A Wideband MNG-TL Dipole Antenna With Stable Radiation Patterns

Kunpeng Wei, *Student Member, IEEE*, Zhijun Zhang, *Senior Member, IEEE*, Zhenghe Feng, *Fellow, IEEE*, and Magdy F. Iskander, *Life Fellow, IEEE*

***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]. LMHs 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 can not 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 wavelength, 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

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K. Wei, Z. Zhang, and Z. Feng are with State Key Lab of Microwave and Communications, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China (e-mail: zjzh@tsinghua.edu.cn).

M. F. Iskander is with HCAC, University of Hawaii at Manoa, Honolulu, HI 96822 USA (e-mail: iskander@spectra.eng.hawaii.edu).

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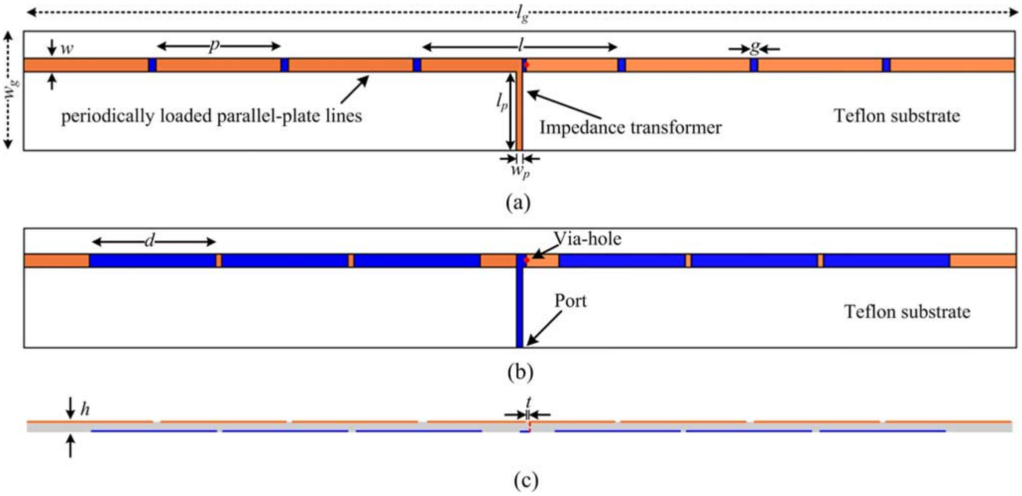


Fig. 1. Configuration of the proposed wideband MNG-TL dipole antenna. (a) Top view. (b) Bottom view. (c) Side view.

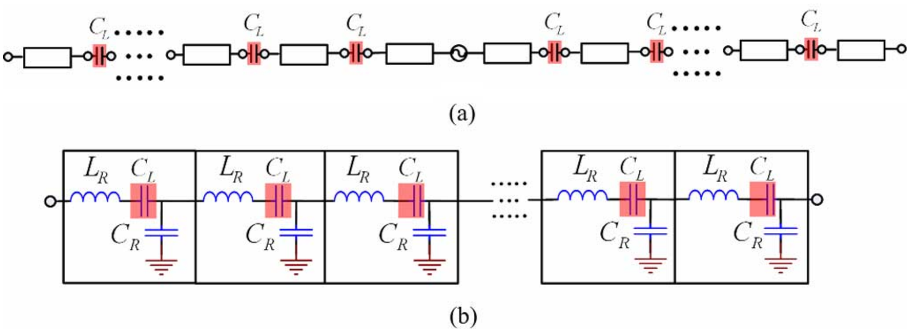


Fig. 2. (a) Corresponding equivalent TL circuit model of the proposed antenna. (b) Corresponding equivalent MNG-TL lumped-element circuit model.

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 L_R 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 β_{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_g, the length of the substrate; w_g, the width of the substrate.

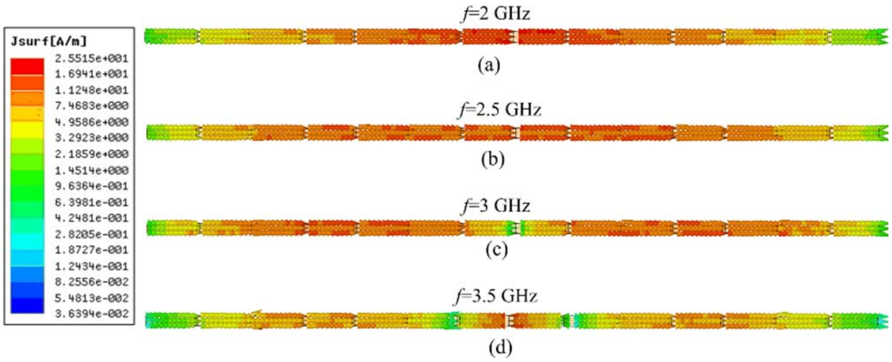


Fig. 3. Simulated surface currents distribution versus frequency. (a) $f = 2$ GHz. (b) $f = 2.5$ GHz. (c) $f = 3$ GHz. (d) $f = 3.5$ GHz.

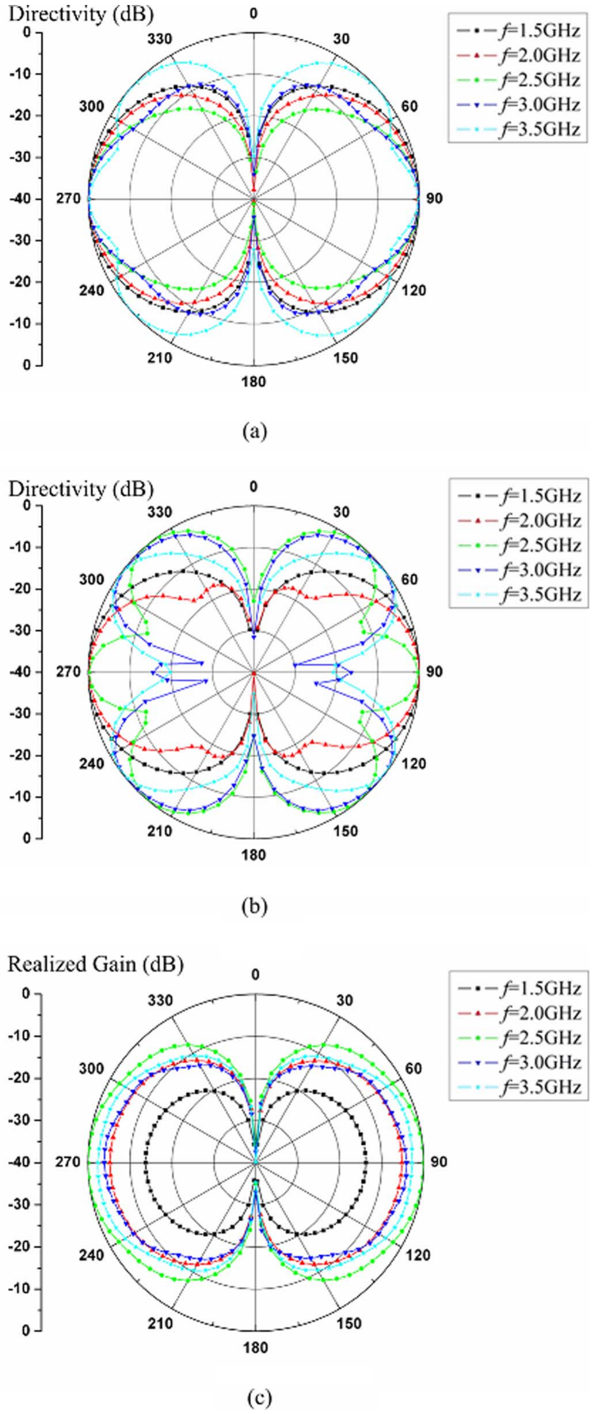
TABLE I
DETAILED DIMENSIONS OF THE PROTOTYPE (mm)

Parameter	w	g	p	d	h
Value	2	1	19	19	1
Parameter	l	t	l_g	w_g	
Value	30	0.6	150	18	

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 $p, d, w, g,$ 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 p and d of periodically loaded parallel-plate lines. In order to reduce the complexity of the optimization, the length p and d of periodically loaded parallel-plate lines on the 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 $p, d, w, g,$ 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 $2.3\lambda_{\text{eff}}$). This reveals that it can be used to improve the current distribution and achieve a stable omnidirectional radiation pattern in the azimuth plane within a wide band. To demonstrate the improvement of the radiation pattern, Fig. 4(a)–(b) shows the simulated E-plane normalized directivity of the conventional dipole antenna with the same geometries (approximately 2.3 λ_{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) do not exhibit any beam splitting over a bandwidth of 1.5–3.5 GHz. However, in the conventional half-wavelength dipole antenna, the resonance frequencies ω_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 recitation 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 ω_m correspond to frequencies where the physical length L of the dipole is an odd multiple of



(a)

(b)

(c)

Fig. 4. Simulated normalized E-plane radiation pattern versus frequency. (a) Directivity of the proposed MNG-TL dipole antenna. (b) Directivity of conventional dipole antenna with the same geometries (approximately $2.3\lambda_{\mathrm{eff}}$). (c) Realized gain of the conventional half-wavelength dipole ($0.5\lambda_{\mathrm{eff}}$ at 2.5 GHz) with the same width.

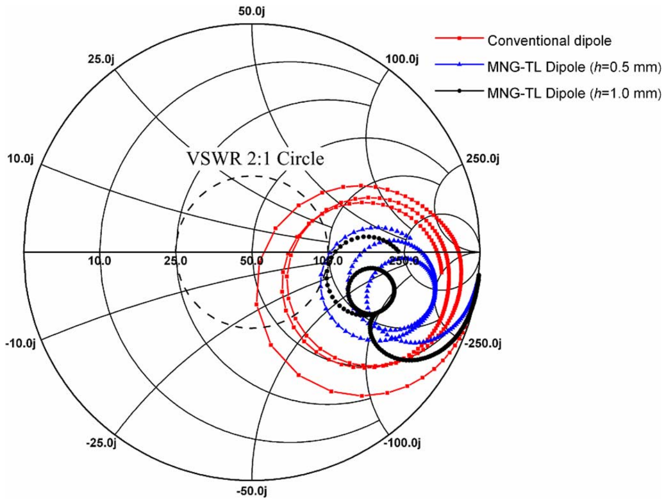
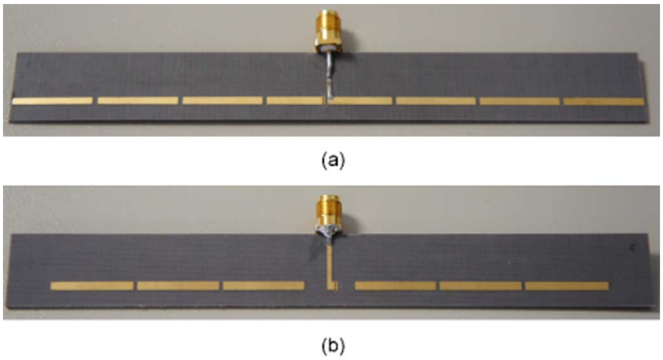


Fig. 5. Simulated input impedance from 0.5 GHz to 5 GHz for conventional dipole antenna and the different substrate thickness h in the MNG-TL dipole without the impedance transformer.



(a)

(b)

Fig. 6. Photograph of the fabricated prototype. (a) Front view. (b) Back view.

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

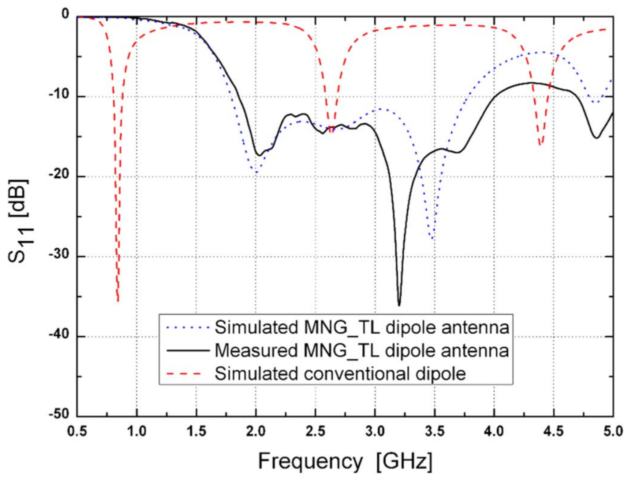


Fig. 7. Simulated and measured reflection coefficient values S_{11} of the proposed MNG-TL dipole antenna with the impedance transformer.

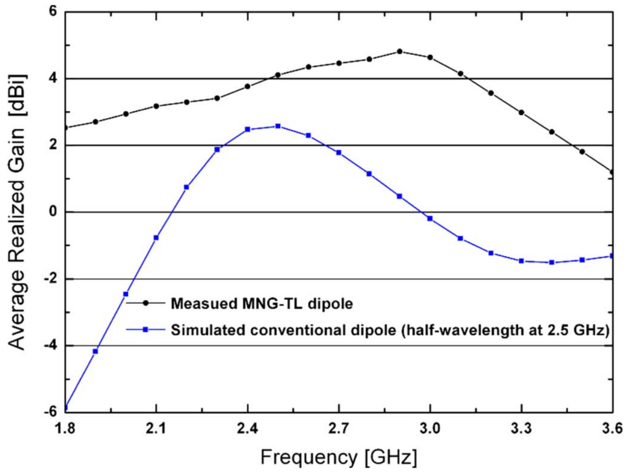


Fig. 8. Measured antenna average realized gain at the azimuth plane of the proposed MNG-TL dipole antenna.

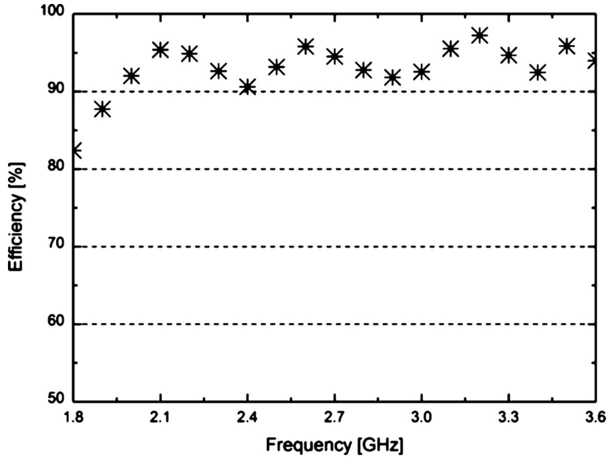


Fig. 9. Measured antenna efficiency of the proposed MNG-TL dipole antenna.

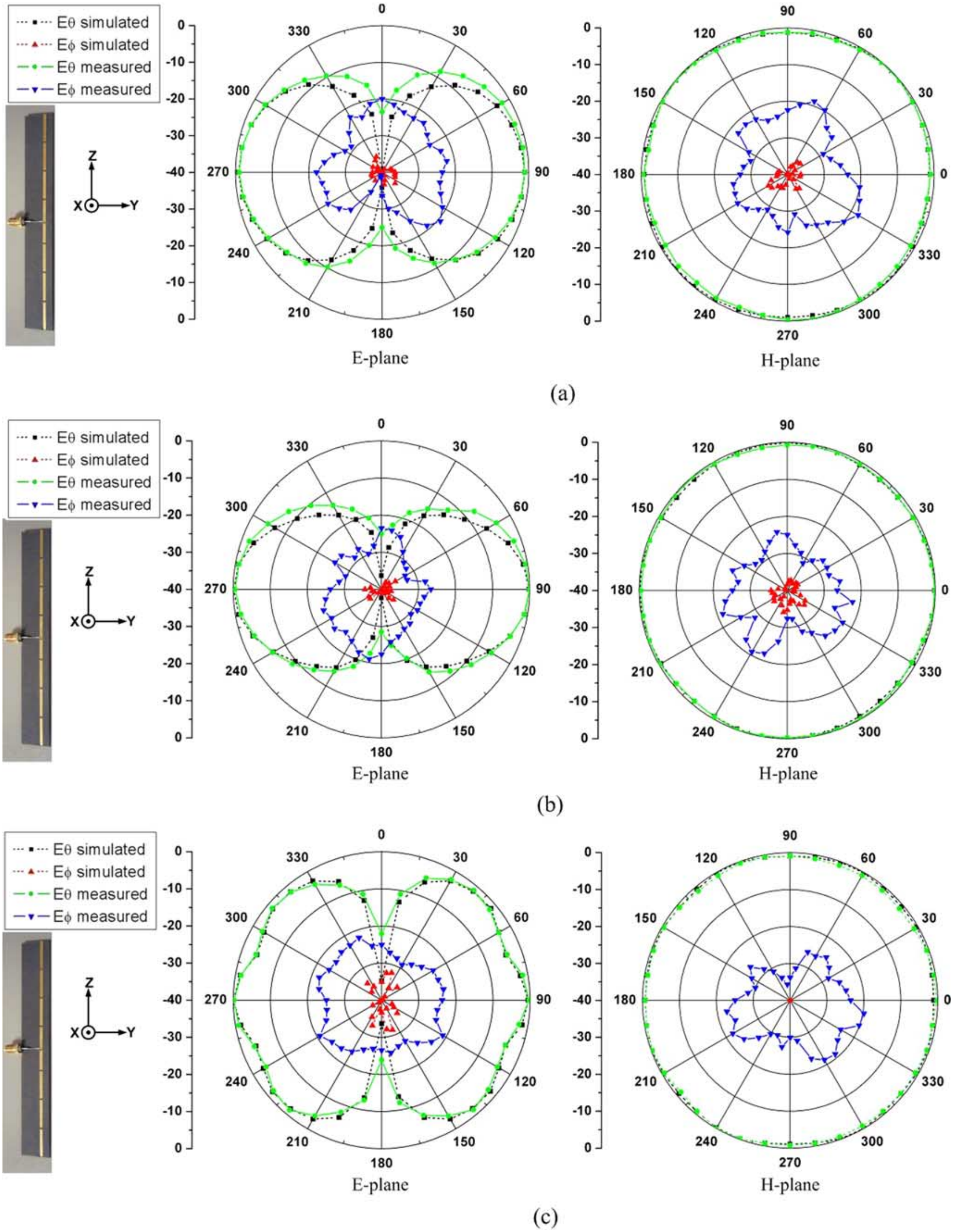
upshifting of the matching frequencies occurs for the measured data compared to the simulated results. The impedance bandwidth ($\mathrm{S}_{11} \leq -10$ dB) of the MNG-TL dipole antenna were simulated and measured as 2 GHz (1.78–3.78 GHz, bandwidth ratios of 2.12:1) and 2.15 GHz (1.85–4 GHz, bandwidth 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 ($\mathrm{S}_{11} \leq -10$ 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 $f = 3.40$ 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 ($x - z$ 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 ($x - y$ 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



(a)

(b)

(c)

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 ($\mathrm{S}_{11} < -10$ 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.

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Kunpeng Wei (S'10) was born in Nanchang, China, in 1987. He received the B.S. degrees in electronic and information engineering from the HuaZhong University of Science and Technology, Wuhan, China, in 2008. He is currently working toward Ph.D. degree in electrical engineering from Tsinghua University, Beijing, China.

His current research interests include antenna design and theory, particularly in omni-directional antennas and base station antennas.

Zhijun Zhang (M'00–SM'04) received the B.S. and M.S. degrees from the University of Electronic Science and Technology of China, in 1992 and 1995, respectively, and the Ph.D. degree from Tsinghua University, Beijing, China, in 1999.

In 1999, he was a Postdoctoral Fellow with the Department of Electrical Engineering, University of Utah, UT, USA, where he was appointed a Research Assistant Professor in 2001. In May 2002, he was an Assistant Researcher with the University of Hawaii at Manoa, Honolulu, HI, USA. In November 2002, he joined Amphenol T&M Antennas, Vernon Hills, IL, USA, as a Senior Staff Antenna Development Engineer and was then promoted to the position of Antenna Engineer Manager. In 2004, he joined Nokia Inc., San Diego, CA, USA, as a Senior Antenna Design Engineer. In 2006, he joined Apple Inc., Cupertino, CA, USA, as a Senior Antenna Design Engineer and was then promoted to the position of Principal Antenna Engineer. Since August 2007, he has been with Tsinghua University, where he is a Professor in the Department of Electronic Engineering. He is the author of *Antenna Design for Mobile Devices* (Wiley, 2011). He is serving as Associate Editor of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION and the *IEEE Antennas And Wireless Propagation Letters*.

Zhenghe Feng (F'12) received the B.S. degree in radio and electronics from Tsinghua University, Beijing, China, in 1970.

Since 1970, he has been with Tsinghua University, as an Assistant, Lecture, Associate Professor, and Full Professor. His main research areas include numerical techniques and computational electromagnetics, RF and microwave circuits and antenna, wireless communications, smart antenna, and spatial temporal signal processing.

Magdy F. Iskander (F'93–LF'12) is the Director of the Hawaii Center for Advanced Communications (HCAC), College of Engineering, University of Hawaii at Manoa, Honolulu, Hawaii, HI, USA (http://hcac.hawaii.edu). He is Co-director the NSF Industry/University Cooperative Research Center with four other universities. From 1997–99 he was a Program Director at the National Science Foundation, where he formulated a "Wireless Information Technology" Initiative in the Engineering Directorate. Much of his research is funded by the National Science Foundation, CERDEC, and Office of Naval Research including Major Research Instrumentation grant for establishing wireless testbed and indoor antenna range, and multiple grants on innovative multiband antenna designs and propagation modeling techniques for wireless communications. His Center HCAC has an ongoing 10-year grant (2005–2014) for partnership in the NSF Industry/University Cooperative Research Center in Telecommunications with the University of Arizona, Arizona State University, and the Ohio State University. His research focus is on antenna design and propagation modeling for wireless communications and radar systems and his group recently received two NSF grants for International collaboration on the development of the "Microwave Stethoscope" for vital signs monitoring in remote patients and school students. He authored the textbook *Electromagnetic Fields and Waves* (Prentice Hall, 1992; and Waveland Press, 2001; 2nd edition 2012), edited the *CAEME Software Books*, Vol. I, II 1991–94; and edited four books on *Microwave Processing of Materials* (Materials Research Society, 1990–1996). He has published over 230 papers in technical journals, has eight patents, and made numerous presentations in national and International conferences. He is the founding editor of the *Computer Applications in Engineering Education Journal* (Wiley, 1992–present).

Dr. Iskander is a Fellow (1993) and a Life Fellow (2012) of the IEEE. He received the 2012 IEEE AP-S Chen To Tia Distinguished Educator Award for "Innovation and distinguished contribution to engineering education and STEM outreach programs." He received the 2010 University of Hawaii Board of Regents' Medal for Teaching Excellence, the 2010 Northrop Grumman Excellence in Teaching Award, the 2011 Hi Chang Chai Outstanding Teaching Award, and the University of Utah Distinguished Teaching Award in 2000. He also received the 1985 Curtis W. McGraw ASEE National Research Award, 1991 ASEE George Westinghouse National Education Award, 1992 Richard R. Stoddard Award from the IEEE EMC Society. He was a member of the 1999 WTEC panel on "Wireless Information Technology-Europe and Japan", and chaired two International Technology Institute Panels on "Asian Telecommunication Technology" sponsored by NSF/DoD in 2001 and 2003. He was Guest Editor of two Special Issues of the IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION on Wireless Communications Technology, 2002 and 2006, and co-edited a Special Issue of the *IEICE Journal* in Japan in 2004. He was the 2002 President of IEEE Antennas and Propagation Society, Distinguished Lecturer for IEEE AP-S (1994–97).