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Coplanar waveguide-fed slot antennas on cylindrical substrates

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Abstract

This paper describes cylindrical coplanar waveguide (CCPW)-fed slot and folded slot antennas encompassing cylindrical substrates. Using a 1.27 cm diameter Teflon 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 CCPW feedline. A 1.6 GHz slot antenna on a 1.27 cm diameter alumina substrate was also fabricated using a novel direct-write technique, and shown to have comparable performance characteristics.

The results include measured data and simulated data using a 3D cylindrical finite difference time domain (FDTD) code.

Keywords: Coplanar waveguide; Finite Difference Time Domain; Antennas; Cylindrical substrate

1. 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, for example cylindrical conformal patch and slot antennas [1–3], microstrip [4–6] and coplanar-like transmission lines [7–10].

In this paper, cylindrical coplanar waveguide (CCPW)-fed slot antennas printed on both Teflon and alumina are presented. The cylindrical configuration is shown to be advantageous in that an omnidirectional pattern is achieved with the possibility of a well-defined null normal to the antenna axis. This makes the antenna well suited for use in hand-held wireless applications, for example. In instances where the cylinder is extended to displace the slot antenna from other circuitry, it has also been shown that passive elements (filters and matching networks) can be incorporated into the otherwise unused space [8].

The first part of the paper describes single- and folded-slot antennas on Teflon 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 and 2.8 dB, respectively. In the second part of the paper, a 1.6 GHz slot antenna is presented 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.

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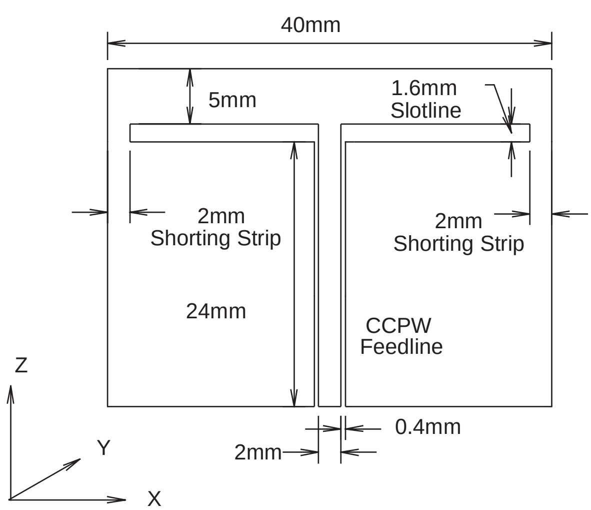
2. Slot antennas on teflon

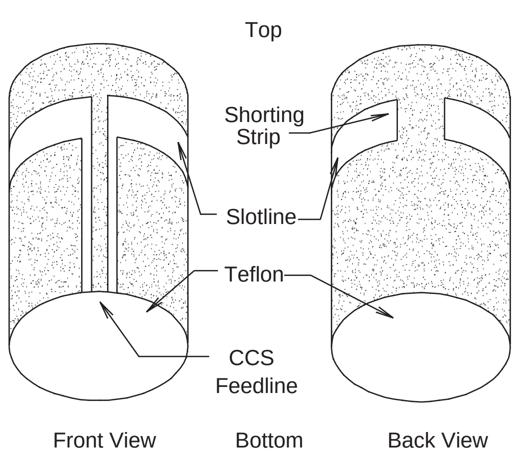
2.1. Geometry and fabrication

The cylindrical slot- and folded-slot antenna designs for the Teflon substrate are shown in Figs. 1a and 2a, respectively. The antennas were constructed with a conductive strip across the radiating slotline, placed opposite the CCPW center conductor. The CCPW feedline center conductor and slot widths are 2 and 0.4 mm, respectively. These CCPW dimensions correspond to a characteristic impedance of 76 Ω, as determined from a conformal mapping program [11]. Three-dimensional views of the antennas are offered in Figs. 1b and 2b.

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 $\frac{1}{3}$ oz (12 μm) and a dielectric thickness of 3 mil (76.2 μm). After processing, the thin substrate was wrapped around the cylindrical Teflon rod and soldered to form a continuous ground plane on the side opposing the feedline. An SMA connector was fastened to one end of the dielectric rod and soldered to the CCPW center conductor and ground planes.

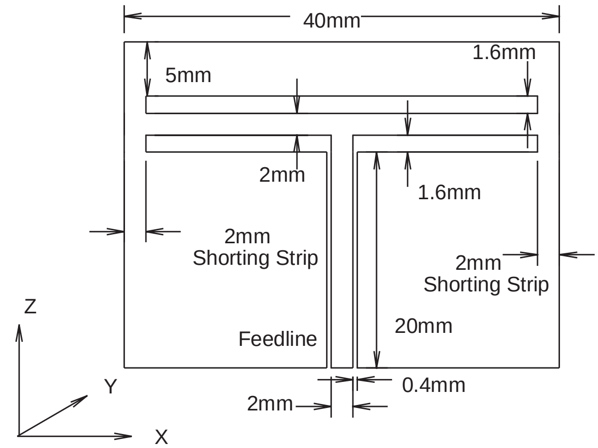


(a)

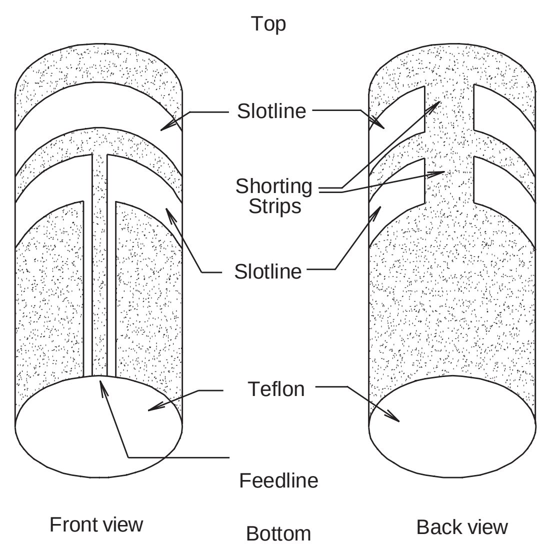


(b)

Fig. 1. Cylindrical slot line antenna on Teflon: (a) two-dimensional view illustrating line and slot widths, (b) three-dimensional view with metal regions shaded (SMA connector not shown).



(a)



(b)

Fig. 2. Cylindrical folded slot line antenna on Teflon: (a) two-dimensional view illustrating line and slot widths, (b) three-dimensional view with metal regions shaded (SMA connector not shown).

2.2. 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 CCPW standards. The antenna designs were also simulated using a three-dimensional finite difference time domain

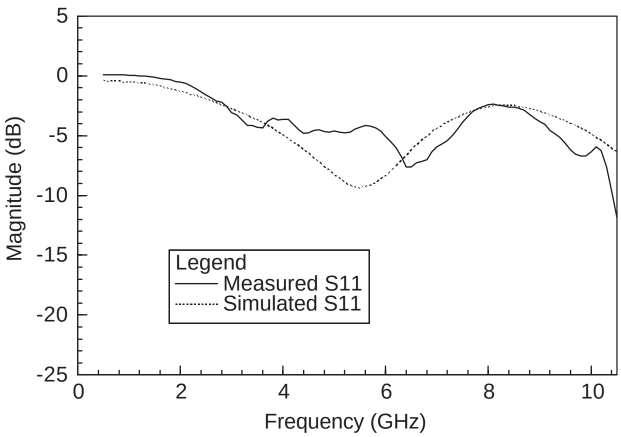


Fig. 3. Comparison between measured and simulated data for the cylindrical slot antenna.

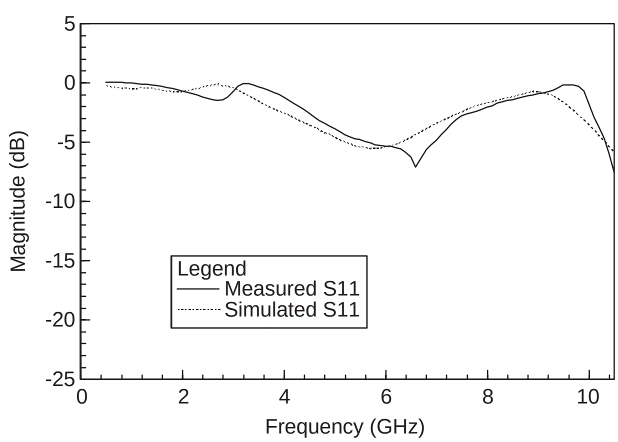


Fig. 4. Comparison between measured and simulated data for the cylindrical folded slot antenna.

(3D-FDTD) method [8]. A comparison between measured and simulated data is shown in Figs. 3 and 4. The difference between the two sets of data is most likely due to the physical construction of the antennas specifically, the soldering performed to connect each ground plane edge around the cylinder, and to attach the SMA connector.

The input impedances determined for the slot and folded slot around the 7 GHz resonance frequency were 36 and 21 Ω, respectively. In order to improve the match to the 76 Ω reference impedance, $\lambda/4$ impedance transformers were incorporated into the feedlines of the antennas. Each impedance transformer was designed for a reference impedance of 76 Ω, and had a characteristic impedance of 52 and 40 Ω for the slot and folded slot, respectively. The return loss for the modified antennas is shown in Fig. 5. 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].

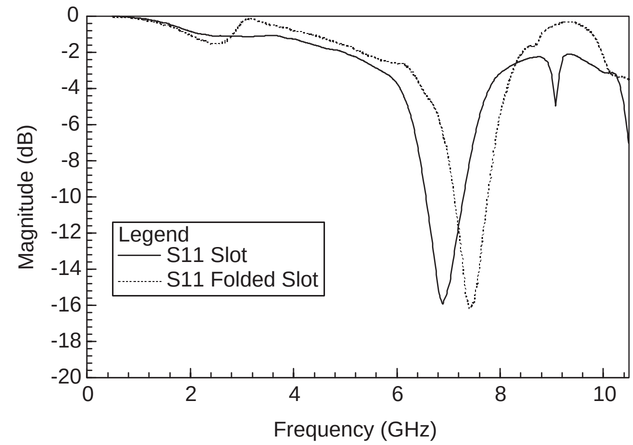


Fig. 5. Measured response of the antennas on Teflon with a 52 Ω (slot) and 40 Ω (folded slot) $\lambda_g/4$ impedance transformer.

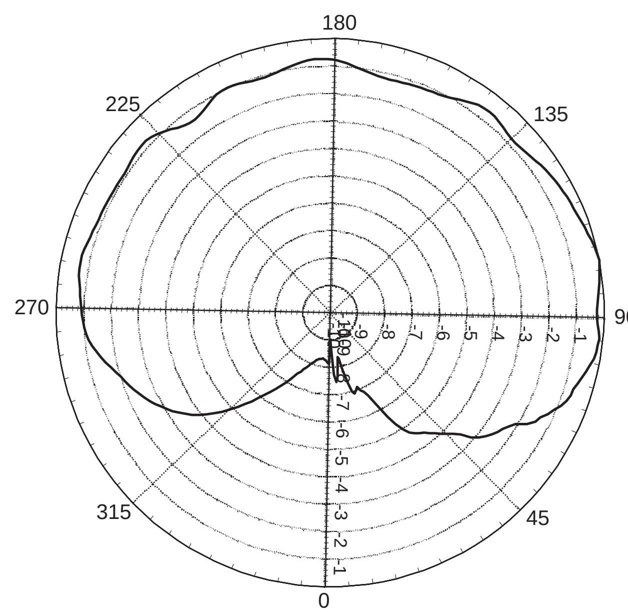


Fig. 6. *H*-plane slot antenna radiation pattern with CCPW feedline side of antenna referenced to 0°.

The *H*-plane patterns for the slot and folded slot antennas are shown in Figs. 6 and 7, respectively. (The *H*-plane corresponds to the x–y plane as indicated in Figs. 2a and 3a.) In each case a well-defined null occurs around the $\phi = 0$ degree direction, corresponding to the feedline side of the cylinder. The pattern asymmetry is believed to 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 CCPW feedline and the presence of the SMA connector, it was not possible to accurately measure *E*-plane patterns. However, the approximate measurements demonstrated a broad beamwidth with no observable *E*-plane null at the non-connector end, consistent with theoretical

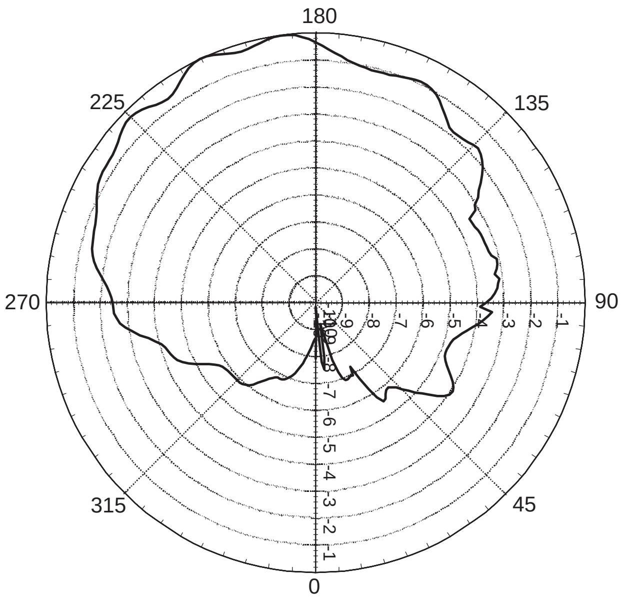


Fig. 7. *H*-plane folded slot antenna radiation pattern with CCPW feedline side of antenna referenced to 0°.

expectations. Using a standard gain horn as the reference antenna, the maximum gain was determined to be 1.48 and 2.84 dB for the slot and folded slot, respectively.

3. Slot antenna on alumina

3.1. Geometry and fabrication

As illustrated in Fig. 8, 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 CCPW feed has 1.14 mm-wide slots separated by 2.5 mm. The characteristic impedance of the feedline is 50 Ω.

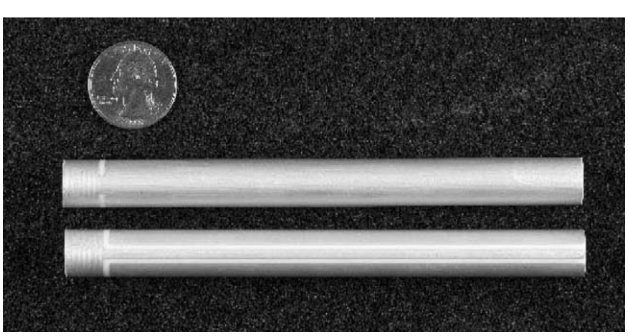


Fig. 8. Photograph of the cylindrical slot antennas fabricated on 1.27 cm-diameter alumina rods. The upper photograph shows the shorted ends of the slot on the back side of the antenna. The lower photograph shows the cylindrical CPW feedline.

The use of the alumina substrate for designing a cylindrical slot antenna proves to offer 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 is comprised of deposition techniques for both thick and thin film applications. The existing tool comprises two separate instruments: (1) MicroPen for thick film paste dispensing and (2) laser chemical vapor deposition (LCVD) for thin film deposition.

The MicroPen is a tool capable of dispensing pastes with a vast range of viscosities (0.001–900 Pa/s). The line width resolution of the pen varies from 50 μm to several millimeters. The MesoTool process for pastes that are deposited using this method is to dispense and then sinter the paste with laser heat. To date silver pastes are available that can be processed with a laser at 200 °C. In this work, the MicroPen was used to deposit 37 μm-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. While it is common to grow 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 (e.g., gold, copper and tin) and dielectric materials.

3.2. 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° 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, an advantage of the cylindrical ground plane is that the parasitic even-mode on the CCPW feedline is naturally suppressed. For a comparable uniplanar coplanar waveguide, air-bridges would be required at the

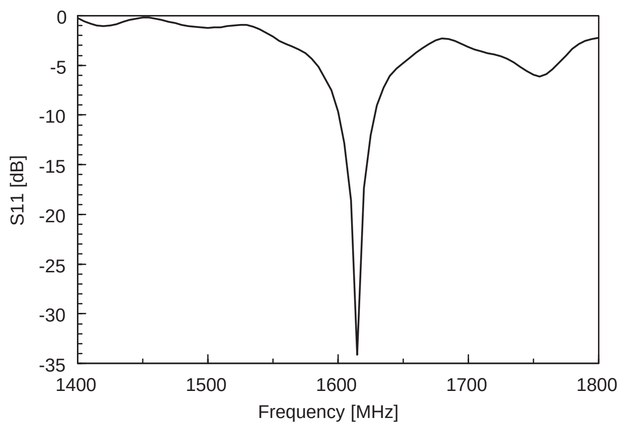


Fig. 9. Measured input reflection coefficient (S11) for the cylindrical slot antenna on alumina.

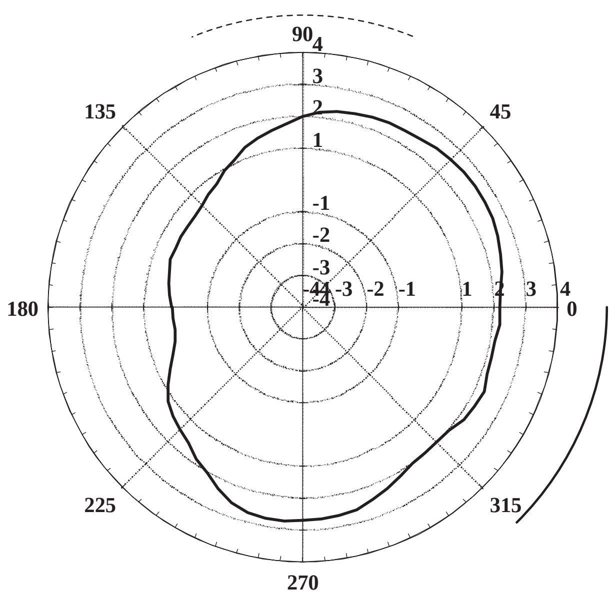


Fig. 10. Measured H-plane gain pattern for the cylindrical slot antenna on alumina. The feedline location is indicated by the dashed line centered around 90°, while the shorted slot section is indicated by the solid line centered around 348°.

feedpoint in order to equalize the potential on the ground planes. The measured input reflection coefficient (S11) is given in Fig. 9. The 10-dB return loss bandwidth is approximately 2%.

The measured H- and E-plane gain patterns of the antenna are given in Figs. 10 and 11, respectively. 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 Teflon (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 Teflon case, the rod diameter

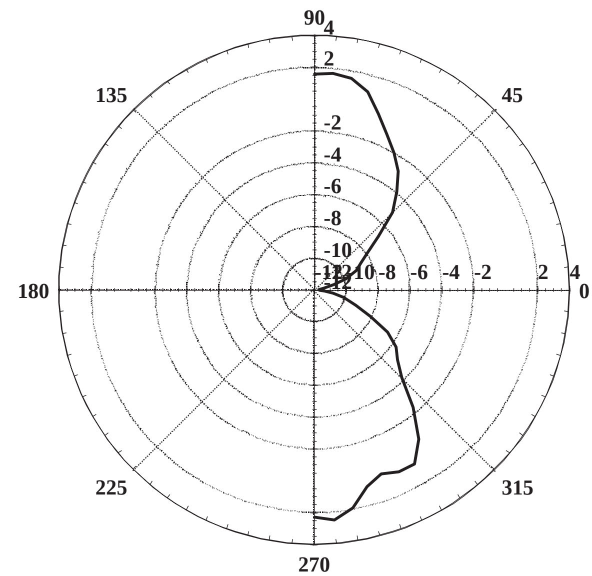


Fig. 11. Measured E-plane gain pattern for the cylindrical slot antenna on alumina. The top of the cylindrical alumina rod corresponds to 0°.

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.

4. Conclusions

Cylindrical slot and folded slot antennas on Teflon and alumina have been presented. The antennas exhibit broad beamwidths with the possibility for well-defined pattern nulls normal to the axis of the CCPW. 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, was demonstrated.

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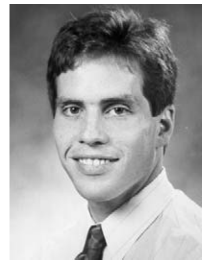

T. Weller is an associate professor of Electrical Engineering at the University of South Florida. He received his Ph.D. in Electrical Engineering from the University of Michigan in 1995. His current research interests include microwave MEMS and micromachining, planar circuit and antenna design and microwave modeling. He has published more than 75 technical papers. He can be reached at Email: weller@eng.usf.edu

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B. King is an RF and microwave engineer with 7 years of experience in high-frequency design and system integration. He is currently employed with Science Applications International Corporation (SAIC). His experience includes work on amplifier design, passive element and transmission line modeling, high reliability space applications and transmitter/receiver design. He has bachelor and master of science degrees in Electrical Engineering from the University of South Florida.