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A Compact Dielectric-Filled Slotted Cavity MIMO Antenna

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Abstract—This paper presents a compact slotted MIMO cube antenna operating at 5.8 GHz, consisting of three orthogonal slots, each with a distinct main direction of radiation. Each slot produces linear polarization enabling the structure to radiate three orthogonal polarizations. This provides spatial diversity which helps mitigating the effects of multipath propagation and enhances the diversity gain. The cube is filled with a dielectric with a relative permittivity, ε_r thus reducing the minimum dimension of the cube by a factor of $1/\sqrt{\varepsilon_r}$. The antenna has a return loss of 20 dB and a coupling of less than −26 dB between the ports. This paper describes the principle operation as well as the design and manufacturing process of the proposed antenna.

1. INTRODUCTION

Communication channels in urban and indoor environments are characterized by multipath fading effects which degrade the channel quality and restrict the achievable data rate. This problem can be overcome by using antenna diversity where multiple antennas receive uncorrelated signals. Alternatively, multiple-input-multiple-output (MIMO) systems can be utilized, where multiple antennas are used at both the transmitter and the receiver to create antenna diversity.

Several factors need to be considered with multiport antennas for MIMO applications. The physical size of the antenna system is often restricted when it is to be used on compact platforms, thus necessitating compactness. Mutual coupling between the antenna elements should preferably be low, the antennas should be well matched and display high efficiency. The frequency bandwidth of the antenna should meet the system requirements. Important radiation characteristics include antenna gain, high cross-polar discrimination and multiple spatial radiation pattern capability.

The most common way to achieve polarization diversity is to arrange antennas orthogonally to each other on a compact, three-dimensional platform and to excite each element with a distinct port. The MIMO cube [1, 2] consists of 12 dipoles located on the edges of a cube. Practical issues such as high mutual coupling between the dipoles, impedance matching of the dipoles, radiation efficiency of the structure, forming the cube assembly with all the 12 feeders and other aspects influence the operation and the capacity of the MIMO cube [1]. In order to reduce mutual coupling between ports, slot dipoles are implemented on separated plates in [3]. A different take on this was proposed in [4], where three orthogonal slots on different faces of a rectangular metallic cavity are used as radiating elements and individual elements are excited by probes on alternating faces. The minimum dimension of the cube is $a = \lambda_0/\sqrt{2}$ where λ_0 is the free-space wavelength at the design frequency. The voltage distribution of the slots resembles the current distribution of the dipoles, however, a much greater magnitude of current is required to produce a given power output using the dipole antennas [5]. Another advantage of using slots is that the feed section which energizes the slot may be placed below the metal surface in which the slot is cut. Each of the rectangular slots produces linear polarization which enables the

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structure to radiate three orthogonal polarizations in order to reduce fading effects. Each slot radiator has a distinct main direction of radiation, thus achieving radiation diversity as well. The combination of radiation and polarization diversity reduces the correlation of signals received or transmitted by each slot and therefore enhances the diversity gain.

In this paper, we extend this design by using a cavity filled with a dielectric with a relative permittivity ε_r, thus reducing the minimum dimension by a factor of $1/\sqrt{\varepsilon_r}$. This variation introduces additional challenges in the design of the slot feed structures. The reduced dimensions of the cube precludes the use of conventional cylindrical monopoles as probes. The close proximity of the ends of the posts at the center of the cube introduces unwanted coupling that makes implementation of decoupled ports virtually impossible, and decreases the capacity of the antenna [1]. To overcome this problem, shortened probes consisting of metallic cylinders terminated in conical frustums were used instead. The probe is designed to replace the center pin of a male SMA connector. The feed points were off-centered, and their positions were optimized to minimize the coupling between the three ports while ensuring a good impedance match.

The radiation efficiency impacts on various parameters of the antenna like the Q factor, bandwidth and gain [6]. The complex manufacturing and the presence of a dielectric necessitates the investigation of the radiation efficiency of the proposed antenna which provides a simple feasibility check of the proposed antenna. The radiation efficiency of the proposed antenna has been compared to the theoretical bound [7]. The proposed antenna displays a theoretical efficiency of better than 98%.

2. PRINCIPLE OF OPERATION

The principle of operation involves exciting the TE_{101} mode in the cube shaped metallic cavity, cutting slots in three of the faces in an arrangement such that only one of the slots would radiate. The TE_{101} fields in a cavity of side length a are given by [8]

$$\begin{aligned} H_z &= H_0 \cos(\pi x/a) \\ H_x &= -H_0 \sin(\pi x/a)\cos(\pi z/a) \\ E_y &= -\frac{j\omega\mu a}{\pi} H_0 \sin(\pi x/a)\cos(\pi z/a)\,. \end{aligned} \tag{1}$$

This mode can therefore be excited by inserting a vertical monopole in Face 1 (Port 1) of the cavity, to excite a y-directed electric field. The electric current density on the inner surfaces of an unperturbed cavity is depicted in Figure 1(a) and the locations of the three slots and the ports are shown in Figure 1(b).

An oscillating electric field is set up across the width of a slot when it interrupts electric currents flowing perpendicular to the axis of the slot, assuming that all slots are narrow and are located in the

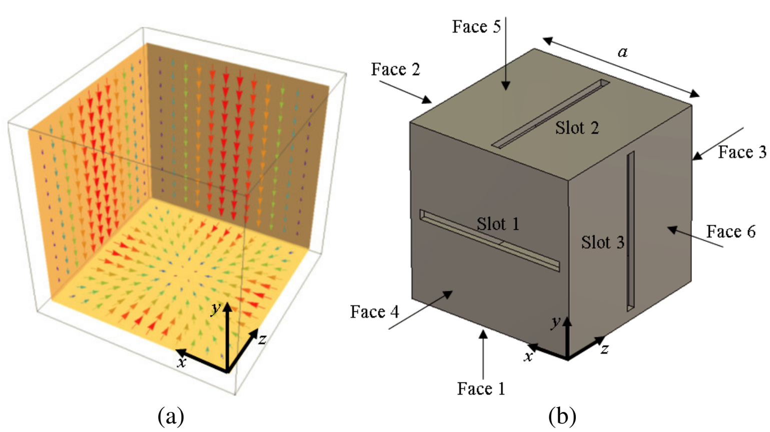


Figure 1. (a) Electric surface currents on the inner walls on an unperturbed cavity when fed by a monopole in the bottom face and (b) the positions of the three slots.

center of a face. It is evident that on feeding Port 1, Slot 1 on Face 4 interrupts the electric current which excites a y-directed electric field in the slot, causing it to radiate. Slot 2 on Face 5 is located at $x = a/2$, where the x-directed current density is essentially zero. The slot will therefore not interrupt current flow perpendicular to its axis, and will consequently not radiate. On Face 6, the electric currents flow in the y-direction, and since Slot 3 is aligned with the current flow, it will not radiate. From symmetry, it follows that a monopole probe inserted in Face 2 (Port 2) and Face 3 (Port 3) will excite an electric field across Slot 2 and Slot 3, respectively. The slots radiate perpendicular polarizations and inherently provide polarization diversity.

3. DESIGN

For a chosen center frequency f_0, the dimensions of the dielectric-filled cavity are calculated to achieve resonance of the TE_{101} mode, giving

$$a = \frac{\lambda_0}{\sqrt{2\varepsilon_r}}. \tag{2}$$

Resonant slots in waveguide arrays typically have a resonant length in the range of $0.48\lambda_0$ to $0.51\lambda_0$ [9, 10]. The requirement for the slot length to be smaller than the cavity dimension imposes an upper limit of the usable dielectric constant of $\varepsilon_r < 2.2$. In this case, Teflon ($\varepsilon_r = 2.1$) was chosen as the dielectric material. With a design frequency of $f_0 = 5.8\,\text{GHz}$, the slot length was set to $l = 24.96\,\text{mm}$ (i.e., $0.48\lambda_0$). The dimension given in (2) is for an unperturbed cavity. The presence of the slots causes a slight shift in resonant frequency, and consequently the cavity dimensions were adjusted through numerical experimentation to $a = 26.25\,\text{mm}$.

The monopole probes which excite the individual slots are geometrically orthogonal and largely excite electric fields aligned with the axis of the monopole. However, the reduction in cavity dimensions, close proximity of the dipoles, and some degree of cross polarization of the fields radiated into the cavity, introduce unwanted coupling at the external ports. For that reason, shortened probes consisting of metallic cylinders terminated in conical frustums were used. The probe is designed to replace the center pin of a male SMA connector. The dimensions of this probe are shown in Figure 2. With symmetry taken into consideration, the scattering parameters of the antenna array are given by

$$\mathbf{S} = \begin{bmatrix} S_{11} & S_{21} & S_{21} \\ S_{21} & S_{11} & S_{21} \\ S_{21} & S_{21} & S_{11} \end{bmatrix}. \tag{3}$$

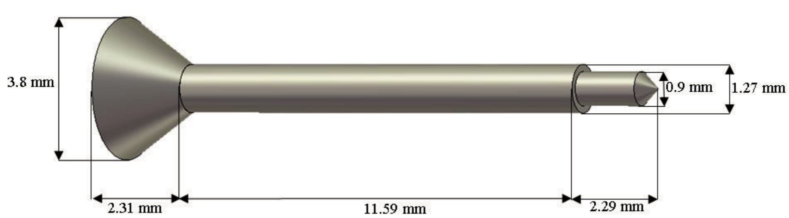


Figure 2. Dimensions of the shortened probe consisting of a metallic cylinder terminated in a conical frustum.

The objective of the design is to achieve a good impedance match while ensuring minimal coupling between the ports. To simultaneously meet these requirements, CST Microwave Studio simulations were carried out while varying the overall length of the probes and the position of the feed points to maximize the radiated power. The fraction of radiated power from each slot is given by

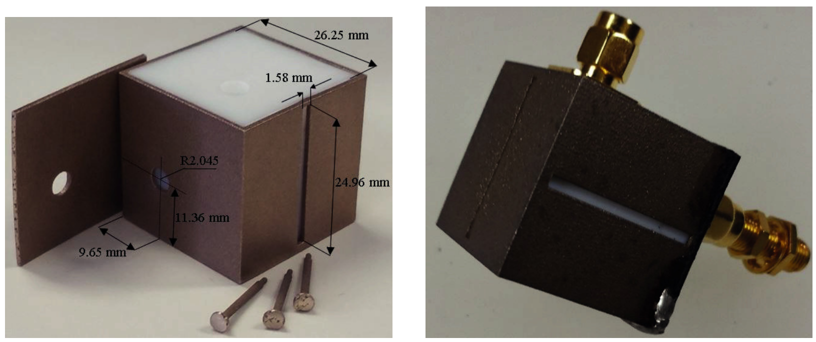
$$p = 1 - |S_{11}|^2 - 2|S_{21}|^2. \tag{4}$$

The cost function used in the optimization procedure in order to arrive at the dimensions shown in Figure 3(a) is therefore

$$f = |S_{11}|^2 + 2|S_{21}|^2. \tag{5}$$

4. MANUFACTURING AND RESULTS

An antenna prototype was manufactured using laser sintering technology. The conducting shell of the cavity was made from bronze (DM20) in two pieces: the first consisting of Faces 2 to 6 of the cavity walls, and a separate single face (Face 1) made to the correct dimensions and with the hole for the probe in the correct position. The probes were manufactured using the same technology. Subsequently, a block of Teflon was CNC machined to fit into the cavity and holes were drilled to accommodate the probes. Figure 3(a) shows a photograph of the different components of the prototype. Face 1 was soldered onto the shell to enclose the Teflon inside the cavity. The center conductors of male SMA connectors were removed and replaced by the shortened probes and the connectors were soldered onto the conducing shell. The assembled antenna is shown in Figure 3(b).



(a) (b)

Figure 3. (a) Components of the prototype antenna and (b) assembled slotted cavity MIMO antenna.

The measured scattering parameters of the antenna are shown in Figure 4. The resonant frequency is shifted by approximately 1% to 5.85 GHz, where it is well matched with a return loss exceeding 20 dB. The coupling between the ports is below −26 dB for the entire frequency range. The antenna has a narrow bandwidth of 2%, as the frequency at which the antenna resonates is strictly dependent on the dimensions of the structure.

The radiation efficiency, η_r, of an antenna impacts on the bandwidth and the gain of the antenna as reported in [11]. Figure 5 compares the radiation efficiency of the proposed antenna to the physical bound from [7]:

$$\eta_r = \frac{\sigma\eta_0 k_0^2 S\delta}{\sigma\eta_0 k_0^2 S\delta + 3\pi}, \tag{6}$$

where S, δ and k_0 are the surface area, skin depth and wave number respectively. It can be seen that the efficiency of the proposed antenna satisfies the general bound for a conductivity greater than 10^6 S/m, below which the results start to deviate similar to results presented in [7]. The efficiency of the proposed antenna indicates a very low reduction in efficiency due to the presence of the dielectric.

The E-plane and H-plane radiation patterns, depicted in Figure 6, show good agreement with the theoretical results. The antenna has a gain of 7 dB. The Envelope Correlation Coefficient (ECC) ρ_e, is an important figure of merit in evaluating MIMO antennas [12]. The ECC of the MIMO is calculated from [13]:

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1 - (|S_{11}|^2 + |S_{21}|^2))(1 - (|S_{22}|^2 + |S_{12}|^2))}. \tag{7}$$

Figure 7 compares the measured and simulated envelope correlation coefficients. The measured ECC is of the same order of magnitude as the simulated results, with a maximum value of 2×10^{-5} over the bandwidth at which the antenna resonates.

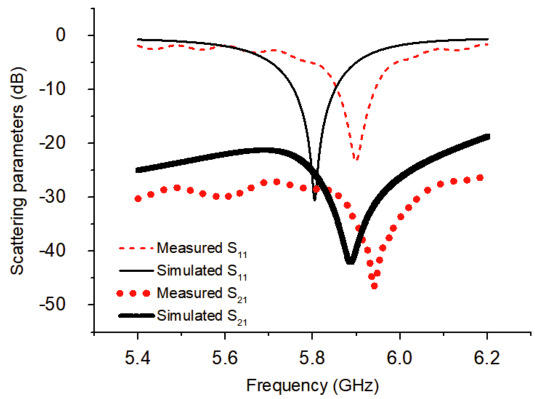


Figure 4. Simulated and measured scattering parameters of the prototype antenna.

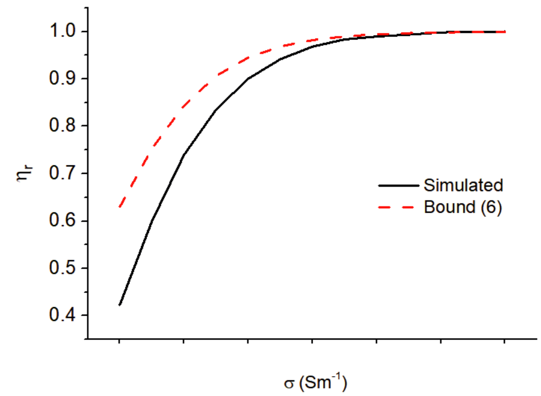
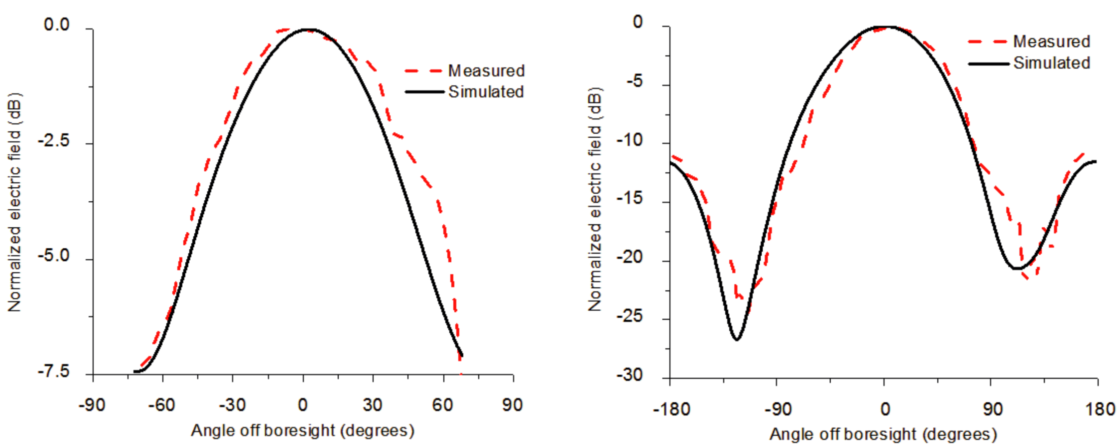


Figure 5. Variation of the efficiency (η_r) with conductivity (σ): the general bound (6) compared to the proposed antenna.



(a) (b)

Figure 6. Simulated and measured (a) E-plane and (b) H-plane radiation patterns.

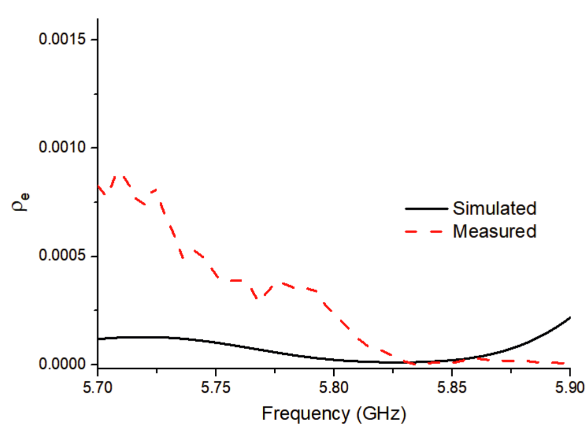


Figure 7. Simulated and measured ECC (ρ_e).

5. CONCLUSION

This paper presents a dielectric-filled, slotted cavity MIMO antenna with three orthogonal slots. Each of the rectangular slots has a distinct direction of maximum radiation and produces orthogonal polarization which enhances the diversity gain. The presence of dielectric results in approximately a 25% reduction in size compared to the air-filled antenna and displays a theoretical efficiency of more than 98%. This antenna provides a low return loss and high isolation between the input ports which makes it suitable for implementation in spatial multiplexing MIMO systems. This antenna can be used for high data-rate communication systems such as wireless local area networks.

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