, a row of holes along the antenna perimeter was used.

The antenna was simulated using the CST MWS Frequency-Domain Solver. The parameter values are: $l_a = 57$ mm; $l_b = 57.1$ mm; $s_p = 2.25$ mm; $l_{db} = 36.8$ mm; $l_{wa} = 35.8$ mm; $W_1 = 1.5$ mm; $\Delta s = 3$ mm; $W_3 = 5.0$ mm; $\Delta s = 14.0$ mm; $\Delta s = 2.0$ mm; $l_s = 12.0$ mm; $l_{pwe} = 50.8$ mm; $W_X = 20.0$ mm; $l_X = 29.7$ mm; $s = 64$ mm. The width of tuning stubs are $W_1 = 9.0$ mm for layer C side and $W_2 = 6.0$ mm for layer A.

III. SIMULATION AND MEASUREMENTS

The antenna radiates right handed circular polarization (RHCP) for both the upper and lower frequencies of 1.565 GHz ($S_{11} = -22.8$ dB) and 1.329 GHz ($S_{11} = -11.7$ dB) respectively, with a frequency ratio of 1.178. This is smaller than presented in [13], [12] and can be easily returned to fit into the E5a, E5b, L2 or even the E6 band. The simulated AR in the $xz$-plane varies from 1.2 dB to 2.9 dB for the lower band and from 2.5 dB to 5 dB for the upper band. The antenna was prototyped and tested. Fig. 2 shows good $S_{11}$ agreement between simulation and measurement. The simulated radiation efficiency is 62% for the lower band and 50% for the upper band.

The measured $S_{11}$ exhibits a good dual-band response, with no additional modes between bands (as expected by employing only a single slot per mode). The measured AR is shown in Fig 3 and remains between 0.4 dB to 3.8 dB for the lower band and is in reasonable agreement with the simulation. For the higher band the AR varies 0.6 dB to 4.4 dB. Although it is higher than a 3 dB limit popularly accepted for unidirectional CP antennas, it still provides better than 12 dB isolation between RHCP and LhCP over the full omnidirectional plane. Fig. 4 depicts the AR as a function of both angle and frequency. The measured frequency ratio is 1.182. A clear omnidirectional and dual-band pattern can be seen. The radiation patterns are shown in Figs. 5-6 for the $zx$ (omnidirectional) plane and in Figs 7-8 for the $zy$ plane. The RHCP gain ranges from -0.7 dBic to -4.5 dBic for the upper band and from -0.7 dBic to -4 dBic for the lower band. The gain for the upper frequency is in good agreement but for the lower band is up to 2 dB less than simulated. This is because of feeder cable effects due to the small ground plane. Additional simulations, which incorporated the feeder cable section as in [15] support this explanation, but are not shown for brevity.

Fig. 1 Antenna geometry with key parameters across different layers of metallization (for convenience substrate thickness on the left is not to scale).
Fig. 2 The measured and simulated $S_{11}$ for the proposed antenna.

Fig. 3 The simulated and measured axial ratio for the lower and upper frequency.

Fig. 4 The measured axial ratio as a function of angle and frequency. For convenience, values above 6 dB are denoted by the grey color. Optimum frequencies are 1.325 GHz and 1.567 GHz.

Fig. 5 The measured and simulated radiation patterns in the $zx$-plane ($\phi = 0$ cut) for the lower band. Angle $\theta = 0$ corresponds to the direction of $z$-axis.

Fig. 6 The measured and simulated radiation patterns in the $zx$-plane ($\phi = 0$ cut) for the upper band. Angle $\theta = 0$ corresponds to the direction of $z$-axis.

Fig. 7 The measured and simulated radiation patterns in the $zy$-plane ($\phi = 90$ cut) for the lower band. Angle $\theta = 0$ corresponds to the direction of $z$-axis.
Fig. 8 The measured and simulated radiation patterns in the $xy$-plane ($\phi = 90^\circ$ cut) for the upper band. Angle $\theta = 0^\circ$ corresponds to the direction of $z$-axis.

IV. DESIGN PROCESS

The overview of the design sequence used is as follows:

1) Calculate the initial lengths of the patch ($l_a$ and $l_b$, which at this stage can be equal), which should be approximately one half of an electrical wavelength at the lower resonant frequency (TM$_{100}$ mode) for the given substrate.

2) Initially set the slot length $l_{s0} = l_{sb} = 0.63 \ l_e$; the slot-to-edge separation $s_e = 0.04 \ l_a$ and the slot width $W_s = 0.026 \ l_e$. With these values, increased lumped element capacitance (within 1 - 2 pF range) reduces the frequency ratio (FR). This property and a full-wave electromagnetic simulation was used to yield the desired FR. Note that the FR reduction factor may vary for different substrates.

3) The lumped capacitors should lower both resonant frequencies. Therefore additional adjustment is needed, by properly setting the patch size ($l_1$ and $l_2$) and slot parameters ($l_{sb}$, $l_{sa}$ and $W_s$).

4) The impedance match is adjusted by proper selection of parameters $s_e$ and $\Delta l$, as well as small variations in the ground plane size $S$.  

5) The AR at both frequencies is tuned to achieve omnidirectional CP radiation. This requires adjustment of stub widths $W_1$ and $W_2$, as well as introducing a small difference between slot lengths $l_{sa}$ and $l_{sb}$, and between the patch dimensions $l_a$ and $l_b$. (Note that where the symmetry is compromised an independent adjustment might be necessary).

The following sections provide a more in-depth description of the design steps.

A. Dual-band Operation

In [10] a simple model was proposed for prediction of the upper resonant frequency. The model was given for a linearly polarized antenna with two slots without capacitors. It approximates the area around a slot as a thin microwave resonating stub (as shown in Fig. 9). The proposed antenna is significantly different to [10] and [12], as it employs additional stubs, single slot per mode and a connection between both patches. Some coupling will exist for slots in close proximity, resulting in less accurate predictions [10]. To minimize this, the slots have been separated ($\Delta s = 3 \ mm$). Despite these differences, the model is still useful to qualitatively demonstrate the operation principle of the proposed antenna.

The lower band is also influenced by the slots, as shown in Fig. 10. The resonant frequency decreases with increased slot length $l_{sb}$ and $l_{sa}$. For longer slots the TM$_{010}$ and TM$_{011}$ mode currents are more disturbed, resulting in poor matching.

The ratio between the two frequencies can be varied by changing the lumped capacitance. As can be seen in Fig. 11, greater capacitance values shift both operating bands downwards and also reduce the FR. To tune the antenna for the L1/L2 GPS band a capacitor of approximately 1 pF should be used, which gives a FR of around 1.26. Table 1 provides some typical FR values for different values of ideal capacitors. As the FR is also dependant on the size and location of the slots all values in Table 1 are given for $l_{sb} = 36.8 \ mm$ and $l_{sa} = 35.8 \ mm$. Above a certain value there is no further decrease in FR, although both operating frequencies continue to decrease.

Fig. 9 The edge of the patch illustrating the resonating stub. The length of the stub is $W_s = 2 \ * \ l_{sa} / 2$.

Fig. 10 The simulated $S_{11}$ for different slot lengths ($l_{sa} - l_{sb} = 1 \ mm$ for all configurations).
A small difference between the slot lengths has been used for CP generation in [12]. Fig. 13 shows the simulated $S_{11}$ for different values of $l_{sb}$. As $l_{wa}$ is kept constant, this parameter also controls the lower orthogonal mode. In general for $l_{wa} > l_{sb}$, LHCP is achieved (assuming no other perturbation elements).

A small difference between the slot lengths should be considered, as the AR is heavily dependent on this parameter. Fig. 14 shows that even a small variation of 1 mm can strongly degrade the AR, as well as shift its optimum frequency (here by up to 6 MHz).
frequency ratio of 1.182, a good AR for both bands and more than 12 dB of cross-polar isolation.

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V. CONCLUSION

A back-to-back microstrip patch antenna was shown to provide omnidirectional circular polarization over two frequency bands. The structure employs a small ground plane and lumped capacitor loaded slots which enable the generation of TM_{200} and TM_{020} modes. The prototype antenna has a low

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Dr. Ammann received a best paper award at the 2006 Loughborough Antennas and Propagation Conference, the 2009 SPI best paper award in the China Ireland International Conference in ICT and commercialization awards for work with DecaWave Ltd, Taoglas Ltd and Sequoia Smart Solutions. He also received a 2008 CST University Publication Award for work on a “Wideband Reconfigurable Rolled Planar Monopole Antenna” and a 2011 CST Award for work on “Miniature Ceramic Dual-PIFA Antenna to Support Band Group 1 UWB Functionality in Mobile Handset”. He sits on the management committee of the EU COST Action IC1102, “Versatile, Integrated, and Signal-aware Technologies for Antennas (VISTA)” and is active in the EurAAP working group on small antennas. As a member of the IEEE International Committee for Electromagnetic Safety, he participated in the revision of the IEEE Std. C95.1, 2005 & 2012 standards for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz. He is also a member of the URSI Committee for Communications and Radio Science within the Royal Irish Academy and official member of URSI Commission K: Electromagnetics in Biology and Medicine. He has chaired and organized special sessions on small antennas, UWB antennas and UWB Wireless Communication Systems at EuCAP and IEEE APS and chaired the Antennas and Propagation Track for the 65th IEEE VTC, Dublin 2007. He was the local chair for the October 2008 EuCAP IC0603 workshop and meeting in Dublin. He is currently associate editor for the IEEE Antennas & Wireless Propagation Letters.