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Olusola O. Olaode, W. Devereux Palmer, William T. Joines

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14. ABSTRACT
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Block 13: Supplementary Note

Effects of Meandering on Dipole Antenna Resonant Frequency

Olusola O. Olaode, *Member, IEEE*, W. Devereux Palmer, *Senior Member, IEEE*, and William T. Joines, *Life Fellow, IEEE*

***Abstract*—In low-frequency applications, antenna designers find that it is beneficial to adjust the resonant frequency while preferably maintaining the physical size as a means of improving the antenna's radiation resistance, which in turn improves the radiation efficiency. The closer the resonant frequency is to the frequency of operation, the more efficient the antenna is. Addition of bends is one such technique for increasing the electrical size of a dipole antenna while maintaining the same overall physical length. This letter presents a study of the effects of bends on the resonant frequency of a dipole antenna in the VHF frequency range. A broadband equivalent circuit model for a straight dipole from previous work is adapted to a three-bend meander dipole antenna, and its performance is compared to that of a straight dipole having the same overall physical length. The predicted frequency response of the broadband model is calculated using circuit simulation software and compared to results from computational electromagnetic modeling and network-analyzer measurement of prototype straight and meandered dipole antennas.**

***Index Terms*—Dipole antennas, electrically small antennas, equivalent circuits, meandered line.**

I. Introduction

ANTENNA designers have a difficult choice between operating frequency and size for low-frequency applications. Due to the inverse relationship between frequency and wavelength, antennas operating in the VHF frequency band, for example, can be up to several meters in length. As a result, adaptation of such antennas for indoor use is often impractical. There is also the question of radiation efficiency. A straight-line dipole antenna (SLDA) is most efficient when the imaginary component of its complex input impedance is zero. This occurs when the electrical length of each leg of the dipole is slightly less than $\lambda/4$ at the frequency of operation [1]. Therefore, practical low-frequency antennas often are electrically small, i.e., $\ll \lambda/4$, and thus have low radiation resistance and narrow bandwidth.

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O. O. Olaode and W. T. Joines are with the Department of Electrical and Computer Engineering, Duke University, Durham, NC 27708 USA (e-mail: olusola.olaode@duke.edu; william.joines@duke.edu).

W. D. Palmer is with the Engineering Sciences Directorate—Electronics Division, US Army Research Office, Durham, NC 27709 USA (e-mail: william.d.palmer44.civ@mail.mil).

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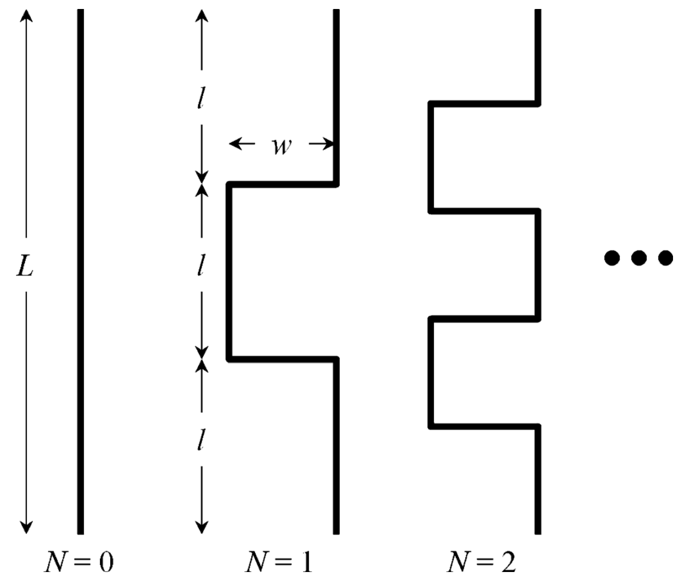

Fig. 1. One arm of an SLDA compared to one arm of MLDAs with increasing numbers of bends N. For each meandered dipole arm, all horizontal segments are of equal length w, and all vertical segments are of equal length l. Dimensions and resonant frequency for $L = 30$ cm and cases up to $N = 6$ meanders are shown in Table I.

TABLE I
RESONANT FREQUENCY AS A FUNCTION OF NUMBER OF MEANDERS

Meanders (N)	l (cm)	w (cm)	P (cm)	f_0 (MHz)
0	30	-		238
1	10.0	5.00	40.00	195
2	6.00	5.00	50.00	169
3	4.28	5.00	59.96	152
4	3.33	5.00	69.97	140
5	2.73	5.00	80.03	131
6	2.31	5.00	95.49	124

Several approaches have been tried in an attempt to increase the radiation resistance and broaden the bandwidth of electrically small antennas such as folding [2]; strategic loading with inductive, capacitive, or resistive components [3]; or a combination of these methods [4]. Many engineers have proposed using fractal geometries as well. Fractal-based antennas and meandered-line dipole antennas (MLDA) such as those shown in Fig. 1 have been used in applications in the microwave frequency range and higher. However, to the best of our knowledge, application of the MLDA at lower frequencies has not been studied.

Meander-line antennas have been widely applied in passive RFID applications on tags where the size, form, and impedance match to the RFID chip and radiation resistance are critical [5]–[7]. Additionally, meander antennas have been typically evaluated with frequency-dependent models that are inherently narrowband [8], [9]. However, no prior papers have explored the effect of meandering on antennas operating in the VHF frequency range and below.

This letter reports analysis of a regular MLDA designed to operate in the VHF band and contrasts its resonant frequency with that of an SLDA of the same overall size. The analysis is done through numerical modeling in EMCoS Antenna VLab [10], equivalent circuit simulation in NI Multisim [11], and experimental measurement using an Agilent E8362B PNA Network Analyzer.

II. Simulation of the Effects of Multiple Bends on Resonant Frequency

To aid our study of the MLDA, an SLDA was modeled, constructed, and measured to serve as a reference. The wire length and overall mechanical length L of each arm $=$ 30 cm. The resonant frequency f_0 is predicted to be 238.3 MHz using (1) from [12]

$$L(m) = \frac{143}{f_0\,(\mathrm{MHz})}. \tag{1}$$

Shifting the resonant frequency of an antenna downwards is generally a method to improve the radiation efficiency of an electrically small antenna since such an antenna would normally be severely inefficient in low-frequency applications. Prior works [2], [8], [9] suggest that bending an antenna to the same overall mechanical length as an SLDA lowers the resonant frequency of the resulting MLDA. Note that in the MLDA, the "mechanical length" L is the length of the antenna structure without considering the horizontal segments, while the "physical length" P represents the total wire length accounting for the horizontal segments. However, none of the previous work conclusively determines whether the addition of more bends N while keeping the overall mechanical length L the same continuously shifts the resonant frequency downward or if there is a "saturation point," i.e., a point when adding more bends results in little or no further reduction of the resonant frequency. Therefore, to determine the relationship between the number of bends and the reduction in resonant frequency, an SLDA ($N = 0$) and MLDAs with $N = 1$ to 6 were simulated. EMCoS Antenna Vlab uses the moment method, which divides the model under simulation into segments (or meshes) and solves for the electromagnetic fields in each segment. A 1-V source was used to excite both MLDA and SLDA models. The simulation results are tabulated in Table I and plotted in Fig. 2.

In Fig. 2, we observe that with few bends, the magnitude of the resonant frequency shift is more significant. However, the general trend of the curve signifies that adding more bends yield lesser and lesser frequency shift.

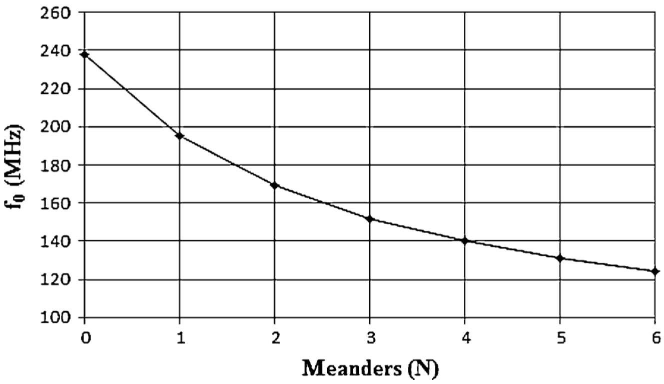

Fig. 2. Relationship between the number of meanders N and the resonant frequency f_0 for the SLDA ($N = 0$) and the MLDA with $N = 1$ to 6. The strongest effect on the resonant frequency is observed at low values of N.

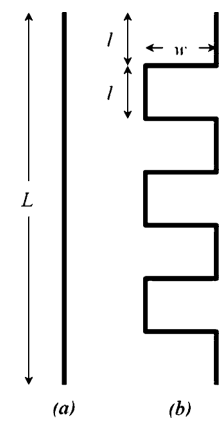

Fig. 3. (a) One arm of an SLDA and (b) a three-bend MLDA. For both antennas, the overall mechanical length $L = 30$ cm and the wire radius $a = 0.05$ cm. For the meandered-line dipole antenna, $L = 30$ cm, $l = w = 4.3$ cm, and the total wire length, the physical length P, is 55.71 cm.

III. Equivalent Circuit Modeling

A broadband equivalent circuit model developed explicitly for a meandered-line dipole antenna seems not to exist in any previous work, as far as we know. However, an equivalent circuit model for a straight-line dipole had been proposed by Tang *et al.* in [13] and proven valid by us through simulations in EMCoS Antenna Vlab software [5]. Since the inductance of a wire segment is constant regardless of folding, the straight-line dipole antenna model could be adapted for the meandered-line antenna. The three-bend MLDA was selected from the different antenna configurations examined in Section II to be studied in detail with the equivalent circuit model. In addition, the three-bend MLDA offers the best compromise between the complexity of the antenna structure and the magnitude of the reduction in resonant frequency.

The equivalent circuit model shown in Fig. 4 with parameter values from (2a)–(2d) [13] was used in NI Multisim to calculate the expected frequency response for both antennas shown in Fig. 3. The frequency response of both antennas was simulated using EMCoS Antenna VLab

$$C_{31} = \left\{ \frac{12.0674L}{\log\left(\frac{2L}{a}\right) - 0.7245} \right\} \mathrm{pF} \tag{2a}$$

$$C_{32} = 2L \left\{ \frac{0.89075}{\left[\log\left(\frac{2L}{a}\right)\right]^{0.8006} - 0.861} - 0.02541 \right\} \mathrm{pF} \tag{2b}$$

$$L_{31} = 0.2L \left\{ \begin{array}{c} \left[1.4813 \log\left(\frac{2L}{a}\right)\right]^{1.012} \\ -0.6188 \end{array} \right\} \mu\mathrm{H} \tag{2c}$$

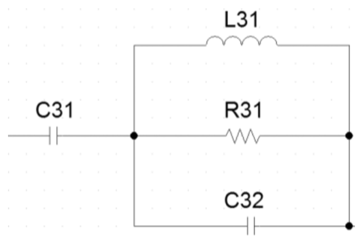

Fig. 4. Broadband equivalent circuit model from [13] used for both the SLDA and three-bend MLDA.

TABLE II
PARAMETER VALUES FOR THE EQUIVALENT CIRCUIT MODEL SHOWN IN FIG. 4

Parameter	SLDA	Three-bend MLDA
C_{31}	1.55 pF	1.47 pF
L_{31}	0.24 μH	0.49 μH
R_{31}	9.00 kΩ	19.5 kΩ
C_{32}	0.32 pF	0.54 pF

$$R_{31} = \left\{ \begin{array}{c} 0.41288 \left[\log\left(\frac{2L}{a}\right)\right]^2 + \\ 7.40754\,(2L/a)^{-0.02389} - 7.27408 \end{array} \right\} \mathrm{k}\Omega \tag{2d}$$

where the radius of the antenna wire $a = 0.05$ cm. To calculate the equivalent-circuit model parameters of the three-bend MLDA using equations for the SLDA circuit model (2a)–(2d), the physical length $P = 55.71$ cm of the MLDA was substituted for L in (2c) to compute its inductance (L_{31}). Since the resonant frequency of the three-bend MLDA (160 MHz) was determined in the EMCoS simulation, its capacitance $(C_{31} + C_{32})$ was then calculated using

$$f_0 = \frac{1}{2\pi\sqrt{L_{31}(C_{31} + C_{32})}} \tag{3}$$

where f_0 is the resonant frequency. It is well known that a meandered wire is electrically shorter relative to its straight-wire equivalent with equal physical length. Therefore, the total capacitance of a meandered wire will be less than that of a straight wire with equal physical length. For example, the total capacitance of the three-bend MLDA $(C_{31}+C_{32})$ was calculated from (3) as 2.01 pF compared to 3.11 pF from (2a) and (2b).

In Table II, values for the parameters C_{31}, L_{31}, and C_{32} under the SLDA column were derived from (2a)–(2c) where $L = 30$ cm. In both SLDA and MLDA, R_{31} was optimized to match the value of S_{11} at resonance with the value calculated in the EMCoS simulation. R_{31} represents the radiation resistance and ohmic losses in the antenna, and thus does not change the resonant frequency predicted by the equivalent circuit model, only the magnitude of S_{11} at resonance.

IV. EXPERIMENTAL MEASUREMENT

To verify and validate the calculations and simulations, prototype SLDA and three-bend MLDA antennas with the geometries shown in Fig. 3 and dimensions from Table I were constructed and measured. The antenna arms were formed from 18 gauge enamel-insulated copper wire, cut to length and bent to the desired shape using hand tools. The antenna arms were then secured with tape to extruded polystyrene (XEPS) insulation foam to hold the antenna geometry constant during measurement. The XEPS is transparent at microwave frequencies and thus does not measurably perturb the antenna impedance or radiation pattern. The dipoles were center-fed using an SMA connector soldered directly to the antenna arms. The prototype antennas are shown in Fig. 5.

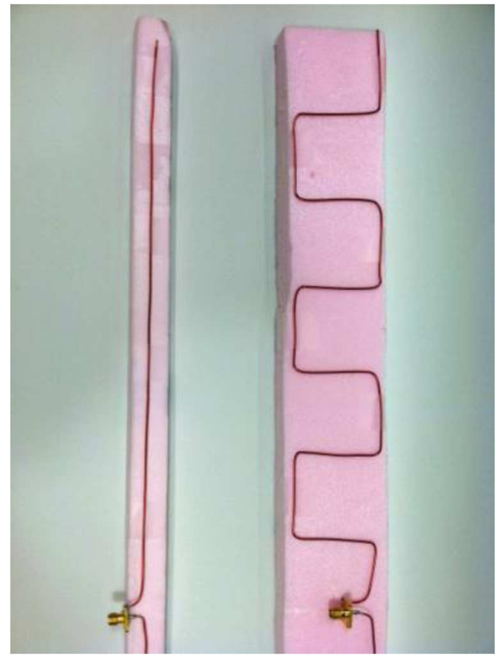

Fig. 5. Prototype SLDA and three-bend MLDA antennas. The antennas are constructed from 18-gauge enamel-insulated copper wire and fastened with tape to extruded polystyrene foam blocks to hold the antenna geometry constant. The antennas are center-fed using SMA connectors soldered directly to the antenna arms.

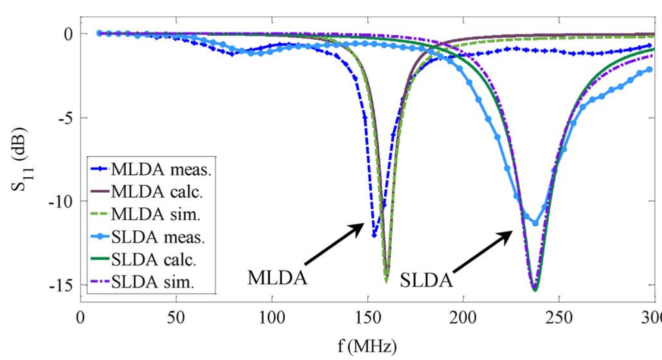

Fig. 6. Overlay of the calculated, simulated, and measured return loss of the SLDA and MLDA antennas shown in Figs. 3 and 5. Agreement is generally good, with the measured frequency of the MLDA varying from the calculated and simulated values by less than 6 MHz, or 4%.

The return loss was measured over the same frequency range as the calculations and simulations on both antennas using an Agilent E8362B PNA Network Analyzer. A ferrite choke was used to eliminate coupling to and radiation from the coaxial feed line. The measurement was performed in the laboratory with the antenna under test suspended in free space, far from nearby objects to prevent any appreciable effects on the antenna impedance. The calculated, simulated, and measured data for both antennas are plotted in Fig. 6.

V. Results and Discussion

Calculated, simulated, and measured return loss data indicate that a three-bend MLDA indeed has a lower resonant frequency than an SLDA with the same overall mechanical size. The results shown in Table II and Fig. 6 indicate that the resonant frequency shifts from 238 MHz for the SLDA to approximately 160 MHz for the three-bend MLDA, a shift of approximately 80 MHz or about 33%. Agreement between calculation, simulation, and measurement is generally good, with the measured resonant frequency of the MLDA varying from the calculated and simulated values by less than 6 MHz, or 4%.

VI. Conclusion

This letter has demonstrated that adding bends to a straight-line dipole antenna, producing a meandered-line dipole antenna, is an effective way to lower the resonant frequency of an antenna without increasing its overall mechanical size. A broadband equivalent circuit model for the SLDA developed previously by other researchers was shown to produce accurate results when applied to the MLDA with appropriate modifications to the antenna capacitance.

From calculation and simulation, three bends appears to be the best tradeoff between MLDA performance and complexity. Further shifts in the resonant frequency are achievable with additional bends. However, the magnitude of the shifts diminishes with each additional bend. Measured performance verifies and validates the equivalent circuit model and simulation techniques, indicating that these are useful tools for designing MLDAs for new applications.

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