Analysis of a Broadband Low-Profile Two-Strip Monopole Antenna

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***Abstract*: A broadband low-profile monopole antenna is analyzed by using balanced and unbalanced mode decomposition. The broadband antenna consists of an S-strip and a folded T-strip that are separately printed on the two sides of a thin planar substrate, forming a two-strip monopole. The two-strip antenna can achieve a bandwidth (VSWR≤2) of ~40% with a height of 0.08λ_0. It is revealed that the broadband performance of the two-strip antenna is a result of the combination of an unbalanced mode and a balanced mode. Experimental results verify the theoretical analysis.**

1. Introduction

Monopole antenna is attractive for wireless applications because of its simple structure and omni-directional radiation pattern. However, a straight monopole usually has a height of larger than ~0.15λ_0 (λ_0 is the operating wavelength in free space) [1]. A simple way to reduce the antenna height is to bend or fold the straight monopole into some type of low-profile configuration, such as an inverted L or an inverted F [2], a double S [3] or a double T [4], or a meandered shape [5]. But a low-profile monopole can lead to a narrow impedance bandwidth. Recently a broadband low-profile monopole antenna was developed in [6]. The broadband antenna consists of an S-strip and a folded T-strip that are separately printed on the two sides of a thin planar substrate, forming a two-strip monopole. The bandwidth enhancement is due to the electromagnetic coupling between the S-strip and the T-strip. There is no theoretic analysis in [6]. In this paper, a balanced and unbalanced mode analysis will be presented to understand the operating principle of the two-strip antenna.

2. Antenna configuration

The configuration of a broadband two-strip monopole antenna is illustrated in Fig. 1. This antenna is designed at a 2-GHz band based on an RT/Duroid 5880 planar substrate that has a dielectric constant of ε_r=2.2 and a thickness of t=10 mils (0.254 mm). The antenna is printed on both sides of the substrate. On the front side, there is a T-strip whose lower section is folded and extended to a 50-Ω microstrip line. On the backside of the substrate, there is an S-strip that is terminated at a ground plane. The upper section of the T-strip is fitted

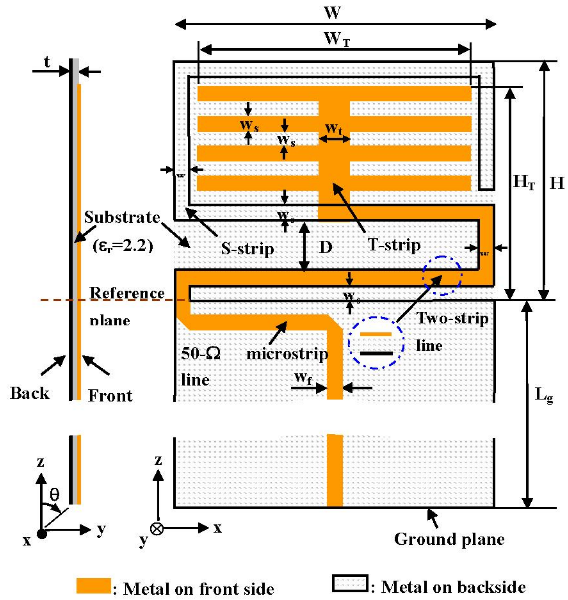


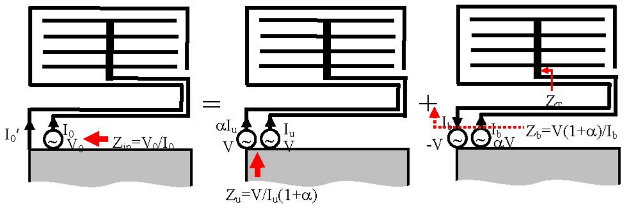
Fig. 1. Configuration of a broadband two-strip monopole antenna. (Geometrical parameters: H=12 mm, W=16 mm, H_T=10.75 mm, W_T=13.5 mm, W_t=1.5 mm, w_s=0.75 mm, w_f=0.75 mm, t=0.254 mm, and L_g=20 mm.)

into an area surrounded by the upper section of the S-strip. Therefore, the height (H_T) and width (W_T) of the T-strip are slightly shorter than those (i.e., H and W) of the S-strip. The crossbar of the T-strip is divided into narrow strips whose width and separation are equal to the width (w_s) of the S-strip, which is equal to the width (w_f) of the 50-Ω microstrip line. The folded lower section of the T-strip on the front side overlaps with the lower section of the S-strip on the backside, forming a two-strip line. There is no direct electrical connection (e.g., by a shorting via) between the front side and the backside. The spacing (D) between the upper and lower sections of the S-strip/T-strip is reserved for a dual-frequency operation which requires additional parasitic elements. If only a single-frequency broadband operation is required, then the spacing D can be minimized to D=w_s for lowering the total height (i.e., H) of the two-strip monopole [6]. The two-strip antenna is excited by a wave-port at the end of the ground plane.

3. Analysis

To understanding the operating mechanism of the two-strip monopole, we decompose the antenna into an unbalanced mode and a balance mode, as shown diagrammatically in Fig. 2 [7]. In the two-strip monopole, the microstrip line is simplified as an input voltage source V_0 and the currents in the T-strip and in the S-strip are denoted by I_0 and I_0', respectively (see Fig. 2a). Therefore, the input impedance of the two-strip monopole antenna can be expressed as

$$Z_{in} = V_0 / I_0. \quad (1)$$



(a) Two-strip monopole. (b) Unbalanced mode. (c) Balanced mode.

Fig. 2. Mode decomposition of the two-strip monopole antenna.

In the unbalanced mode, there are two identical voltage sources (V) feeding the S-strip and the T-strip, respectively. Due to the shape difference between the S- and T-strips, the currents in the T- and S-strips differ by a current sharing factor α. In effect, the unbalanced mode can be considered as an S-strip monopole parallel with a T-strip monopole (see Fig. 2b). Because the unbalanced mode is a dominant radiating mode, the S- and T-strip combined configuration is called a two-strip monopole. The impedance of the unbalanced mode is given by

$$Z_u = V/(1+\alpha)I_u, \quad (2)$$

where I_u is the unbalanced current at the feeding point.

In the balanced mode, there is a balanced current I_b in the S-strip and in the T-strip. However, the voltage sources feeding the S-strip and the T-strip differ by the factor α. The impedance of the balanced mode is defined as

$$Z_b = (1+\alpha)V / I_b. \quad (3)$$

The balanced mode can be considered as a dipole excited through a two-strip line. Therefore, the balanced-mode impedance also can be written as

$$Z_b = Z_0' \frac{Z_T + jZ_0' \tan \beta l_b}{Z_0' + jZ_T \tan \beta l_b}, \quad (4)$$

where Z_T is the input impedance of the dipole (see Fig. 2c), Z_0', $\beta = 2\pi f \varepsilon_{eff}^{1/2}/c$ (ε_{eff}=the effective dielectric constant and c=the speed of light in free space) and l_b are the characteristic impedance, propagation constant, and the length of the two-strip line, respectively. Because the two-strip monopole is a combination of the unbalanced mode and the balanced mode, the input voltage (V_0) is equal to $(1+\alpha)V$ and the input current (I_0) is I_u+I_b. Thus, the input impedance Z_{in} of the two-strip monopole can be rewritten in terms of Z_u and Z_b as

$$Z_{in} = \frac{V_0}{I_0} = \frac{(1+\alpha)V}{I_u + I_b} == \left[\frac{1}{(1+\alpha)^2 Z_u} + \frac{1}{Z_b}\right]^{-1} = \left[\frac{1}{n^2 Z_u} + \frac{1}{Z_b}\right]^{-1} \quad (5)$$

where $n^2=(1+\alpha)^2$ is called the impedance step-up factor. It is revealed from (5) that the input impedance Z_{in} is equal to the parallel combination of the stepped-up unbalanced-mode impedance and the balanced-mode impedance. An equivalent circuit for the input impedance is given in Fig. 3 with a transformer (n^2:1) and a transmission line to represent the impedance step-up n^2Z_u and the relationship between Z_b and Z_T, respectively.

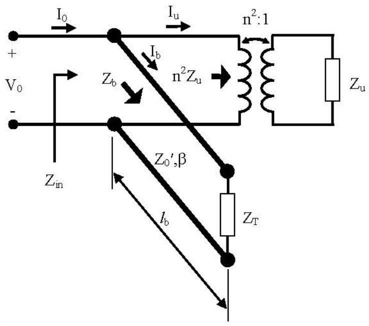


Fig. 3. Equivalent circuit for the input impedance of the two-strip monopole antenna.

To determine the parameters α, n^2, Z_u, and Z_b, we represent the two-strip monopole as a two-part device with Port 1 connected to the S-strip and with Part 2 connected to the T-strip, as illustrated Fig. 4. The two-part device can be described in terms of impedance parameters as

$$V_1 = Z_{11}I_1 + Z_{12}I_2, \quad (6a)$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2, \quad (6b)$$

where Z_{11}, $Z_{12}=Z_{21}$, and Z_{22} are the Z parameters of the two-part network, which is obtained from the S parameters simulated using *MicroStripes 7.0*. Applying the two-part network to the balanced mode (i.e., Fig. 2c), we have

$$-V = -Z_{11}I_b + Z_{12}I_b, \quad (7a)$$

$$\alpha V = -Z_{21}I_b + Z_{22}I_b. \quad (7b)$$

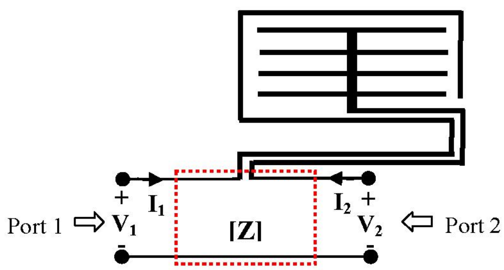


Fig. 4. Two-port network representation of the two-strip monopole antenna.

From (7), we obtain the current sharing factor and the balanced-mode impedance:

$$\alpha = (Z_{22} - Z_{21})/(Z_{11} - Z_{12}), \quad (8)$$

$$Z_b = Z_{11} + Z_{22} - (Z_{12} + Z_{21}). \quad (9)$$

In a similar manner, applying (6) to the unbalanced mode (i.e., Fig. 2b), we get the unbalanced-mode impedance:

$$Z_u = (Z_{11}\alpha + Z_{12})/(1+\alpha) \quad (10)$$

Fig. 5 shows the calculated current sharing factor α and the impedance step-up factor n^2 for the two-strip monopole illustrated in Fig. 1. It is interesting to note that the real part of α is a negative number. This result is completely different from those observed for some typical two-wire structures such as the planar inverted-F antenna [7], where α is usually larger than 1. It is also noted that the magnitude of the impedance step-up factor n^2 is less than 1, which means that the two voltage sources in the unbalanced mode cannot simultaneously serve as a generator.

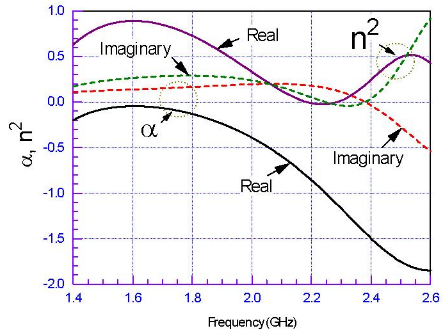


Fig. 5. Current sharing factor α and impedance step-up factor n^2 of a two-strip monopole antenna.

The calculated unbalanced-mode impedance Z_u and the real parts of V/I_u and $V/\alpha I_u$ are plotted in Fig. 6. Note that if $Re(V/I_u)>0$ [or $Re(V/\alpha I_u)$], then the voltage source connected to the T-strip (or the S-strip) serves as a power generator, otherwise it acts as a power absorber. From Fig. 6, we can see that for most of frequencies $Re(V/I_u)>0$ and $Re(V/\alpha I_u)<0$. This implies that if operating in the unbalanced mode, the T-strip will act as a radiator while the S-strip absorbs power from the T-strip. But as a whole structure, the two-strip structure still radiates power even when operating in the unbalanced mode. This can be seen from the unbalanced-mode impedance (Z_u) whose real part is always positive. Note that Z_u has two resonances between 1.8 and 2.4 GHz. The first resonance (appearing around 1.9 GHz) is associated with the T-strip because α is very small at this point. The second resonance appears around 2.25 GHz at which α≈-1. The current will flow from the S-strip to the T-strip and there is a little fraction of current [i.e., $(1+\alpha)I_u$] passing through the voltage source. Therefore, Z_u has a high resonant resistance (~300Ω) at this point, making it difficult to directly match with the 50-Ω characteristic impedance. This difficulty will be overcome by combining the unbalanced-mode impedance with the balanced-mode impedance through the transformer (n^2:1).

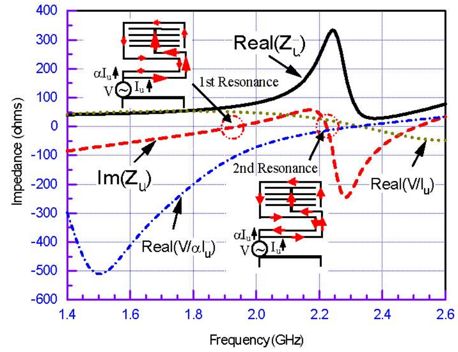


Fig. 6. Calculated unbalanced-mode impedance (Z_u) and the real parts of V/I_u and $V/\alpha I_u$ for a two-strip monopole antenna.

The calculated balanced-mode impedance Z_b is presented in Fig. 7. Two results are compared: one is calculated from transmission-line model [i.e., (4)] while the other is obtained using the Z parameters [i.e., (9)]. Good agreement is observed, which validates the transmission-line model and the two-port representation. The balanced-mode impedance also has two resonances appearing around 1.8 GHz and 2.3 GHz, respectively. The first resonance is due to the resonance for Z_T. The two-strip transmission-line with an electrical length of 90° transforms the shorted-circuit into an open circuit. Therefore the impedance matching around the first resonance is mainly decided by the unbalanced mode. The second resonance in the balanced mode comes from the transformation of Z_T through the two-strip transmission-line with an electrical length of ~115°. The impedance matching around the second resonance is a result of the combination of the unbalanced mode and the balanced mode.

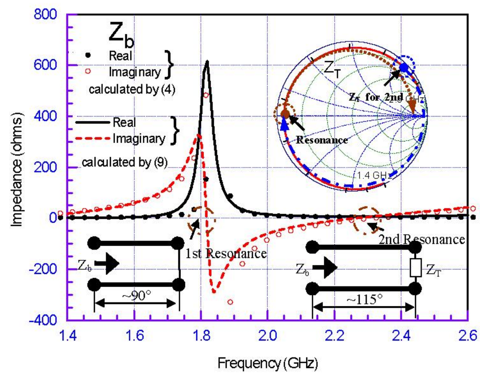


Fig. 7. Impedance of the balanced mode (Z_b) calculated using the Z-parameters (9) and using the transmission-line model (4).

From the mode analysis of the two-strip monopole, we can see two critical parameters which decide the impedance matching: i) the length (i.e., l_b) of the two-strip line and ii) the height (H) of the two-strip monopole. The length l_b should be approximately a quarter of the guided wavelength at the first resonance. The height H controls the dipole impedance Z_T and the coupling between the T-strip and the S-strip, which can be adjusted for an optimal bandwidth performance.

The relationship between the currents in the T-strip (I_0) and in the S-strip (I_0') is shown in Fig. 8. The average phase difference between I_0 and I_0' is about 180° and the magnitude of I_0 is about 1-4 times of I_0'. Fig. 9 compares the input impedance (Z_{in}) calculated using (5) with the simulated result and show good agreement, verifying the effectiveness of the mode decomposition and the two-port network representation.

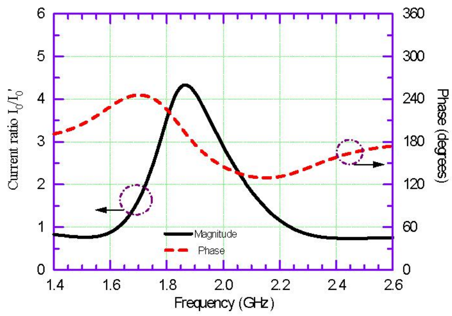


Fig. 8. Relationship between the currents in the T-strip (I_0) and in the S-trip (I_0').

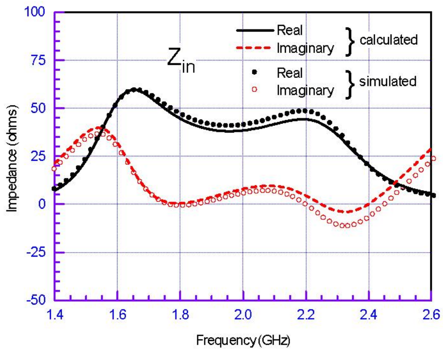


Fig. 9. Comparison of input impedance (Z_{in}) between the calculation using (5) and the simulation.

4. Experimental results

To verify the analysis, a prototype with a height of $0.08\lambda_0$ was fabricated and measured. The calculated and measured results for return loss are compared in Fig. 10. Good agreement is observed, validating the theoretical analysis. The bandwidth for VSWR≤2 is found to be approximately 40%.

5. Conclusion

A broadband low-profile two-strip monopole antenna has been analyzed with the help of mode decomposition. It is revealed that the broadband performance is a result of the combination of an unbalanced mode and a balanced mode. The critical geometrical parameters for a low-profile broadband two-strip monopole include the length of the two-strip line and the height of the two-strip monopole.

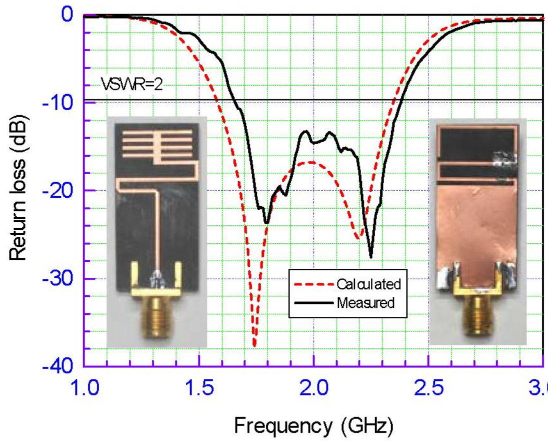


Fig. 10. Calculated and simulated results for return loss of the broadband two-strip monopole antenna with a height of $0.08\lambda_0$.

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References

[1] H.-D. Chen and H.-T. Chen, "A CPW-fed dual-frequency monopole antenna," *IEEE Trans. Antennas Propagat.*, vol. 52, no. 4, pp. 978-982, April 2004.

[2] H. Nakano, Y. Sato, H. Mimak, and J. Yamauchi, "An Inverted FL antenna for dual-frequency operation," *IEEE Trans. Antennas Propagat.*, vol. 53, no. 8, pp. 2417-2421, Aug. 2005.

[3] W.-C. Liu, W.-R. Chen, and C.-M. Wu, "Printed double S-shaped monopole antenna for wideband and multiband operation of wireless communications," *IEE Proc.-Microw. Antennas Propag.* vo1. 151, no. 6, pp. 473-476, Dec 2004.

[4] Y.-L. Kuo and K.-L. Wong, "Printed double-T monopole antenna for 2.4/5.2 GHz dual-band WLAN operations," *IEEE Trans. Antennas Propagat.*, vol. 51, no. 9, pp. 2187-2192, Sept. 2003.

[5] N. T. Pham, G.-A. Lee, and F. D. Flaviis, "Minimized dual-band coupled line meander antenna for system-in-a-package applications," *IEEE AP-S International Symposium*, vol. 2, pp. 1451-1454, 2004.

[6] B. Pan, R. L. Li, J. Papapolymerou, J. Laskar, and M. M. Tentzeris, "Low-Profile broadband and dual-frequency two-strip planar monopole antennas," *IEEE AP-S International Symposium*, Albuquerque, July 2006.

[7] K. Boyle and L. P. Ligthart, "Radiating and balanced mode analysis of PIFA antennas," *IEEE Trans. Antenna Propagat.*, vol. 54, no. 1, pp. 231-237, Jan. 2006.