A Wideband, Dual-Polarized, Differentially-Fed Cavity-Backed Slot Antenna

***Rajesh C. Paryani*[1], *Parveen F. Wahid*[1], *and Nader Behdad*[1]**

[1]School of Electrical Engineering and Computer Science
University of Central Florida,
4000 Central Florida Blvd., Orlando, FL 32816, U.S.A.
email: paryani@mail.ucf.edu, wahid@mail.ucf.edu, behdad@mail.ucf.edu

Abstract

A new technique for designing wideband dual-polarized cavity-backed slot antennas, that are especially suitable for operation in an array environment, is presented. The proposed structure is in the form of a double-resonant, differentially-fed dual-polarized slot antenna backed by a shallow cavity with a height of $\lambda_0/10$. The dual-polarized nature of this radiating element allows for synthesis of any desired polarization. The double-resonant behavior observed in this antenna is utilized to enhance its bandwidth compared to a typical cavity-backed slot antenna. Measurement results indicate that a bandwidth of 21%, an average gain of 5 dB, and a differential isolation of 30 dB can easily be achieved using this technique.

1. Introduction

The past several decades have seen an ever-growing proliferation of wireless communications systems and increased congestion in the electromagnetic spectrum. Pushing the capabilities of systems beyond what has been achieved so far presents new challenges which must be overcome by design engineers. Topping the list of design challenges are antennas needed to satisfy these requirements. To increase the capacity and/or the reliability of wireless communications systems, new technologies such as receiver diversity (both spatial and polarization) or multiple input multiple output (MIMO) communications have been developed. For the same bandwidth and frequency of operation, using two orthogonal polarizations allows for doubling the transmission capacity, as commonly used in Direct Broadcast Satellite (DBS) systems. In other situations two orthogonal polarizations can be used to allow diversity schemes when a channel is found to be insufficiently performing. Moreover, wideband dual-polarized antennas are frequently used in polarimetric and other radar applications. Therefore, the need for the development of highly reliable low-profile and low-cost wideband antennas, with the capability to operate under arbitrary polarization, is now felt more than ever.

The current state of the art in the design of wideband dual-polarized antennas seems to be dominated by microstrip antennas, which suffer from inherent narrow bandwidths and are susceptible to surface wave propagation, especially when used in array environments. Techniques such as aperture coupling have been used to increase the bandwidth of dual-polarized or circular-polarized microstrip antenna, however the methods employed often lead to narrow polarization purity bandwidths or require large feeding networks. Furthermore, these antennas still remain as susceptible to surface wave propagation as any other microstrip patch antenna. Therefore, microstrip radiating elements, in spite of their well-known advantages, are not ideal radiating elements for such applications. The cavity-backed slot antenna (CBSA) has also been investigated as a wideband dual-polarized radiator. This element can also be implemented to obtain circular polarization with a hemispherical radiation pattern. Single feed designs achieve good polarization purity and maintain compactness; however, they remain very narrow band. Strip or microstrip line fed variations have also been reported [1], but exhibit bandwidths of less than 10%. A CBSA with a bandwidth of 20% was reported in [2], and a ridged cavity was used by [3] to achieve a 32% bandwidth. However, in both cases the slot length was greater than a wavelength. These electrically large antennas will not be ideal choices for use in an array environment.

In this paper, we propose a wideband dual-polarized differentially-fed cavity-backed slot antenna (DFCBSA). The use of differential feeding allows the antenna to achieve a high degree of isolation between its two differential feeding ports. Moreover, the antenna demonstrates a unidirectional radiation pattern, which remains consistent across its entire frequency band of operation and provides a front-to-back ratio of about 14 dB. The antenna is designed with a simple and inexpensive fabrication process in mind. This makes it widely suitable for a multitude of applications which require wideband polarization diversity, dual-polarization, or circular polarization, but are restricted from using other topologies which are prohibitively high cost or involve complex design or manufacturing procedures. Examples include

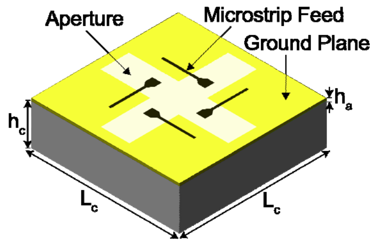

Figure 1: 3D view of the dual-polarized CBSA.

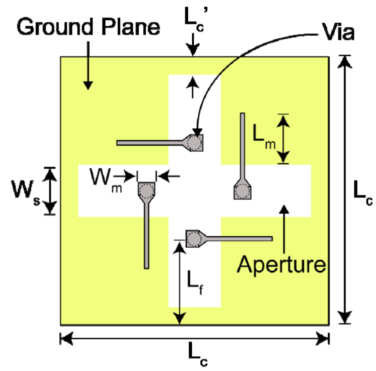

Figure 2: Detailed top view of the DFCBSA.

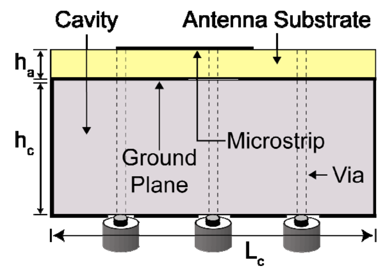

Figure 3: Detailed side view of the DFCBSA.

electronically steerable array applications, automotive radars, on the move (OTM) communications, or satellite telemetry and tracking to name a few. In the following sections, the antenna topology is described and the principles of its operation are outlined. Basic design considerations and simulation results for an X-Band proof of concept prototype are presented. Finally, a prototype antenna is fabricated and characterized, and a discussion on how to improve the performance of the design is given.

2. Principles of Operation

Figure 1 presents a perspective view of the wideband dual-polarized differentially-fed CBSA. The antenna consists of a symmetric aperture situated on top of a shallow cavity. The use of a cavity serves two main purposes. It prevents the propagation of surface waves and creates a unidirectional radiation. This way, a hemispherical radiation pattern with a high front-to-back ratio is obtained. The antenna aperture is composed of two orthogonal wide slots, forming a cross at the center of the cavity. A dual differential feeding scheme is used to feed the crossed-slot and prevent coupling between the orthogonal modes. This enables the DFCBSA to maintain a high degree of isolation between the two differential ports over a wide impedance bandwidth. Four microstrip lines are printed on top of a second substrate located above the cavity and are used to feed the slots. Detailed views of the antenna stackup as well as the relative locations of the feeding elements with respect to the radiating elements are shown in Figure 2 - Figure 3.

The four microstrip line feeds are connected to four feeding coaxial cables located behind the cavity using four vias that extend from the microstrip layer on the top to the bottom of the cavity, where they are connected to the center conductors of their respective coaxial cables as shown in Figure 3. It is also possible to use a different feeding arrangement in which the microstrip lines are placed below the slot layer. This design will have the advantage of isolating the feeding structure from the outside world but is considerably more difficult to fabricate. In the present form, the antenna aperture, which also serves as the microstrip ground plane, can be directly connected to the cavity walls. This facilitates the fabrication of the antenna and the tuning of the feed network after the antenna is fabricated. In [4] it was shown that a wide radiating slot can demonstrate a double-resonant behavior if it is fed with an off center microstrip line. The second resonance is caused by a fictitious short circuit created by that portion of the microstrip line without any ground plane, which acts as an electrically small Hertzian dipole. Thus, by changing the location of the microstrip line, the frequency of the second resonance can be adjusted and either a wideband or a dual-band response can be obtained. The use of an open circuited microstrip stub provides a degree of flexibility in matching the input impedance of the antenna to that of its feeding transmission line. To ensure that the antenna is fed in a balanced fashion and undesired modes are not excited, a differential feeding scheme is employed, whereby each slot is fed on either end of the junction with equal amplitude and 180˚ phase difference. As a result of the differential feeding, the electric field distribution is anti-symmetric along one slot. Therefore, this slot does not significantly contribute to the far-field radiation. On the other hand, the field distribution along the orthogonal slot is symmetric and resembles that of a half wavelength slot. This allows the antenna to operate with vertical, horizontal, or dual-polarization while maintaining good isolation between its two differential ports. Quadrature feeding may be employed to achieve circular polarization, resulting in feeding the 4 ports of the antenna with equal amplitudes and phases of 0˚, 90˚, 180˚, and 270˚.

3. Design Procedure and Simulation Results

A prototype antenna similar to the one shown in Figure 1 is designed and simulated using the commercial electromagnetic simulation software CST Microwave Studio. The slot length, L_s, is the primary factor that determines the first resonant frequency of the antenna. The frequency of the second resonance is adjusted by adjusting the location of the microstrip feeds. The distance measured from the edge of the slot to the feed point, L_f, also determines the location of the vias. The probes are found to have the least effect when situated at the center of the slot. Increasing the slot width, W_s, increases the bandwidth of the antenna. A detailed description of the double-resonant nature of wide, microstrip-fed slot antennas along with a parametric study on the effect of changing the design variables (L_f, L_m ...) are presented in [4] and will not be repeated here. Once the two resonances are obtained at the desired frequencies, the antenna is impedance matched by tuning the length of the open circuited microstrip stubs, L_m. The reactive impedance introduced by the stub will compensate the reactive part of the antennas input impedance. The physical dimensions of the antenna are optimized simultaneously, with each slot having the same length and width, and each of the four feeds remaining identical. In order to achieve a wide bandwidth, a low dielectric constant material (Rogers® RT/duroid 5880) is chosen for the cavity and the antenna substrate. The time domain (FIT based) solver of CST Microwave Studio is used to perform the full-wave simulations and the 4 port S-parameter results are further processed with CST's integrated circuit simulation package to introduce the required 180˚ phase differences required for the proposed differential feeding scheme. Differential port 1 (DP1) is obtained by feeding the two ports of one slot with the same magnitude and 180˚ phase shift. Similarly, differential port 2 (DP2) is obtained by feeding the two ports of the orthogonal slot with the same magnitude and 180˚ phase shift. The optimized dimensions of the X-band prototype are presented in Table 1. Simulated results indicate each differential port achieves a 22% impedance bandwidth ($D-S_{11} < -10$ dB). In addition, the isolation between the two differential ports ($D-S_{21}$) is predicted to be better than 80 dB.

Parameter	Value (mm)	Parameter	Value (mm)
L_s	14.0	L_m	0.0
W_s	3.1	h_c	3.175
L'_c	0.1	h_a	0.508
L_f	3.5		

Table 1: Optimized physical dimensions of the X-band prototype

4. Measurement Results

A prototype antenna is fabricated using the fabrication facilities at the Antenna, RF, Microwave, and Integrated Systems (ARMI) lab of the University of Central Florida. The S-parameters of the fabricated antenna are characterized using an Agilent N5230A two-port Vector Network Analyzer. Then, in the post processing step, the required 180˚ phase shifts are added in Agilent Advanced Design System (ADS) software in a manner similar to that described in [5]. The

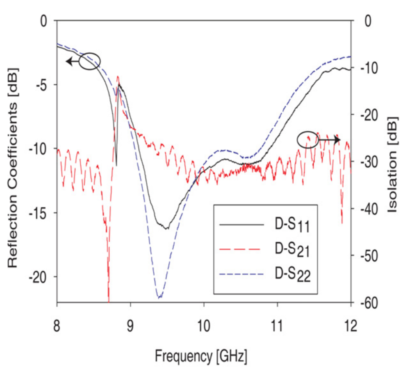

Figure 4: Measured S-parameters of the differentially-fed cavity-backed slot antenna.

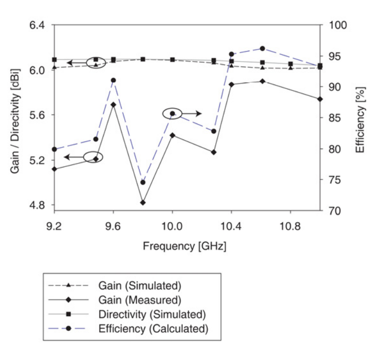

Figure 5: Measured and Simulated Gain, Directivity, and Radiation Efficiency

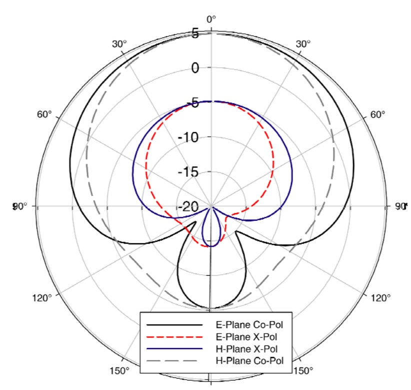

Figure 6: Simulated Radiation Patterns of the DFCBSA at 9.044 GHz

measured input reflection coefficient for each differential port and the isolation between the two differential ports are plotted Figure 4.

It is observed that an impedance bandwidth of 21.4% is obtained for both DP1 and DP2 ($D-S_{11} < -10$ dB, $D-S_{22} < -10$ dB). In addition, the isolation between the two differential ports is maintained at about 30 dB. The discrepancies between the simulated and measured results, notably the difference between the measured and predicted isolation, are attributed to the fabrication tolerances such as the photomask resolution, alignment of the double sided antenna substrate, etc. as well as simulation inaccuracies. Nevertheless, the measured results indicate an acceptable performance and isolation levels. Other radiation parameters of the antenna including its radiation patterns, gain, and radiation efficiency are measured in the anechoic chamber of the University of Central Florida. The co-polarized and cross-polarized components of the E-plane and H-plane radiation pattern are measured at several frequencies, for each differential port. They are found to be in good agreement with the predicted results, however are omitted here for the sake of brevity. The observed hemispherical radiation patterns are consistent throughout the wide operational bandwidth, exhibiting a good front-to-back ratio of 14 dB. The simulated radiation patterns at the first resonance are presented in Figure 5. Complete radiation pattern measurements will be presented at the URSI General Assembly. In order to measure the gain of the antenna, an X-band standard gain horn is used as the reference. The measured and simulated gain, directivity, and calculated radiation efficiency are plotted in Figure 6. Finally, it is noted that there is a significantly high (approximately −10 dB) level of cross polarized radiation in each of the radiation patterns. This is due to an oversight when designing the microstrip feed lines. The network had been designed to be rotationally symmetric; however it is not electrically symmetric. Since the direction of the microstrip lines are opposite each other for each pair of differential feeds, the excited modes are 180° out of phase with one another. When the additional 180°, required to achieve the differential feeding, is added, it actually causes the microstrip currents to be in phase thus creating a high level of cross polarized radiation. To address this problem, the antenna is simulated with the direction of the microstrip lines for each differentially fed pair adjusted to the same direction. The observed result is a large decrease in the cross polarization level to about −25 dB at boresight. The corrected feed geometry will be incorporated into future designs to improve the performance of the antenna.

5. Conclusion

A new technique for designing wideband dual-polarized differentially-fed cavity-backed slot antennas was presented in this paper. The design has been validated in the X-band, and achieves a wideband operation with a hemispherical pattern, and a uniform gain and front-to-back ratio over its operational range. A technique to improve the cross polarization level was also presented. The proposed antenna will be an ideal candidate for a variety of applications which require wideband dual-polarized or circular polarized radiation.

6. Acknowledgments

The authors would like to thank the Rogers Corporation for providing samples of RT/duroid 5880 dielectric substrate for this project.

7. References

1. C. A. Lindberg, “A shallow-cavity uhf crossed-slot antenna,” *IEEE Trans. Antennas Propag.*, **17**, Sep. 1969, pp. 558–563.

2. H. E. King and J. L. Wong, “A shallow ridged-cavity crossed-slot antenna for the 240- to 400-mhz frequency range,” *IEEE Trans. Antennas Propag.*, **23**, Sep. 1975, pp. 687–689.

3. N. T. Kazaross, H. H. Chung, and S. Y. Peng, “Improvement of crossed-slot element design for msat-x applications,” *International Symposium on Antennas and Propagation Proceedings*, San Jose, CA, 1989, pp. 1336–1339.

4. N. Behdad and K. Sarabandi, “A wide-band slot antenna design employing a fictitious short circuit concept,” *IEEE Trans. Antennas Propag.*, **53**, Jan. 2005, pp. 475–482.

5. L. Sun, Z. Wang, and J. Gao, “A method for on-wafer s-parameter measurement of a differential amplifier by using two-port network analyzer,” *Asia-Pacific Conference Proceedings*, Suzhou, China, 2005.