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# DIPOLE ANTENNA WITH LEFT-HANDED LOADING OPERATING AT A ZERO ORDER MODE

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**Abstract**—This paper presents a printed dipole with left-handed loading and electrically small dimensions. Uniform currents are obtained at 750 MHz, proving zero order (i.e., $n = 0$) mode operation. Comparisons are made with other left- and right-handed antennas. Good agreement is achieved between simulation and measurement. The antenna has various applications in RFID systems and wireless environments.

## 1. INTRODUCTION

Previous research has shown that artificial materials can be designed with physical phenomena that are not found in nature. In particular, metamaterial based transmission lines have been shown to exhibit antiparallel phase and group velocity, as well as zero or negative propagation constant at a certain frequency [1, 3]. The unusual nature of these structures has been exploited in order to realize a leaky

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wave [4], dipole [5, 6], and omnidirectional loop [7] antenna with unique electrical and magnetic properties. The designs discussed in these papers exploit the fundamental properties of modes having a phase constant which is zero or negative. Furthermore, the electrical size, input impedance and operating frequency of the antenna depend on the loading elements. In this article, we present a novel dipole with left-handed loading that operates in the zeroth order mode (i.e., $n = 0$), not achievable by conventional right-handed antennas. To this aim, the antenna is shorted at both ends and the values of the loading elements were carefully selected. The main advantage of the proposed structure is the possibility of obtaining uniform currents independently of the dipole length. Thus, the antenna yields a wider return loss bandwidth along with good input impedance matching and efficiency. This performance enhancement is obtained without any constraint on radiation patterns, or arrangement of loading elements. The Letter's content is organized as follows. Section 2 discusses the antenna design and presents a lumped element circuit model. Sections 3 and 4 present the main properties of the structure in comparison with that of other left- and right-handed antennas. Finally, the main conclusions of the study are outlined in Section 5.

## 2. ANTENNA DESIGN

The unit cell of the antenna is constructed from a T-network of components. Although four unit cells are shown in this particular case, the complete antenna can contain any number of unit cells. The network is comprised from lumped capacitors (denoted $C_L$) in the series arm, and lumped inductors (denoted $L_L$), in the shunt arm. The antenna is shorted at each of the two ends, as shown in Figure 1.

In this left-handed antenna configuration, the resonant frequency and input impedance are controlled by the values of the loading elements $L_L$, and $C_L$, independently of the length of the antenna. The capacitors $C_L$ are introduced into the arm of the ladder network which also incorporates the feed point. This leads to a difference in amplitudes of the currents $I_1$ and $I_2$. For this reason these out-of-phase currents do not completely cancel in the far field, and as a result they radiate. Thus, the proposed antenna allows size reduction whilst maintaining impedance matching by the adjustment of $L_L$ and $C_L$. The structure is fed at the centre of the line so that the input signal can be distributed to both arms in a similar way to a conventional printed planar dipole antenna.

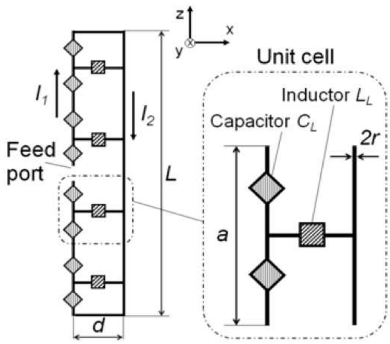


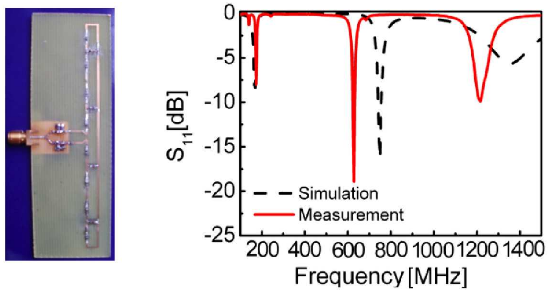

**Figure 1.** Model of the dipole antenna with left-handed transmission line. Dipole parameters are $C_L = 2.3\,\text{pF}$, $L_L = 280\,\text{nH}$, $a = 25$, $d = 10$ and $r = 0.7$. Units are in mm.

## 3. SIMULATED AND MEASURED RESULTS

The antenna, described in the previous section, was fabricated on an FR4 substrate having a thickness of $h = 0.8\,\text{mm}$ and a relative permittivity of $\epsilon_r = 4.4$, see Figure 2(a).

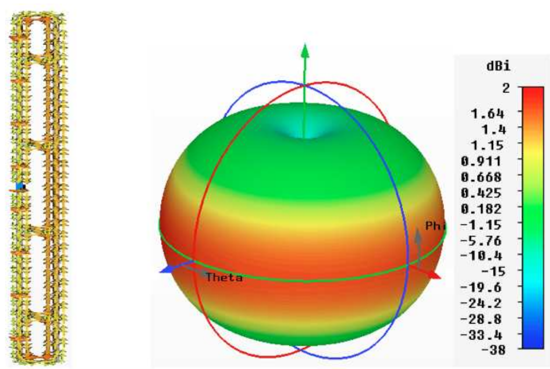
The dimensions of the antenna and the values of the lumped components are given in Figure 1. Losses within the metal conductors, substrate, and lumped elements were considered. The antenna is fed through a balun. The balun, described in Ref. [5], consists of a high pass filter and a low pass filter connected by means of a $T$-junction. The balun has an impedance of $Z_b = 50\,\Omega$, at the balanced port, and $Z_u = 50\,\Omega$, at the unbalanced port. There is good agreement between the simulated and measured return loss coefficients for the left-handed dipole, as shown in Figure 2(b).

In the frequency range under examination there are three resonances in the simulation results. These occur at 750 MHz for $n = 0$, 1355 MHz for $n = 1$, and 170 MHz for the balun resonance. From the measured results, the resonances were observed at 629 MHz, 1216 MHz and 174 MHz, respectively. Possible fabrication errors and permittivity tolerances could have led to these differences. In order to confirm zero order ($n = 0$) mode operation at the first antenna resonance, we have obtained the surface current distribution along with the radiation pattern. At 750 MHz uniform current distribution is achieved for this particular choice of left-handed loading elements (i.e. $L_L$, $C_L$), see also Figure 3(a). It is worth mentioning that the $n = 0$ mode operation can only be obtained using certain lumped element values. The difference in the amplitudes of currents $I_1$ and $I_2$ can be attributed to the presence




(a) (b)

**Figure 2.** (a) Picture of the prototype. (b) Simulated and measured return loss for the 4 unit cell left-handed dipole.




(a) (b)

**Figure 3.** (a) Current distribution, and (b) 3D far field radiation pattern at 750 MHz $n = 0$ mode.

of the capacitors in just one side of the line. In addition, the far field radiation pattern is shown in Figure 3(b). A common apple shaped pattern with a highest directivity of 2.0 dBi is found.

## 4. COMPARISON WITH RIGHT-HANDED AND OTHER LEFT-HANDED LOADED ANTENNAS

Generally speaking the performance of an antenna is degraded as its size is reduced. In particular, it is well known that size reduction is obtained at the expense of efficiency and bandwidth. Therefore, it is important to examine the fundamental limits and parameter tradeoffs involved. A comparative study of different antenna configurations, working at the same frequency (i.e., 750 MHz) is carried out. In this regard, the Chu [8] and Harrington limit [9] give information about the highest achievable bandwidth and gain, see Equations (1) and (2). The quality factor $Q$ is defined as the radian frequency ($\omega$) times the ratio of the reactive energy, stored around the antenna, to the total radiated power. The bandwidth can be obtained from its inversion. The gain $G$ can be defined as the ratio of a signal that is received or transmitted by a given antenna, in a given direction, compared to that associated with an isotropic antenna.

$$Q = \frac{1}{(kr_e)^3} + \frac{1}{(kr_e)} \tag{1}$$

$$G = (kr_e)^2 + 2\,(kr_e) \tag{2}$$

where $k$ is the wave number associated with the electromagnetic field and $r_e$ radius of a sphere enclosing the antenna. Four different antennas are compared. The antennas are shown in Figure 4.

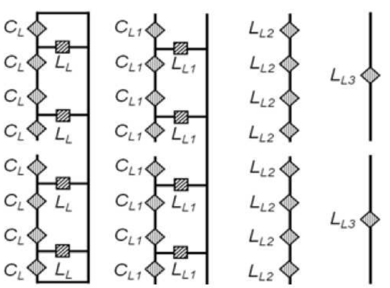



**Figure 4.** Different antenna configurations. (a) Left-handed dipole with shorted ends, (b) left-handed dipole, (c) right-handed dipole with lumped inductors at periodic intervals, (d) right-handed dipole with two lumped inductors. Element values are $C_L = 2.3\,\text{pF}$, $L_L = 280\,\text{nH}$, $C_{L1} = 113\,\text{pF}$, $L_{L1} = 22\,\text{nH}$, $L_{L2} = 16.5\,\text{nH}$, and $L_{L3} = 53\,\text{nH}$.

The proposed left-handed dipole, working in the $n = 0$ mode (Figure 4(a)), is compared with a left-handed dipole working in the $n = -1$ mode (Figure 4(b)) and two conventional inductance loaded dipoles working in the $n = 1$ mode (Figures 4(c) and 4(d)). Left-handed performance is achieved for the first two antennas, while right-handed behavior is obtained for the others.

Table 1 shows the simulated input impedance, total efficiency, gain and fractional bandwidth ($FBW$) of the left- and right-handed

**Table 1.** Performance of loaded dipole antennas in Figure 4. Chu and Harrington limit is $FBW = 36.8\%$ and $G = 3.4\,\text{dBi}$ for an enclosing sphere of radius 55 mm. Each antenna is 100 mm ($0.25\lambda_0$) long.

| Antenna (operation mode) | Imp. ($\Omega$) | Eff. (%) | FBW (%) | Gain (dBi) |
|---|---|---|---|---|
| LH dipole ($n = 0$) | 52.1 | 55.5 | 3.1 | 1.11 |
| LH dipole ($n = -1$) | 52.2 | 59.8 | 2.7 | 1.15 |
| RH dipole ($n = 1$) | 50.0 | 79.3 | 2.2 | 1.46 |
| RH dipole ($n = 1$) | 52.9 | 94.0 | 2.0 | 1.65 |

antennas. It is important to note that the left-handed structures have wider $FBWs$ than those having conventional (right-handed) loading. However, this improvement is obtained at the expense of efficiency and gain. We have added an L-type lumped element matching circuit to each of the right-handed antennas in order to improve the impedance match at 750 MHz and thus create conditions for a clear comparison. For the right-handed dipole in Figure 4(c) the matching circuit consisted of a series inductor and a shunt capacitor. Whereas the dipole in Figure 4(d) required a matching circuit comprised from series capacitor and a shunt inductor.

Before adding the matching circuit the total efficiency for the first right-handed antenna (shown in Figure 4(c)) was 64.3%. After adding the matching circuit the total efficiency was 79.3%. The matching circuit for the second right-handed antenna (Figure 4(d)) increased the total efficiency from 51.3% to 94%. In each case an external L-type matching circuit was employed. The circuit was designed using standard design equations [10]. The two left-handed dipoles exhibit similar values of gain and efficiency. The first left-handed dipole (Figure 4(a)) exhibits the lowest values of gain and efficiency. However, it provides the greatest $FBW$ of 3.1%. The dipoles shown in Figures 4(b), (c) and (d) exhibit progressively better gain and efficiency, but a progressively lower $FBW$. This is the first time that a bandwidth study has been conducted for this kind of small antenna. It is believed that the left-handed antennas have a wider $FBW$ than the conventional dipoles due to their highly dispersive behaviour. Interestingly the right-hand loaded dipole, with just one loading element per arm, provides improved performances with respect to a loaded dipole having several elements. As expected, all bandwidth and gain values are below the Chu and Harrington limits, which are $FBW = 36.8\%$ and $G = 3.4\,\text{dBi}$ for a sphere of radius $r_e = 55\,\text{mm}$.

This can be attributed to the low efficiency with which these structures use the available space within the enclosing sphere.

On the other hand, it is expected that distributed element configurations [7, 10] for the left-handed antennas can provide similar or higher efficiencies than conventional right-handed loading without the necessity of using external impedance matching networks.

## 5. CONCLUSION

This contribution presents a new concept for an efficient planar left-handed antenna working in the zero order mode (i.e., $n = 0$). This approach takes advantage of the left-handed topology to achieve well matched input impedance values and a miniaturized antenna, with improved performances with respect to conventional left-handed loading. Furthermore, an efficiency study for small antennas using left- and right-handed loading has been conducted. This sort of study sheds light onto the potential uses of metamaterials, since conventional and emerging technologies have been compared directly. Several possible applications for these metamaterial based antennas can be foresee in emergent technologies such as radiofrequency identification (RFID), automotive electronics, TV, and radio reception.

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