A Wideband MNG-TL Dipole Antenna
With Stable Radiation Patterns

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Abstract—This paper presents the successful design and physical realization of a wideband MNG-TL dipole antenna. An artificial mu-negative transmission line (MNG-TL) structure is realized by employing periodically loaded parallel-plate lines. It is known that the current reversal, which occurs at frequencies much beyond the dipole natural frequency, disturbs the omnidirectional radiation pattern in the azimuth plane. The MNG-TL has a unique property to support a zero propagation constant ($\beta = 0$) with non-zero group velocity at the zeroth-order resonance. Due to the unique property of an infinite wavelength, the current distribution of the dipole antenna can be improved. Furthermore, the MNG-TL dipole is also useful to achieve a wide impedance bandwidth. A prototype of the proposed MNG-TL dipole is fabricated and measured. It can provide a wide effective bandwidth of about 1.55 GHz (1.85–3.40 GHz) with VSWR 2:1 ($S_{11} < -10$ dB) impedance matching and stable omnidirectional radiation patterns in the azimuth plane.

Index Terms—Dipole antennas, omnidirectional radiation patterns, mu-negative transmission line (MNG-TL), wideband, wire antennas.

I. INTRODUCTION

DURING the last few years, the linearly polarized and omnidirectional radiation pattern of a vertical dipole antenna has led to a wide range of applications in wireless communications such as wireless local area networks (WLANs) and radio broadcasting [1]. In the conventional dipole antenna, the antenna only resonates at the frequencies where the physical length $L$ of the dipole is an odd multiple of a half wavelength. It is known that the direction of the current on a long dipole antenna flips every half wavelength. The natural standing wave current distribution on a resonant long dipole antenna produces one radiation lobe for each half-wavelength antenna section [2].

As a result of the reverse current, the main beam splits and drifts away from the azimuth plane when the operating frequency increases [3]. In short-wave communications, in order to have omnidirectional pattern radiation and keep the main beam at the azimuth plane within a wide band, the physical length $L$ of the dipole has to be less than a wavelength and the dipole is resistive or capacitive loaded. However, the dipole antenna has a small radiating resistor at the lower frequency band because of the short electrical size, resulting in very poor radiation efficiency. Therefore, the design of a wideband wire antenna with stable omnidirectional radiation patterns in the azimuth plane and good radiation efficiency is still a challenge.

Recently, studies on left-handed metamaterials (LHMs) based on periodic structures for microwave applications have progressed rapidly to enhance antenna performances [4]–[6]. LHMs with dimensions smaller than the guided wavelength have attracted considerable attention in view of minimizing antenna size. Transmission lines loaded with reactive components that have left-handed wave behavior were applied to conventional dipoles design [7]–[10]. In the past few years, extensive research has been carried out on metamaterial realization of artificial magnetic conductors (AMCs) [11]. As revealed in [12], the use of AMCs to load a monopole antenna is useful to improve the omnidirectional radiation pattern at the third harmonic of the main resonant frequency. However, suffering from the narrowband and loss of AMCs, the AMC loaded monopole still cannot achieve stable omnidirectional radiation patterns in the azimuth plane and good radiation efficiency within a wideband. In this paper, a novel wideband MNG-TL dipole antenna structure is proposed, which is realized by employing periodically loaded parallel-plate lines. The MNG-TL has a unique property to support a zero propagation constant ($\beta = 0$) with non-zero group velocity at the zeroth-order resonance. With the unique property of an infinite wavelength, a closer examination of the MNG-TL dipole reveals that it can be used to improve the current distribution. Moreover, the structure is also useful to obtain a wide impedance bandwidth so that a wideband wire antenna with stable omnidirectional radiation patterns in the azimuth plane and good radiation efficiency is achieved. Details of the considerations of the proposed designs and the experimental results of the constructed prototype are presented and discussed.

II. MNG-TL DIPOLE ANTENNA

When the length of the conventional dipole antenna is several operating wavelengths, it will exhibit the main beam splitting and drifting away from the azimuth plane by the reason of the reverse current effects. In this paper, a MNG-TL dipole antenna
is proposed to increase the omnidirectional radiation bandwidth. Fig. 1 shows the overall configuration of the proposed MNG-TL dipole antenna. The dipole is composed of a plurality of periodically loaded parallel-plate lines. The parallel-plate line in this structure consists of two parallel conducting strips separated by a Teflon substrate ($\varepsilon_r = 2.65$ and $\tan \delta = 0.002$) with the thickness $h$.

It is well known that a dipole antenna can be considered as an uneven transmission line with radiation characteristics. To determine the dispersion relation and resonances of the proposed structure, the radiation resistances are neglected without affecting the resonance characteristic. Therefore, the corresponding equivalent TL circuit model of the proposed antenna is shown in Fig. 2(a), where the periodically loading series capacitance $C_L$ represents the coupling of the adjacent parallel-plate transmission line sections. Compared to the model of conventional dipole antennas, the periodically loading series capacitances $C_L$ are added periodically in the proposed antenna. The artificial mu-negative transmission line (MNG-TL) structure composed of a plurality of periodically loaded parallel-plate lines was firstly presented to obtain a zero order resonance (ZOR) loop antenna. In order to examine the resonances of the structure further, it is instructive to replace the TL sections with their equivalent distributed inductance and capacitance $C_R$ as shown in Fig. 2(b). It is clear that the proposed antenna employs an artificial mu-negative transmission line (MNG-TL) structure. The proposed MNG-TL only requires a left-handed series capacitance $C_L$ to be added to the right-handed transmission line. The MNG-TL composed by periodically loaded parallel-plate lines has been modeled and analyzed in detail in [13], so the theoretical analytic of the equivalent model shown in Fig. 2 has been omitted in this paper.

According to the previous literature [14], [15], the MNG-TL supports an infinite wavelength at the zeroth-order resonance ($\beta = 0, \omega \neq 0$), where the effective permeability is zero. Therefore, the MNG-TL supports a special dispersion relation and has a smaller phase constant $\beta_{\text{MNG}}$ compared to the conventional right-handed transmission line. This means that the currents of the MNG-TL dipole antenna remain in-phase even though the length of the dipole is several operating wavelength. The bandwidth of the MNG-TL dipole antenna is not limited by the reverse current effects, and stable omnidirectional radiation patterns within the bandwidth (ranging from $f_L$ to $f_U$) can be achieved. The proposed antenna is indicated with the main geometrical parameters as $p$ and $d$, the length of periodically loaded parallel-plate lines on the top and bottom layer; $w$, the width of periodically loaded parallel-plate lines; $g$, the gap between the conducting strips on the same layer; $h$, the thickness of the substrate; $l_y$, the length of the substrate; $w_y$, the width of the substrate.

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**Fig. 1.** Configuration of the proposed wideband MNG-TL dipole antenna. (a) Top view. (b) Bottom view. (c) Side view.

**Fig. 2.** (a) Corresponding equivalent TL circuit model of the proposed antenna. (b) Corresponding equivalent MNG-TL lumped-element circuit model.
To clarify the design concept, a prototype of the proposed MNG-TL dipole antenna with 150 mm (approximately 1.6\(\lambda_{\text{eff}}\) at 2.5 GHz) length was designed, and it was simulated using an Ansoft HFSS full-wave simulator. The antenna parameters of the MNG-TL dipole antenna have been optimized to improve the omnidirectional radiation bandwidth. It is found that the parameters \(w, d, w, g, \) and \(h\) shows a severe effect on antenna performance and determines the maximum operating frequency \(f_U\), which is because that the equivalent left-handed series capacitances \(C_L\) and right-handed series inductances \(L_R\) shown in Fig. 2 are determined by these parameters. For example, decreasing substrate thickness \(h\) or increasing width \(w\) of periodically loaded parallel-plate lines or decreasing the gap \(g\) offers stronger electromagnetic coupling and causes a larger equivalent capacitance \(C_L\). The equivalent inductance \(L_R\) mainly increases with increasing the length \(l\) and \(d\) of periodically loaded parallel-plate lines. In order to reduce the complexity of the optimization, the length \(l\) and \(d\) of periodically loaded parallel-plate lines on both layers are chosen to the same size. In order to keep the currents of the MNG-TL dipole antenna in-phase within a wide band, the equivalent left-handed series capacitances \(C_L\) and right-handed series inductances \(L_R\) should be chosen appropriately. The parameters \(w, d, w, g, \) and \(h\) are finally optimized to maximize the in-phase current distribution bandwidth. The detailed dimensions of the prototype are listed in Table I.

To investigate the radiation pattern of the proposed MNG-TL dipole antenna intuitively, the simulated surface currents distribution versus frequency is shown in Fig. 3. It is clear that the currents of the MNG-TL dipole antenna remain almost in-phase until 3.5 GHz (approximately 2.3\(\lambda_{\text{eff}}\)) and the proposed MNG-TL dipole antenna when the frequency varies from 1.5 GHz to 3.5 GHz in 0.5-GHz increments. As revealed in Fig. 4(a)–(b), the radiation pattern of the MNG-TL dipole improves considerably compared to that of the conventional dipole antenna with the same geometries. It is evident that the distortion of the omnidirectional radiation pattern in the azimuth plane occurs at frequencies higher than 2.5 GHz for the conventional dipole antenna, while the radiation pattern of the MNG-TL dipole is almost stable until 3.5 GHz. Actually, the conventional half-wavelength dipole (\(0.5\lambda_{\text{eff}}\) at 2.5 GHz) does not exhibit any beam splitting over a bandwidth of 1.5–3.5 GHz. However, in the conventional half-wavelength dipole antenna, the resonant frequencies \(\omega_m\) correspond to frequencies where the physical length \(l\) of the dipole is an odd multiple of a half wavelength. The impedance of the conventional half-wavelength dipole varies acutely with changes in frequencies. As we all known, it is very difficult for the conventional thin wire half-wavelength antenna to achieve wide impedance bandwidth. The mismatch results in very poor radiation efficiency. As shown in Fig. 4(c), the realized gain decreases acutely with changes in frequencies by the reason of poor radiation efficiency. The results are also presented in the Section III together with the experimentally measured data. The effective bandwidth of the proposed MNG-TL dipole improves significantly compared to that of the conventional half-wavelength dipole antenna.

The other major problem of the conventional dipole antenna is the wideband impedance matching. The input impedance of the proposed MNG-TL dipole antenna is significantly affected by the equivalent series capacitances \(C_L\) introduced by the coupling of the adjacent parallel-plate lines. As mentioned previously, the equivalent series capacitances \(C_L\) can be controlled by varying the substrate thickness \(h\) and the width \(w\). In order to investigate the impedance matching of the proposed MNG-TL dipole antenna without the impedance transformer, simulated input impedance from 0.5 GHz to 5 GHz on a Smith chart for a conventional dipole antenna and the different substrate thickness \(h\) in the MNG-TL dipole without the impedance transformer is shown in Fig. 5. In the conventional dipole antenna, the resonance frequencies \(\omega_m\) correspond to frequencies where the physical length \(l\) of the dipole is an odd multiple of
a half wavelength. The impedance of the conventional dipole varies acutely with changes in frequencies as confirmed by Fig. 5. However, due to the unique property of the MNG-TL, it is very easy for the MNG-TL dipole antenna to achieve wide impedance bandwidth. As we can see, the curve of the input impedance of the MNG-TL dipole antenna shrinks as the thickness $h$ is increased. This means that the impedance of the MNG-TL dipole antenna can maintain a stable value within a broad band, when the thickness $h = 1$ mm. Therefore the MNG-TL dipole can be matched by a simple impedance transformer and obtain good radiation efficiency at the same time. As shown in Fig. 1, the parallel-plate line with length $l_p$ and width $w_p$ act as an impedance transformer to achieve good impedance matching. The parallel-plate line has been optimized with the following parameters: $l_p = 12$ mm and $w_p = 1$ mm. Simulation results of the final design with the impedance transformer are presented in the next section together with the experimentally measured data.

III. EXPERIMENT RESULTS

A prototype of the proposed MNG-TL dipole antenna with the impedance transformer was fabricated and tested to provide verification of the novel design method. As shown in Fig. 6, the antenna was constructed on a Teflon PCB board. Fig. 7 shows the measured and simulated reflection coefficient of the constructed prototype. For comparison, the simulated $S_{11}$ of the conventional dipole antenna with the same geometries of the proposed MNG-TL dipole antenna is also shown in Fig. 5. It is clearly that the impedance bandwidth of the proposed segmented dipole antenna is improved significantly. The measured data in general agrees with the simulated results. Only a little
Fig. 7. Simulated and measured reflection coefficient values $S_{11}$ of the proposed MNG-TL dipole antenna with the impedance transformer.

upshifting of the matching frequencies occurs for the measured data compared to the simulated results. The impedance bandwidth ($S_{11} \leq -10$ dB) of the MNG-TL dipole antenna were simulated and measured as 2 GHz (1.78–3.78 GHz, bandwidth ratios of 2.12:1) and 2.15 GHz (1.85–4 GHz, bandwidth ratios of 2.16:1) respectively.

The radiation characteristics of the fabricated prototype were also studied. Ferrite beads were used to cover the part of the test cable that is close to the antenna. The length of the ferrite-bead covered section of the feed cable is about 80 mm. The measured average realized gain in the azimuth plane of the proposed antenna is presented in Fig. 8 as a function of the operating frequency. The effective bandwidth is defined as the frequency range over which the main beam with an omnidirectional radiation pattern remains in the azimuth plane and the antenna obtains good impedance matching ($S_{11} \leq -10$ dB). The measured effective bandwidth is about 1.55 GHz (1.85–3.40 GHz, bandwidth ratio of 1.8:1). Across the measured effective bandwidth, the measured average realized gain in the azimuth plane is in a range of about 2.4–4.8 dBi. It is shown that the average realized gain in the azimuth plane decreases fast at frequencies higher than 3.5 GHz. This is because the omnidirectional pattern in the azimuth plane is distorted by the reverse current effects. For comparison, the average realized gain in the azimuth plane of a conventional dipole antenna (half-wavelength at 2.5 GHz) with the same width is also presented in Fig. 8. As revealed in Fig. 8, the effective bandwidth of the MNG-TL dipole improves significantly compared to that of the conventional dipole antenna (half-wavelength at 2.5 GHz). The measured antenna efficiency of the proposed MNG-TL dipole antenna is shown in Fig. 9. The efficiency is defined as the ratio of radiated power to total power available from the power source. Thus the efficiency value includes all impacts from mismatch loss, dielectric loss, and conductor loss. The measured efficiency of the MNG-TL dipole antenna is above 85% within the effective bandwidth.

The measured normalized radiation patterns of the fabricated prototype in the pattern bandwidth are shown in Fig. 10. Only three representative frequencies ($f = 1.85$ GHz, $f = 2.50$ GHz, and $f = 3.46$ GHz) are presented. Measurements at other operating frequencies across the bandwidth (not shown here for brevity) also show radiation patterns similar to those plotted here. As can be seen from all the E-plane ($xz$ plane) radiation patterns, the main beam is approximately fixed toward the azimuth plane. From these results, it is clear that good omnidirectional radiation with vertical polarization in the H-plane ($xy$ plane) with a small gain variation of less than 1.2 dB is obtained. It is clear that a wideband MNG-TL dipole antenna with stable omnidirectional radiation patterns is achieved.

IV. CONCLUSION

The design of a novel wideband MNG-TL dipole antenna with stable omnidirectional radiation patterns has been introduced in this paper. An artificial mu-negative transmission line (MNG-TL) structure is realized by employing periodically loaded parallel-plate lines. Due to the unique property of the MNG-TL, the current distribution of the dipole antenna can be improved, while the impedance of the MNG-TL dipole antenna can maintain a stable value within a broad band. The design was discussed in detail and simulation results were compared
Fig. 10. Measured normalized radiation patterns of the fabricated prototype. (a) $f = 1.85$ GHz. (b) $f = 2.50$ GHz. (c) $f = 3.40$ GHz.

to those of a conventional dipole antenna. An MNG-TL dipole was also fabricated and measured. The measured results were found to agree very well with simulated data. The fabricated prototype can provide a wide effective bandwidth of about 1.55 GHz (1.85–3.40 GHz) with VSWR 2:1 ($S_{11} < -10$ dB) impedance matching and stable omnidirectional radiation patterns in the azimuth plane. The measured efficiency of the MNG-TL dipole antenna is above 90% within the effective bandwidth. The experimental results show that this design is ideally practical for a wideband dipole antenna with stable omnidirectional radiation patterns.

REFERENCES
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