COUPLED SECTORIAL LOOP ANTENNA (CSLA) FOR ULTRA-WIDEBAND APPLICATIONS*

Nader Behdad, and Kamal Sarabandi
Department of Electrical Engineering and Computer Science
University of Michigan, Ann Arbor, MI, 48109-2122
behdad@eecs.umich.edu, saraband@eecs.umich.edu

Abstract: A novel ultra-wideband antenna is proposed, which achieves ultra-wideband operation through proper magnetic coupling of two adjacent sectorial loop antennas in a symmetrical arrangement. A large number of CSLA antennas with different geometrical parameters are fabricated and their measured responses are used to experimentally optimize the geometrical parameters of the antenna to achieve ultra wideband operation. It is shown that, after optimizing the geometrical parameters of this antenna, it shows a VSWR of lower than 2 across an 8.5:1 frequency range while maintaining excellent polarization purity. Furthermore, the antenna has consistent radiation patterns in the first two octaves of its impedance bandwidth. Modified versions of the CSLA are also designed to reduce the overall metallic surface of the antenna while maintaining its wideband characteristics.

1. INTRODUCTION

A few decades after the early investigations on ultra-wideband (UWB) wireless systems, they have found various applications in a number of different wireless systems. Ground penetrating radars, frequency hopping communication systems for military applications, and UWB short pulse radars can be named as few examples. Such systems require antennas that are able to operate across a very large bandwidth with consistent radiation parameters. A number of different techniques have been used to design such wideband antennas. Traveling wave antennas and antennas with topologies that are entirely defined by angles are inherently wideband and have been extensively used [1]-[4]. Self complementary antennas provide a constant input impedance irrespective of frequency and have been extensively studied in [5]. Another technique for designing wideband antennas is to use multi-resonant radiating structures. Log-periodic antennas, microstrip patches with parasitic elements, and slotted microstrip antennas for broadband and dual-band applications are examples of this category [2], [6]-[8].

The electric dipole and monopole above a ground plane are perhaps the most basic type of antenna. These antennas are usually narrow-band antennas. However, in recent years, a number of different plate monopole antennas were introduced that have considerably large bandwidths [9]-[11]. Impedance bandwidth characteristics of circular and elliptical monopole plate antennas are examined in [9]. Wideband characteristics of rectangular and square monopole antennas are studied in [10] and a dielectric loaded wideband monopole is investigated in [11]. In this paper, a new type of single-element wideband antenna is proposed. The antenna is composed of two parallel coupled sectorial loop

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antennas (CSLA) that are connected along an axis of symmetry. The geometrical parameters of this antenna are experimentally optimized and it is shown that it can easily provide a wideband impedance match over an 8.5:1 frequency range with consistent radiation patterns across the first two octaves of its impedance bandwidth (a 4:1 frequency ratio). The antenna is then modified such that its overall metallic surface is substantially reduced. This considerably reduces its weight and wind resistance when it is designed to operate at lower frequencies for applications such as ground penetrating radars or TV broadcast where the antenna dimensions become large.

In what follows, first the design and experimental optimization of the geometrical parameters of the CSLA is presented. Then the geometry of this optimized CSLA is modified to reduce the overall metallic surface of the antenna and two modified CSLAs are introduced. Finally, the radiation parameters of these three antennas across their entire bands of operation are presented and discussed.

2. COUPLED SECTORIAL LOOP ANTENNA

a. Antenna Design

The topology of the proposed antenna is shown in Figure 1(b). The antenna is composed of two sectorial loops connected in parallel along the axis of symmetry (z-axis) as shown in Figure 1(a). The three parameters that affect the antenna response are the inner and outer radii of the loop \( R_{in} \) and \( R_{out} \) and the angle \( \alpha \) as shown in Figure 1. In this paper, we pursue an experimental approach to optimize these geometrical parameters to achieve UWB operation. For the antenna shown in Figure 1(a), the lowest frequency of operation is determined by the overall effective circumference of the loop as expressed by the following approximate formula:

\[
\frac{f_t}{(\pi - \alpha + 2)} = \frac{2c}{\sqrt{\varepsilon_{eff} (R_{in} + R_{out})}}
\]

Where \( \varepsilon_{eff} \) is the effective dielectric constant of the antenna's surrounding medium, \( c \) is the speed of light, and \( R_{in}, R_{out}, \) and \( \alpha \) are the geometrical parameters of the antenna as shown in Figure 1. The average radius of the loop, \( R_{av} = (R_{in} + R_{out})/2 \), is determined using (1). Therefore the parameters that remain to be optimized are \( \alpha \) and \( t = (R_{out} - R_{in}) \).

In order to obtain the optimum value of \( \alpha \), nine different antennas with \( \alpha \) values from \( 5^\circ \) up to \( 80^\circ \) with \( R_{in} = 13 \text{mm} \) and \( R_{out} = 14 \text{mm} \) were fabricated and their responses were measured. Since the antenna topology shown in Figure 1 needs a balanced feed, the topology in Figure 2 was used, where half of the CSLA over a ground plane is used and a simple coaxial probe feeds the antenna. For simplicity in the fabrication process, the antenna is printed on a thin dielectric substrate with dielectric constant of \( \varepsilon_R = 3.4 \) and thickness of \( 500 \mu\text{m} \) and is mounted on a \( 10\text{cm} \times 10\text{cm} \) ground plane. For brevity, only measured \( S_{11} \) values for \( \alpha = 5^\circ, 20^\circ, 40^\circ, 60^\circ, 80^\circ \) are presented in Figure 3(a). It is seen that as \( \alpha \) increases from \( 5^\circ \) to \( 90^\circ \) the impedance bandwidth increases and reaches its maximum at \( \alpha = 60^\circ \) with an impedance bandwidth from 3.7 GHz to 10 GHz. The next step in the experimental optimization is to find the optimum \( t \) value. For doing so, three different antennas with \( \alpha = 60^\circ, R_{av} = 13.5 \text{mm}, \) and \( t = 0.4, 1.0, \) and 1.6 mm are fabricated and the measured \( S_{11} \) of these antennas are shown in Figure 3(b). As can be seen,
decreasing \( t \) results in achieving a wider bandwidth. This trend can be continued and wider bandwidths can be obtained by further decreasing \( t \) as is shown in the next subsection.

\textit{b. Radiation Parameters}  
In the previous section, the optimum geometrical parameters of the antenna were experimentally obtained. Based on this process, a CSLA with \( R_{in}=27.8\text{mm}, R_{out}=28\text{mm}, \) and \( \alpha=60^\circ \) is fabricated and mounted on a 20cm×20cm ground plane. The dimensions are increased to lower the lowest and highest frequencies of operation and simplify the radiation pattern measurements. The antenna has a VSWR of lower than 2.2 from 1.7GHz to 14.5GHz (see Figure 9), which is equivalent to an 8.5:1 impedance bandwidth. The radiation patterns of the antenna are measured across the entire frequency band and are presented in Figures 4, 5, and 6. Figure 4 shows the far-field co- and cross polarized (\( E_\theta, E_\phi \)) radiation patterns in the azimuth plane (x-y plane). It is seen that the patterns are consistent up to \( f=8 \) GHz. As the frequency increases beyond 8 GHz, the radiation patterns start to change; however, they are similar to each other for \( 10 \) GHz \( \leq f \leq 16 \) GHz. The radiation patterns in the elevation planes are also measured for two different planes at \( \varphi=0^\circ, 180^\circ, 0^\circ \leq \theta \leq 180^\circ \) (x-z plane) and \( \varphi=90^\circ, 270^\circ, 0^\circ \leq \theta \leq 180^\circ \) (y-z plane) and are presented in Figures 5 and 6 respectively. As frequency increases, the electrical dimensions of the antenna increase and as a result, the number of lobes increases. Also, the number of minor side lobes in the back of the ground plane \( (90^\circ \leq \theta \leq 180^\circ) \) increases significantly. This is caused by diffractions from the edges of the ground plane, which has larger electrical dimensions at higher frequencies. At lower frequencies, the radiation patterns are symmetric; however, as frequency increases, the symmetry is not observed very well. This is caused by the presence of the coaxial cable that feeds the antenna and disturbs the symmetry of the measurement setup. Since the cable is electrically large at higher frequencies, it has a larger effect on the radiation patterns of the antenna at these frequencies. In all the measured radiation patterns, the cross polarization level (\( E_\phi \)) is seen to be negligible. This is an indication of good polarization purity across the entire frequency band.

\textbf{3. MODIFIED CSLAs}  
\textit{a. Antenna Design}  
It is possible to scale the dimensions of the CSLA such that it operates at lower frequencies for applications such as TV broadcasting or ground-penetrating radars. For these applications the wavelength is large, therefore the antenna dimensions become very large. This increases the antenna weight and its wind resistance; therefore, it is desirable to reduce the metallic surface of the antenna as much as possible, while maintaining its characteristics. In order to do this, the electric current on the antenna surface is examined using numerical simulations based on the method of moments. The magnitude of the electric current on the surface of the antenna is shown in Figure 7 at four different frequencies. It is observed that the electric current density is very small in the sector confined in the range of \( -30^\circ \leq \theta \leq 30^\circ \). This suggests that this sector of the antenna can be removed without significantly disturbing the current distribution on its surface. This results in a design that is shown in Figure 8(a) and, because of its similarity to the letter
“M”, is called the “M1 CSLA”. Applying the same approach to the “M1” antenna and examining its current distribution reveals that the electric current density is large around $\theta = 30^\circ, 60^\circ, 120^\circ, \text{ and } 150^\circ$ edges and has lower values in between ($30^\circ < \theta < 60^\circ$). Therefore, another pie-slice section of the antenna, which is confined in the ranges $40^\circ < \theta < 50^\circ$ and $130^\circ < \theta < 140^\circ$ can be removed to obtain the antenna shown in Figure 8(b). This antenna is called the “M2” CSLA. Two “M1” and “M2” antennas with $\alpha = 60^\circ$, $R_{in}$=27.8mm and $R_{out}$=28mm are fabricated on a thin substrate with thickness of 0.5mm and dielectric constant of 3.4 and mounted on a 20cm×20cm square ground plane. The measured return losses of these two antennas are given in Figure 9 along with the $S_{11}$ of the original CSLA antenna with the same dimension. It is seen that all of the antennas have VSWRs lower than 2.2 in the frequency range of 2-14GHz as shown in Table I. The best input match is, however, observed for the “M2” CSLA with the VSWR lower than 2 across its entire band of operation.

<table>
<thead>
<tr>
<th>Antenna Type</th>
<th>Frequency Range</th>
<th>BW</th>
<th>MAX VSWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original CSLA</td>
<td>1.7-14.5 GHz</td>
<td>8.5:1</td>
<td>2.2</td>
</tr>
<tr>
<td>“M1” CSLA</td>
<td>2-14.7 GHz</td>
<td>7.35:1</td>
<td>2.2</td>
</tr>
<tr>
<td>“M2” CSLA</td>
<td>2.05-15.3 GHz</td>
<td>7.46:1</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table I. Comparison between the bandwidth of the original, “M1”, and “M2” CSLAs.

b. Radiation Parameters
The radiation patterns of the “M2” CSLA are measured at three different planes across its entire frequency band and are presented in Figures 10, 11, and 12. The co-pol, $E_\theta$, and cross-pol, $E_\phi$, far-field radiation patterns in the azimuth plane are shown in Figure 10 and are observed to be similar to those of the original CSLA. Similar to the previous section, the elevation patterns at x-z ($\varphi=0^\circ, 180^\circ, 0^\circ \leq \theta \leq 180^\circ$) and y-z ($\varphi = 90^\circ, 270^\circ, 0^\circ \leq \theta \leq 180^\circ$) planes are measured and reported in Figures 11 and 12. Similar to the original CSLA, the patterns change as the frequency increases and the minor side lobe levels increase with frequency. The gains of the three CSLA antennas are measured in the anechoic chamber of the University of Michigan in the frequency range of $f=2-16$ GHz using a double-ridge standard horn reference antenna and are presented in Figure 13. The gain of the antennas are measured at $\theta=90^\circ$, $\varphi=90^\circ$. As frequency increases from 2 to 6 GHz, the electrical size of the antenna increases and so does its gain. However, as is observed from Figure 13, the antenna gain decreases as frequency increases from 6 GHz up to 10 GHz. This is a consequence of the change in the direction of maximum radiation in the azimuth plane as is seen from Figure 10.

4. CONCLUSIONS
A novel ultra-wideband coupled sectorial loop antenna is designed that has an 8.5:1 impedance bandwidth. The antenna has consistent radiation parameters over a 4:1 frequency range with excellent polarization purity over the entire 8.5:1 frequency range. Modified versions of this UWB antenna, with reduced metallic surfaces and similar radiation parameters, were also designed, fabricated, and measured. Measurement results indicate that these modifications do not adversely affect the UWB behavior of the antenna.
ACKNOWLEDGMENT
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5. REFERENCES

Figure 1. Topology of a sectorial loop antenna (a) and a coupled sectorial loop antenna (b)
Figure 2. Three dimensional topology of the CSLA above a ground plane.

Figure 3. Measured $S_{11}$ values of a number of CSLAs used in the experimental optimization process. (a) $R_{in}=13\,mm$, $R_{out}=14\,mm$, and different $\alpha$ values. (b) $(R_{in}+R_{out})/2=13.5\,mm$, $\alpha=60^\circ$, and different $R_{out}-R_{in}$ values.

Figure 4. Measured radiation patterns of the CSLA in section 2 in the azimuth plane. The solid line is co-pol ($E_\theta$) and the dash-dotted line is the cross-pol ($E_\phi$) components.
Figure 5. Measured radiation patterns of the CSLA of section 2 in the elevation plane ($\varphi=0^\circ, 180^\circ$, $0^\circ \leq \theta \leq 180^\circ$). The solid line is co-pol ($E_\theta$) and the dash-dotted line is the cross-pol ($E_\varphi$) components.

Figure 6. Measured radiation patterns of the CSLA of section 2 in the elevation plane ($\varphi=90^\circ, 270^\circ$, $0^\circ \leq \theta \leq 180^\circ$). The solid line is co-pol ($E_\theta$) and the dash-dotted line is the cross-pol ($E_\varphi$) components.
Figure 7. Electric current distribution across the surface of the CSLA of section 2 at four different frequencies.

Figure 8. Topology of the modified CSLAs of section 3. (a) “M1” CSLA. (b) “M2” CSLA.

Figure 9. Measured $S_{11}$ values of the original CSLA of section 2 and the “M1” and “M2” CSLAs of section 3.
Figure 10. Measured radiation patterns of the “M2” CSLA in section 3 in the azimuth plane. The solid line is co-pol (E_θ) and the dash-dotted line is the cross-pol (E_φ) components.

Figure 11. Measured radiation patterns of the “M2” CSLA of section 3 in the elevation plane (φ=0°, 180°, 0°≤ θ ≤ 180°). The solid line is co-pol (E_θ) and the dash-dotted line is the cross-pol (E_φ) components.
Figure 12. Measured radiation patterns of the “M2” CSLA of section 2 in the elevation plane ($\phi$=90°, 270°, $0^{\circ} \leq \theta \leq 180^{\circ}$). The solid line is co-pol ($E_{\theta}$) and the dash-dotted line is the cross-pol ($E_{\phi}$) components.

Figure 13. Measured gain of the original CSLA of section 2 and the “M1” and “M2” CSLAs of section 3. The gains are measured in the azimuth plane at $\phi$=90°, $\theta$=90°.