# 2.45 GHz high-gain electrically small antenna with composite right/left-handed ladder structure

K. Takahagi, Y. Otsu and E. Sano

Electrically small antennas are needed to further lower the cost of wireless elements. However, the antenna gain is constrained to the Harrington limit, while the impedance matching and directivity characteristics deteriorate in electrically small antennas. Using a dipole antenna loaded with a left-handed ladder structure is a promising technique for reducing the size of antennas. In this letter, we designed a lumped-component loading left-handed antenna on the basis of the composite right/left-handed transmission line theory. A 4-unit cell left-handed dipole antenna with a size of 20 mm ($0.16\lambda_0$) was fabricated with a T-junction balun. The actual gain of the fabricated antenna was -0.01 dBi, which was about 1 dB lower than the Harrington limit and the highest ever achieved for fabricated antennas operating at around 2.45 GHz ($kr$ = 0.502). The directivity measured in the E-plane was similar to that of typical half-wavelength dipole antennas.

*Introduction:* Recently, there has been significant interest in researching and developing wireless communication circuits for 2.45-GHz, 24-GHz, and 60-GHz band applications. In particular, electrically small antenna technologies are needed to achieve miniaturization of wireless equipment for wireless communication and sensor networks. In recent years, several extensive attempts have been made to fabricate electrically small antennas for system-on-a-chip (SoC) or system- in-a-package (SiP) [1], [2]. However, the antenna gain is constrained to the Harrington limit, while the impedance matching and directivity characteristics deteriorate in electrically small antennas.

Various methods for reducing antenna size have been reported [2-7]. Using a dipole antenna loaded with a left-handed ladder structure is a promising technique for reducing the size of antennas [4]. When parallel plate capacitors and spiral inductors are fabricated on a printed-circuit board with a thickness of a few mm, however, the sizes of the capacitors and the widths of the spiral inductors are expected to be more than 4 × 4 mm and 2 mm for achieving left-handed components operating at 2.4 GHz, and these components cannot reduce the antenna size to be smaller than a conventional dipole antenna. In contrast, lumped components of inductors and capacitors with sizes of 0.4 × 0.2 and 0.6 × 0.3 mm are commercially available.

In this letter, the left-handed dipole antenna with the right/left-handed ladder structure was designed and fabricated using lumped inductors and capacitors.

The highest achievable gain of an electrically small antenna that can be enclosed within a sphere of effective radius $r$ is given by

$$G = (kr)^2 + 2kr \qquad (1)$$

where $k$ is the wave number [4]. The highest gain for small antennas operating at 2.45 GHz is calculated to be 1.0 dBi with an antenna length of 20 mm corresponding to $0.16\lambda_0$ and $kr$ = 0.502 ($\lambda_0$: free space wavelength).

*Antenna design:* The circuit configuration of the designed antenna is depicted in Fig. 1*a*. The antenna was composed of series inductors $L_R$ and shunt capacitors $C_R$ used as right-handed elements and shunt inductors $L_L$ and series capacitors $C_L$ used as left-handed elements. The distributed elements of the two parallel transmission lines were used as the right-handed components. The unit cell combined T-type left-handed elements of a shunt inductor and two series capacitors with right-handed transmission lines. The number of unit cells $N$ was 4. The antenna geometry and the values of $C_L$ and $L_L$ were chosen on the basis of composite right/left-handed transmission line theory [8]. The dispersion characteristics for a composite right/left-handed transmission line is given by

$$\beta p = \cos^{-1}\left[1 - \frac{1}{2}\left\{\left(\omega L_R - \frac{1}{\omega C_L}\right)\cdot\left(\omega C_R - \frac{1}{\omega L_L}\right)\right\}\right] \qquad (2)$$

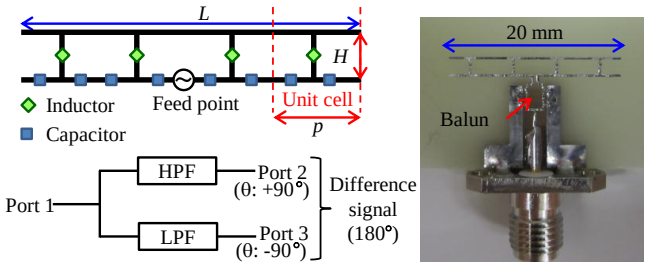
The values of $L_R$ and $C_R$ in the parallel transmission lines are given by

$$L_R = \frac{p\mu_0}{\pi}\ln\left(\frac{H}{R}\right), \quad C_R = \frac{\pi p \varepsilon_0 \varepsilon_r}{\ln(H/R)} \qquad (3)$$

where $H$ is the distance between the two parallel lines and $R$ is the half line width [5]. Since both ends of the lines are open, the phase difference between the two open ends must be $\pi$ at the operating frequency. This means that $\beta p$ must equal $\pi/4$ at the target frequency of 2.4 GHz. The designed values were: the unit cell size = 5 mm, $H$ = 2 mm, $R$ = 0.15 mm, $C_L$ = 0.5 pF, and $L_L$ = 3.9 nH. The antenna was simulated with a finite-difference time-domain (FDTD) electromagnetic simulator (EMpro, Agilent).

A T-junction balun was designed for the differential signal input to the dipole antenna. The balun was composed of a high-pass filter (HPF), a low-pass filter (LPF), and a T-junction (Fig. 1*b*). Fifth-order LC circuits were used for the HPF and LPF, which shifted the signal by +90° in the leading phase and -90° in the lagging phase, respectively. Each element of the balun was simulated with a circuit simulator (ADS). Finally, the impedance matching was simulated for the left-handed antenna combined with the T-junction balun.

*Fabrication:* The antenna with balun was constructed on FR4 substrate with a thickness of 1.6 mm. Commercially available chip capacitors and inductors with a size of 0.6 × 0.3 mm were used. Fig. 1*b* shows a photograph of the fabricated antenna with balun. To eliminate the effect of variation in the lumped elements, we fabricated four antennas and averaged the measured characteristics.

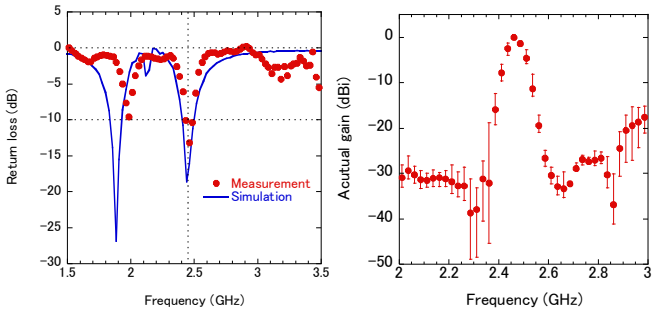



*a* *b*

**Fig. 1** *Configuration of left-handed dipole antenna with balun and photograph of fabricated antenna with balun.*
*a* Circuit configuration
*b* Photograph

*Measurements and results:* The fabricated antennas were measured using a standard dipole antenna with a gain of 2.14 dB and a vector network analyser (VNA). Port 1 of the VNA was connected to one of the fabricated antennas, and Port 2 of the VNA was connected to the dipole antenna. The gain was calibrated with the gain measured between two standard dipole antennas.

Fig. 2*a* shows the measured return losses for each antenna. An impedance matching of less than -10 dB was obtained in the frequency band from 2.4 to 2.5 GHz. The matching between designed and measured return losses was quite good. Fig. 2*b* shows the actual gain for the antenna. The measured antenna gain was -0.01 dBi. The simulated antenna gain (-0.66 dBi) was slightly lower than the measured gain. The difference might have been caused by the variation in the lumped elements and the effect of the solder used to mount the components. Fig. 3 compares measured and simulated directivities. The directivity of the fabricated antenna was measured by changing the angle/theta from 0 to 90 degrees by 5 degree steps in the E-plane. A fairly good agreement was obtained for all degree steps. Fig. 4 compares the antenna gains achieved in this work with those reported in previous literature [2]-[4], [6], [7]. Their measurement values are the highest gain ever achieved for the antennas at the same $kr$ operating at 2.45 GHz.




*a* *b*

**Fig. 2** *Return loss and actual gain*
*a* Measured and simulated return losses
*b* Measured actual gain

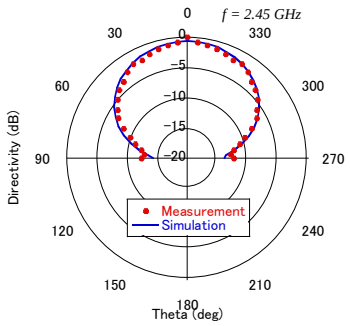



**Fig. 3** *Comparisons between measured and simulated directivity in E-plane*

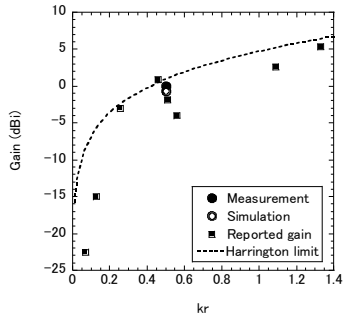



**Fig. 4** *Comparison of fabricated antenna gain with those reported in literature* [2]-[4], [6], [7].

*Conclusion:* On the basis of the composite right/left-handed transmission line theory, we designed the left-handed antenna with the lumped components to reduce the antenna size. The actual gain of the fabricated antenna was -0.01 dBi, which was about 1 dB lower than the Harrington limit and the highest ever achieved for fabricated antennas operating at around 2.45 GHz ($kr$ = 0.502).

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