Coupled Slot-Fed Microwave Slot Antennas on Cylindrical Substrates

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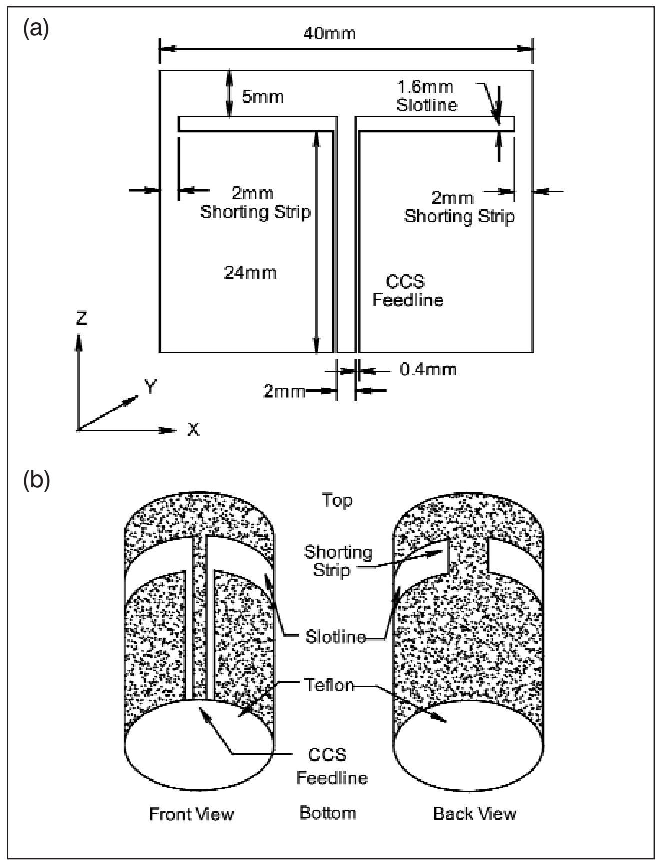
This paper describes cylindrical coupled slotline-fed (CCS-fed) slot and folded-slot antennas encompassing cylindrical substrates. Using a 1.27 cm diameter PTFE substrate, antennas that operate around 7 GHz have been realized with gains of 1.5 dB (slot) and 2.8 dB (folded slot). The antennas have a well-defined pattern null of 8 dB along the side of the CCS feedline. A 1.6 GHz slot antenna on a 1.27 cm diameter alumina substrate was also fabricated using a novel direct-write technique, which demonstrated comparable performance characteristics.

Introduction

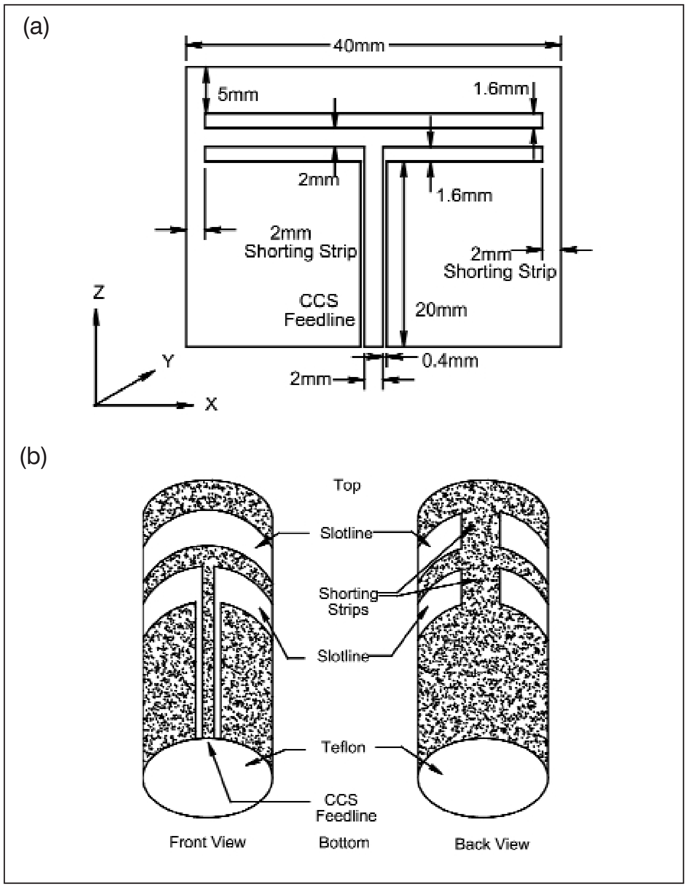
The use of a cylindrical substrate for microwave design is generally driven by the physical attributes of the system rather than by choice, since the analysis and fabrication are more complicated than for a comparable planar implementation. However, the cylindrical geometry can offer certain desirable antenna characteristics that are not provided by planar elements. There are also a variety of configurations that can be realized, such as cylindrical conformal patch and slot antennas [1-3], microstrip [4-6] and coplanar-like transmission lines [7-10].

The CCS-fed slot antennas printed on both PTFE and alumina discussed in this article were proven to be advantageous in that an omni-directional pattern was achieved with the possibility of a well-defined null normal to the antenna axis. Thus, the antenna is well suited for use in hand-held wireless applications. In instances where the cylinder is extended to displace the slot antenna from other circuitry, it was also found that passive elements (filters and matching networks) can be incorporated into the otherwise unused space [8].

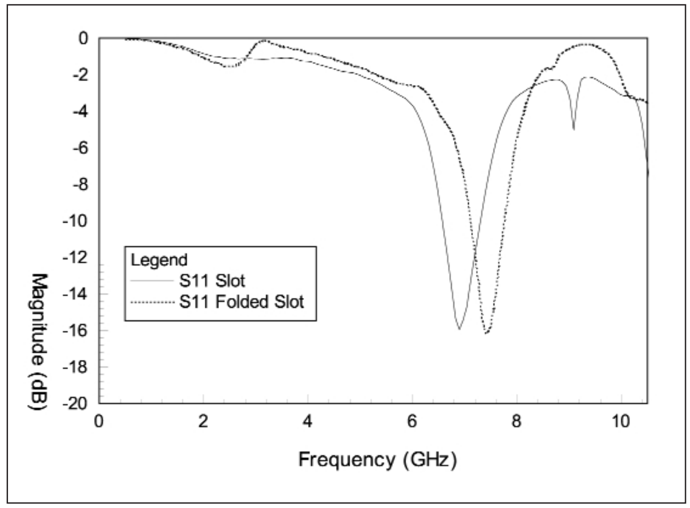


▲ **Figure 1. Cylindrical slot line antenna on PTFE: (a) two-dimensional view illustrating line and slot widths; (b) three-dimensional view with metal regions shaded (SMA connector not shown).**

The first part of this article describes single-



▲ **Figure 2. Cylindrical folded slot line antenna on PTFE: (a) two-dimensional view illustrating line and slot widths; (b) three-dimensional view with metal regions shaded (SMA connector not shown).**



▲ **Figure 3. Measured response of the antennas on PTFE with a 52-ohm (slot) and 40-ohm (folded slot) $\lambda_g/4$ impedance transformer.**

and folded-slot antennas on PTFE designed to operate around 7 GHz. For these designs, quarter-wavelength impedance matching sections have been incorporated into the cylindrical transmission line used to feed the antennas. The gain of the single- and folded-slot antennas was 1.5 dB and 2.8 dB, respectively. The second section describes a 1.6 GHz slot antenna that was fabricated on an alumina rod using a novel direct write technology. In this case, matching was achieved by proper placement of a shorting strip along the circumference of the slot and the measured gain was 2.6 dB. Input match and pattern measurements are presented for all designs.

Slot antennas on PTFE

Geometry and fabrication

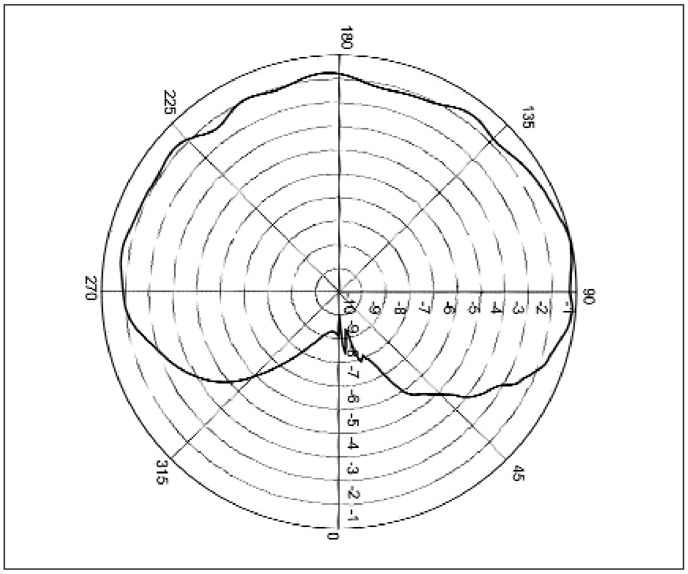
The cylindrical slot- and folded-slot antenna designs for the PTFE substrate are shown in Figures 1(a) and 2(a). The antennas were constructed with a conductive strip across the radiating slotline and placed opposite the CCS center conductor. The CCS feedline dimensions are 2 mm for S and 0.4 mm for W. The CCS dimensions correspond to a characteristic impedance of 76 ohms, as determined from a conformal mapping program [11]. Three-dimensional views of the antennas are illustrated in Figures 1(b) and 2(b).

The antennas were fabricated on a thin microwave substrate material with a dielectric constant (ε_r) of 2.06 [12]. The chosen substrate has a copper conductor thickness of one-third ounce (12 µm) and a dielectric thickness of 3 mils (76.2 µm). After processing, the thin substrate was wrapped around the cylindrical PTFE rod and soldered to form a continuous ground plane on the side opposite the feedline. An SMA connector was fastened to one end of the dielectric rod and soldered to the CCS center conductor and ground planes.

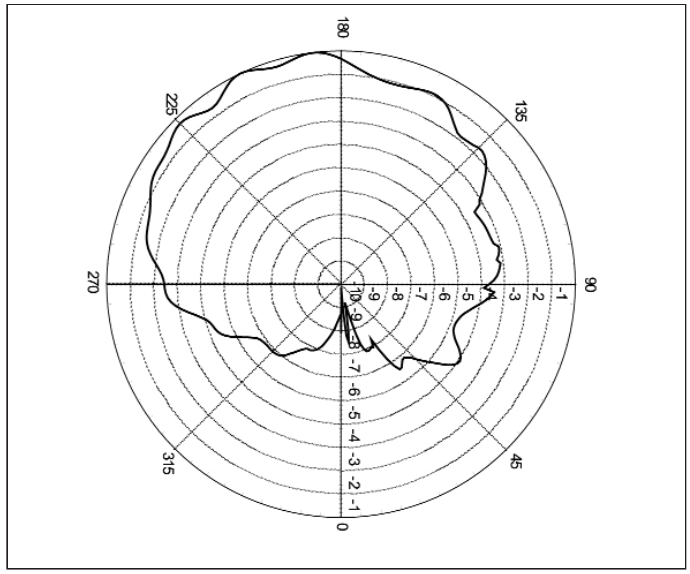
Antenna performance

The return loss of each antenna was measured on a Hewlett-Packard 8510 Vector Network Analyzer (VNA) following a Thru-Reflect-Line (TRL) calibration using CCS standards. Input impedances around the 7 GHz resonance frequency were determined to be 36 ohms for the slot and 21 ohms for the folded slot. In order to improve the match to the 76 ohms reference impedance, $\lambda/4$ impedance transformers were incorporated into the feedlines of the antennas. The return loss for the modified antennas is shown in Figure 3. The center frequency occurs at the point when the slot circumference is approximately λ_g, where λ_g is the guide wavelength using an effective dielectric constant of 1.5 for the slotted region [10].

The H-plane patterns for the slot are shown in Figure 4; the folded slot antenna is shown in Figures 5. (The H-plane corresponds to the *x-y* plane, as indicated in Figures 2(a) and 3(a).) In each case, a well-defined null occurs around the $\phi = 0$ degree direction, corresponding to the feedline side of the cylinder. The pattern asym-



▲ **Figure 4. H-plane slot antenna radiation pattern with CCS feedline side of antenna referenced to 0 degrees.**



▲ **Figure 5. H-plane folded slot antenna radiation pattern with CCS feedline side of antenna referenced to 0 degrees.**

▲ **Figure 6. Photograph of the cylindrical slot antennas fabricated on 1.27 cm diameter alumina rods. The upper image shows the shorted ends of the slot on the back side of the antenna. The lower image shows the cylindrical coupled slot feedline.**

metry could be related to the feedline discontinuities, and the deep cancellation may be due to destructive interference through the center of the cylinder; at 7 GHz, the rod diameter corresponds to $\sim \lambda_g/2$ using the $\varepsilon_r = 2.06$ dielectric constant.

Due to the relatively short length of the CCS feedline and the presence of the SMA connector, it was not possible to accurately measure E-plane patterns. Using a standard gain horn as the reference antenna, the maximum gain was determined to be 1.48 dB for the slot and 2.84 dB for the folded slot.

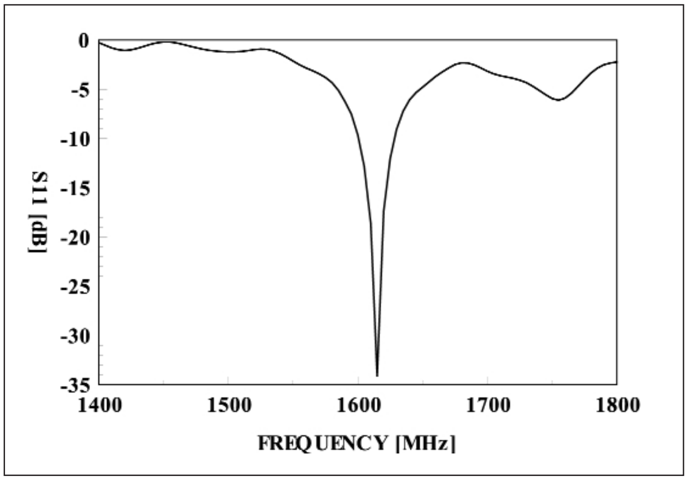
Slot antenna on alumina

Geometry and fabrication

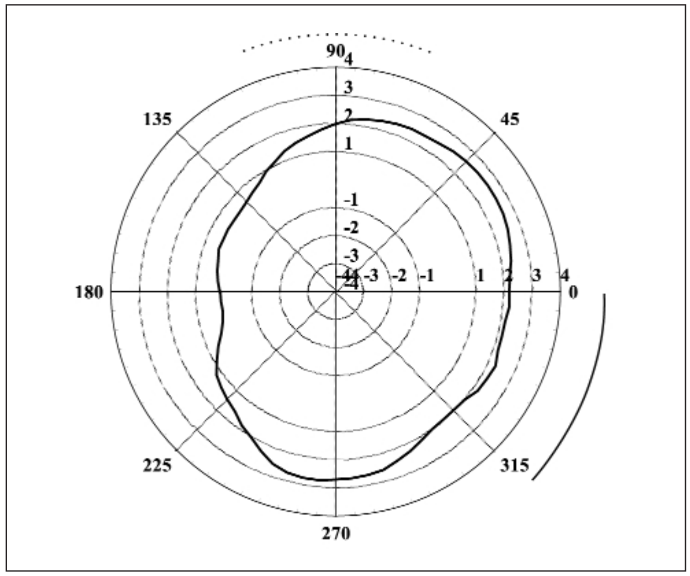
As illustrated in Figure 6, the slot antenna (1.5 mm width) extends partially around the circumference of the 1.27 cm diameter cylinder where it is terminated by a shorting strip with a 4.8 mm arc length. The coupled slotline (CCS) feed has 1.14 mm wide slots separated by 2.5 mm. The characteristic impedance of the feedline is 50 ohms.

The alumina substrate for a cylindrical slot antenna offers the advantages gained by a high ε_r material without the problems often encountered with microstrip patch or planar slot antennas. In this example, the $\varepsilon_r = 9.8$ material provides a relatively small (1.27 cm diameter) antenna with a resonant frequency at 1.6 GHz. Unlike a microstrip patch, the radiation efficiency is not adversely affected by surface mode propagation in the high ε_r material. Unlike a planar slot, the problems associated with reflections at dielectric boundaries (often leading to the use of a dielectric lens) are not encountered, since the cylindrical slot radiates into free-space, rather than into the substrate. One precaution with the cylindrical geometries is to operate below the cutoff frequency of the dominant waveguide mode, which in this case is at 4.4 GHz [9].

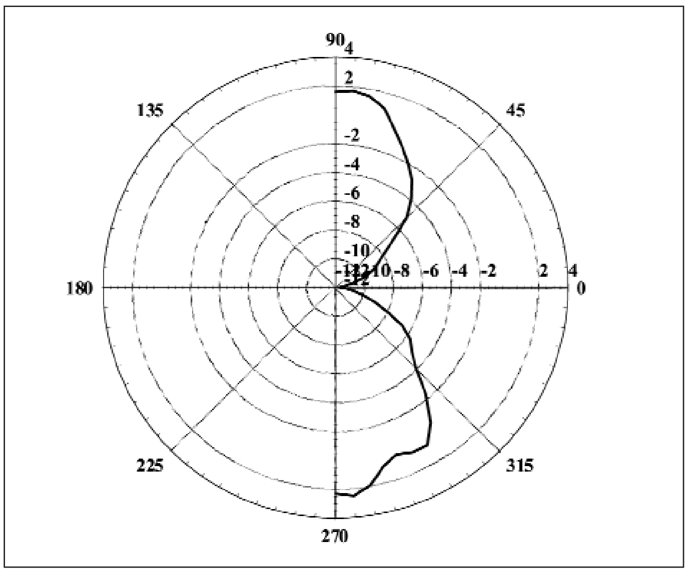
The antenna was fabricated using a prototype direct write tool capable of depositing metals and dielectrics directly onto conformal surfaces. This tool is known as the MesoTool and includes deposition techniques for both thick and thin film applications. It comprises two separate instruments: the MicroPen for thick film paste dispensing and the Laser Chemical Vapor Deposition (LCVD) for thin film deposition. (The development of



▲ **Figure 7. Measured input reflection coefficient (S_{11}) for the cylindrical slot antenna on alumina.**



▲ **Figure 8. Measured H-plane gain pattern for the cylindrical slot antenna on alumina. The feedline location is indicated by the dashed line centered around 90 degrees, while the shorted slot section is indicated by the solid line centered around 348 degrees.**



▲ **Figure 9. Measured E-plane gain pattern for the cylindrical slot antenna on alumina. The top of the cylindrical alumina rod corresponds to 0 degrees.**

this tool is currently being funded by U.S. DARPA.)

The MicroPen is a tool capable of dispensing pastes with a vast range of viscosities (0.001 to 900 Pascal/seconds). The line width resolution of the pen varies from 50 μm to several millimeters. The MesoTool dispenses and then sinters the paste that is deposited with laser heat. Currently, silver pastes are available that can be processed with a laser at 200 degrees Celsius. We used the MicroPen to deposit 37 micron-thick silver lines on the alumina substrate. LCVD can be used to deposit thin films with higher resolution than the MesoTool; line widths in the submicron range are possible. This deposition method can lay down patterns in both two and three dimensions. In addition to growing lines on a flat or curved surface, LCVD also allows growth of vertical lines, thus enabling new possibilities in the area of antenna design. In addition, LCVD permits the deposition of several metals (for example, gold, copper and tin) and dielectric materials.

Antenna performance

By varying the position of the shorting strip relative to the feedline, it is possible to change the input impedance of the antenna. In this design, the optimum location for the center of the shorting strip was found to be approximately 110 degrees from the center of the feedline. At the resonant frequency of 1.6 GHz, the resulting configuration is a slot length of 0.44 guide wavelengths around the cylinder with a feedpoint at 0.125 guide wavelengths from one end. With respect to this offset feed arrangement, one advantage of the cylindrical ground plane is that the parasitic even-mode on the CCS feedline is naturally suppressed. For a comparable uniplanar coplanar waveguide, air-bridges would be required at the feedpoint to equalize the ground planes. The measured input reflection coefficient (S_{11}) is given in Figure 7. The 10 dB return loss bandwidth is approximately 2 percent.

The measured H-plane gain patterns of the antenna are shown in Figure 8, while E-plane gain patterns of the antenna are given in Figure 9. The H-plane pattern, measured around the cylinder, shows a variation between 0 and 2.6 dBi, with the minimum gain occurring approximately opposite the shorting strip. While the location of the pattern minimum is consistent with the results for the antennas on PTFE (opposite the short) the null is not nearly as well defined in this case. This may be explained by differences in the interaction of radiated fields from opposing sides of the cylinder; unlike the PTFE case, the rod diameter is not near a multiple of $\lambda_g/2$ at the resonant frequency (using a dielectric constant of 9.8) and thus less cancellation occurs. The E-plane pattern resembles that of a linear dipole, with the null occurring along the central axis of the cylinder. Some distortion in the E-plane pattern can be attributed to the coaxial connector used to connect to the alumina rod.

Summary

Cylindrical slot and folded slot antennas on PTFE and alumina have been presented. The antennas exhibit broad beamwidths with the possibility for well-defined pattern nulls normal to the axis of the CCS. This type of antenna is useful as a linear dipole replacement when low profile and broadside radiation are desired. A powerful direct-write manufacturing tool capable of depositing metals and dielectrics on virtually any conformal surface has been described. ■

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James Culver has 16 years of experience in microwave circuit and systems design, including five years with Texas Instruments developing narrow and wide band monolithic microwave integrated circuits (MMICs) for use in radar and communication systems. In addition to design, he has extensive experience with linear and nonlinear modeling of active devices and in numerical electromagnetic modeling of passive structures. He is employed as a principal engineer with Raytheon Systems Company, where he designs microwave communications systems. He has a bachelor of arts degree in chemistry, a bachelor of science degree in electrical engineering and a master of science degree in electrical engineering. He is currently pursuing a doctor of philosophy degree in electrical engineering in the area of microelectromechanical systems (MEMS) applied to microwave circuits and antennas. He holds one patent and has authored 15 papers on MMIC and microwave circuit design.

Brett King is an RF and microwave engineer with five years of experience in high-frequency design with Raytheon Systems Company. He is currently employed with Science Applications Inter-national Corporation (SAIC). His experience includes work on amplifier design, passive element and transmission line modeling, high reliability space applications and communication systems integration. He has a bachelor's degree in electrical engineering from the University of South Florida and is currently pursuing a master's degree (MSEE).