DIRECT-WRITE FABRICATION OF ANTENNAS WITH RESISTIVE LOADING ON FLEXIBLE SUBSTRATES

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ABSTRACT

This work presents results of research on constructing antennas with and without discrete resistive loading on flexible substrates using direct-write technologies. Two antenna types, with and without discrete resistive loading, were built and studied: straight monopoles and Vee antennas. For these antennas, discrete resistive loading is used to increase the frequency bandwidth over which the input impedance and radiation patterns are acceptable, at the expense of lower efficiency. The architecture of the Vee antenna offers the property of providing a more directional radiation pattern, which can partially offset the lower efficiency due to the resistive loading. The conductive portions (traces) of the antennas were fabricated on flexible polyimide (i.e., KAPTON®) substrates using the Optomec Maskless Mesoscale Material Deposition (M3D®) or nScrypt material deposition or printing systems. The M3D® system was used to deposit a silver-based nano-ink developed at the South Dakota School of Mines & Technology (SDSM&T) by a stand-off aerosol process onto the substrate. The nScrypt system was used to deposit a commercial material (Parelec Paramod®VLT AMA-300) by a “fountain-pen” process onto the substrate. The traces required curing in an oven to drive off solvents and sinter the material. The discrete resistive loading was implemented using surface mount resistors soldered across gaps in the traces. The measured results (input impedance and radiation patterns) agreed well with simulations. This demonstrates that these antennas can successfully be constructed by direct-write fabrication. Direct-write fabrication of antennas offers significant advantages in ease of construction, cost, design adaptability, as well as the ability to place antennas on flexible substrates.

Keywords
Direct-write, antennas, nanotechnology, nano-inks

INTRODUCTION

This work presents results of research on constructing antennas with and without discrete resistive loading on flexible substrates using direct-write technologies. The intent is to demonstrate that direct-write fabrication techniques
can be used to successfully manufacture these antennas. Two antenna types, with and without discrete resistive loading, were built and studied: straight monopoles and Vee antennas. The conductive portions (traces) of the antennas were made by direct-write fabrication. Unlike wire antennas which can be self-supporting, substrates are needed to provide mechanical support for the traces produced by direct-write fabrication.

Initially, “Altshuler”-type antennas (Altshuler 1961) as well as comparable conductive or resonant monopoles were constructed using direct-write fabrication techniques on flexible substrates. “Altshuler”-type antennas are straight conductive monopoles mounted normal to a conductive ground plane with discrete resistive loading placed a quarter-wavelength ($\lambda/4$) from the open end of the antenna arms (see Figure 1a). The discrete resistive loading was implemented by soldering surface mount technology resistors across gaps in the traces. The comparable conductive monopoles had the same dimensions and architecture as the “Altshuler”-type antennas, but did not have any resistive loading. Both are fed through a conductive ground plane by the center conductor of a coaxial transmission line or connector.

“Altshuler”-type antennas exhibit input impedance frequency bandwidths on the order of 2 to 1 (ratio of the highest to lowest acceptable frequency), whereas comparable conductive or resonant monopoles typically have bandwidths on the order of a few percent about a center frequency. Further, the discrete resistive loading leads to improved (more stable) radiation patterns over an increased bandwidth. The resistive loading induces a traveling wave current distribution between the feed and the resistor at the expense of lower efficiency (i.e., significant power is dissipated in the resistive load, instead of being radiated). Altshuler found that resistors with values near $240 \, \Omega$ were optimal for producing the traveling wave current distribution.

A traveling wave current distribution is one where current flows out from the antenna feed and is not reflected back. A resonant antenna has a standing wave current distribution where the current “resonates” or bounces back and forth between the feed and open end of the antenna. Resonant antennas exhibit large variations in their standing wave current distributions (and hence input impedance and radiation patterns) as the frequency of the input signal is varied.
In addition, Vee antennas, both with and without resistive loading, were constructed using direct-write fabrication techniques on flexible substrates. Vee antennas with discrete resistive loading (Iizuka 1967) seek to combine the desirable properties of conductive/resonant Vee antennas (Carter et al. 1931), e.g., increased directivity in the radiation pattern, with those of “Altshuler”-type antennas, e.g., increased bandwidth. Vee antennas are straight monopoles mounted at an angle less than normal with respect to and over a conductive ground plane (see Figure 1b). For the Vee antennas with discrete resistive loading, the resistor is placed a quarter-wavelength (\(\lambda/4\)) from the open end of the antenna arms. The discrete resistive loading was again implemented by soldering surface mount technology resistors across gaps in the traces. Iizuka found that resistors with values near 250 \(\Omega\) worked well for producing the traveling wave current distribution for Vee antennas that had arms which were one and a half wavelengths (1.5\(\lambda\)) in length at a 30° angle with respect to the ground plane (optimal value varies with both Vee antenna arm length and angle).

METHODS

Several “Altshuler”-type and comparable conductive monopole antennas were constructed using equipment located in the Printed Electronics Laboratory (formerly Direct Write Laboratory) at SDSM&T. Specifically, this equipment included an Optomec Maskless Mesoscale Material Deposition (M'D®) (http://www.optomec.com/) and an nScrypt 600-3Dn-HP (http://www.nscrypt.biz/) material deposition or printing systems. The M'D® system uses a stand-off aerosol process to deposit liquid materials (inks) onto a substrate, whereas the nScrypt system uses a “fountain-pen” process to deposit liquid materials onto a substrate.

First, the M'D® system was used to print the conductive traces of “Altshuler”-type and comparable conductive monopole antennas onto a flexible polyimide substrate using a silver-based nano-ink developed at SDSM&T. After printing, I cured the traces in an oven to drive off solvents and sinter the silver nanoparticles. Then, surface mount resistors were soldered across a gap in the conductive traces for the “Altshuler”-type antennas. Examples of these antennas as well as a close-up of a 220 \(\Omega\) soldered across a gap are shown in Figure 2. Soldering to these traces is challenging due to the solubility of silver in typical lead/tin-based solders, i.e., trace can dissolve in the solder leaving a break or open circuit. The traces produced by the M'D® system are relatively thin (<10 \(\mu\)m) due to the aerosol deposition process. Due to this problem, subsequent work was conducted on antennas fabricated by the nScrypt system.

The nScrypt system was used to deposit a commercial material (Parelec Paramod® VLT AMA-300) onto a flexible polyimide substrate (KAPTON® Type HPP-ST, 127 \(\mu\)m thick, \(\varepsilon_r = 3.5\)) with a length equal to that of the antenna and about 1.5 cm in width. For the antennas shown in Figure 3, the overall lengths were 140.5 mm. The traces (1.55 mm wide, -0.1 mm thick) were cured for an hour at 300 °C. A 237 \(\Omega\) surface mount chip resistor (0805 package- 1.25 mm wide by 2 mm long) was soldered 56.6 mm (on center) from the open end of the
antenna (close-up shown in Figure 3b). This corresponds to a quarter-wavelength at 1.32 GHz in free space.

Next, two monopole Vee antenna designs were constructed using the nScrypt system— one a conductive Vee and one a conductive Vee with discrete resistive loading. The length of the slanted portion (at an angle of 30 degrees to the ground plane) of the Vee antenna arms was 250 mm. Also, a vertical 5 mm trace section was fabricated. It is used to attach the antennas to the center pin of a coaxial connector for testing. For the resistively-loaded Vee antenna, a 249 Ω surface mount chip resistor (0805 package) was soldered 50 mm (on center) from the open end of the monopole (0.25λ in free space at 1500 MHz). The antennas were fabricated using the same Parelec ink and substrate material. The traces (1 mm wide, ~0.1 mm thick) were cured for an hour at 300 °C with a temperature ramp rate of 5 °C/min. Figure 4 shows a Vee antenna with discrete resistive loading after mounting on a copper ground plane.

Figure 2. (a) Silver nano-ink traces produced by M3D® system and (b) close-up of a 220 Ω surface mount resistor soldered across gap in silver nano-ink trace.

Figure 3. (a) Conductive traces produced by nScrypt system and (b) close-up of a 237 Ω surface mount resistor soldered across a gap in the trace.
Antenna measurements, e.g., input impedance and relative radiation patterns, were made in the Antennas, Microwave, & Electronics Laboratory (AMEL) located at SDSM&T. As shown in Figure 5 for an “Altshuler”-type antenna, the antennas were connected to the center pin of an SMA bulkhead coaxial connector centered on a 91.4 × 101.6 cm copper ground plane. The input impedances of the antennas were measured using an Agilent 4396B Network Analyzer and 85046A S-Parameter test set (see left picture in Figure 5). Note that the ground plane is surrounded by radar absorbing blocks (sections removed for pictures) to minimize reflections from surrounding objects. As shown in Figure 5 (right), the relative (i.e., results normalized to maximum measured value) radiation patterns measurements for the antennas were made using this equipment and a monopole receiving/test antenna in a small (~ 2.4 × 2.4 × 1.5 m) anechoic chamber located in a side room of AMEL. The test antenna, a 4.16 cm long monopole made of 20 AWG wire, is centered on an 18 × 18 cm ground plane. For the measurements, it was held a constant distance (55 cm) in the far-field from the antenna under test.

RESULTS

Figure 6 shows the measured input resistance and reactance for the “Altshuler”-type and comparable conductive antennas. Note, the input resistance and reactance are relatively stable over a wide frequency range for the “Altshuler”-type antenna versus those for the comparable conductive antenna. In addition,
the antennas were simulated using Numerical Electromagnetics Code (NEC 2.0) models. As shown, the measured and simulated results are in good agreement. The simulation results (shown on Figure 6 for the “Altshuler”-type antenna) revealed that an effective relative permittivity $\varepsilon_{\text{eff}} \approx 1.1$ was needed to match experimental results. This is due to the polyimide substrate ($\varepsilon_r = 3.5$) on which the antennas were fabricated. The effective relative permittivity will vary with frequency, the geometry of the antenna, and substrate material.

Figure 7 shows the measured input resistance and reactance for the Vee antennas. For the Vee antenna with discrete resistive loading, the input resistance and reactance are relatively stable over a wide frequency range, whereas the input resistance and reactance for the conductive Vee antenna varied greatly.

Figure 8 shows measured and simulated elevation radiation patterns for this “Altshuler”-type antenna and a conductive monopole of the same overall length at frequencies of 800, 1320, and 1800 MHz. The angle $\theta = 0^\circ$ aligns with the axis of the antenna while $\theta = 90^\circ$ (broadside) corresponds to the ground plane. As seen, the radiation patterns for the conductive monopole changes from near resonant at 800 MHz (arm length of $0.3\lambda$) to anti-resonant at 1320 MHz (arm length of $0.5\lambda$) to long at 1800 MHz (arm length of $0.7\lambda$) with associated null and sidelobe development. The radiation patterns of the “Altshuler”-type antenna remain relatively stable over this frequency range, i.e., the main lobe remains in the broadside direction. Some sidelobe development was evident at 1800 MHz. From simulations, the efficiency and maximum gain of “Altshuler”-type antenna ranged from 37% and -3 dBi at 800 MHz to 41.5% and -1 dBi at 1320 MHz to 48% and -2 dBi at 1800 MHz. The efficiency of the comparable conductive monopole was ~99% while the gain was 2.5, 4.3, and 3 dBi at 800, 1320, and 1800 MHz respectively.

![Figure 6. Input resistance and reactance for “Altshuler”-type (measured and simulated) and comparable conductive antennas.](image-url)
The Vee antennas were simulated using NEC 2.0 models. For the Vee antenna geometry, an effective relative permittivity $\varepsilon_{\text{eff}} \approx 1.15$ was needed to match the experimental results. Simulated radiation patterns for the resistively-loaded Vee and comparable conductive Vee antenna are shown in Figure 9 (elevation or E-plane) and Figure 10 (azimuthal or H-plane). For Figure 9, the Vee antennas are oriented as shown in Figure 1b with the open end of the Vee to the right, and the radiation pattern is in the plane of the Vee antennas. For Figure 10, the radiation pattern is in the plane of the ground plane with the open end of the Vee antennas to the right. For the conductive Vee, the simulations showed power gains of 4.5, 5.8, 8, and 8.4 dB with corresponding front-to-back ratios of 2, 2.5, 2, and 2.9 dB at frequencies of 900, 1200, 1500, and 1800 MHz, respectively. For the resistively-loaded Vee, the simulations showed power gains of 1, 2.9, 4.7, and 6.2 dB with corresponding front-to-back ratios of 7, 11.8, 11.6, and 13.4 dB at frequencies of 900, 1200, 1500, and 1800 MHz, respectively. The improved radiation patterns, as evidenced by the front-to-back ratios, can be attributed to a predominantly traveling wave current distribution on the resistively-loaded Vee antennas.
This paper demonstrated the successful construction by direct-write fabrication on flexible polyimide substrates of antennas with and without discrete resistive loading. Direct-write processes have great commercial potential for antenna fabrication due to their inherent flexibility and low cost. Direct-write fabrication or printing of antennas/electronics and nanotechnology (e.g., nano-inks) are two major areas of research that have seen rapid development in recent years. Ink/material development continues to be a key issue facing the implementation of direct-write technology. Some examples of needed developments are lower cure temperatures, resistive inks/materials, improved conductivity, adhesion, and flexibility.

**DISCUSSION**

![Figure 9. Elevation or E-plane simulated radiation patterns for the resistively-loaded Vee and comparable conductive Vee antennas.](image)

![Figure 10. Azimuthal or H-plane simulated radiation patterns for the resistively-loaded Vee and comparable conductive Vee antennas.](image)
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LITERATURE CITED