Investigations on Modeling and Simulation of Printed Folded Dipole Antenna

Prabir Banerjee[1] and Tulshi Bezboruah[2]

[1]Department of Physics, Jagiroad College, Jagiroad 782410, Morigaon, Assam, INDIA
Tel: +91-367-8242308(O)
[2]Department of Electronics & Communication Technology, Gauhati University, Guwahati-781014, Assam, INDIA
Tel: +91361-2671262(O); Fax: +91-361-2700311(O)
prabirjrd1962@ gmail.com1, zbt_gu@yahoo.co.in[2]

Abstract

We have modeled and simulate asymmetric microstrip folded dipole antenna on substrate materials and study the antenna performances. The conventional wire dipole antenna configurations are converted into corresponding microstrip version. The complementary nature of parallel coplanar strip line and waveguide models have been used to model the dipole antenna. The transmission line parameters namely, even-odd mode effective dielectric constant and characteristic impedance have been analyzed. We study the effect of dielectric material on radiation characteristics of the printed folded dipole antenna, such as effective dielectric constant, characteristics impedance, input impedance and bandwidth. The antenna shows bandwidth improvement below 3 GHz frequency with asymmetric form of strip folded dipole.

Keywords: *Bandwidth, Characteristics impedance, Folded Dipole antenna, Input impedance, Microstrip dipole antenna, Waveguide*

1. Introduction

A compact size antenna design with wide bandwidth (BW) characteristics is the major challenge in communication system. Another factor which over shadow its performance is its narrow BW and low efficiency when the size is reduced. First successful design of printed dipole was reported in 1987 by D. Edward *et al.* [1]. With proper design, printed antennas are most suitable for varieties of applications due to their planar structure and compatibility with the printed circuit fabrication techniques [7]. Printed antennas may be classified into two main categories on the basis of width to length ratio, namely: (a) Microstrip antenna and (b) Microstrip dipole antenna [7]. An antenna with narrow strip width less than **0.05 λ_0** (λ_0 =free space wavelength) is called microstrip dipole [7]. Printed dipoles are sometimes used in array application, because they occupy less space compared to conventional microstrip antennas.

The strip folded dipole antenna fabricated on dielectric substrate gives wider BW and provide good matching characteristics due to its large input impedance compared to single element strip dipole.

This antenna serves as a step-up impedance transformer of the single-element impedance, when the spacing(**s**) between the two larger sides is very small (usually *s* < **0.05λ**) [9]. When arm length **L = λ/2**, the antenna is resonant and its impedance is about 300 ohms and can be used for connections to *twin-lead* transmission lines [9].

Our study mainly focused on transition from wire dipole to corresponding printed folded dipole in asymmetric form. We simulate the key antenna parameters with MATLAB simulation software. We investigate the same by considering the parameters namely: (i) input impedance, (ii) BW, (iii) even and odd mode effective dielectric constant and (iv) characteristic impedance of coplanar strips (CPS) in which the folded dipole is a section and (v)) characteristic impedance Waveguide mode.

1.1 Related Works

In the year 1980, G. A. Thiele, E. P. Ekelman, Jr., and L. W. Henderson [2] proposed folded dipole of circular cross section and its equivalent transmission-line and antenna mode models and validated the model by numerical method such as Moment Method.

In the year 1985 and 1986, R. W. Lampe [3, 4] proposed design formulas for asymmetric coplanar strip folded dipole in homogeneous medium.

C. A. Balanis (2005) [9] proposed step by step design procedure of wired folded dipole antenna including expressions for equivalent radius, input impedance, characteristic impedance, current division factor and matching networks.

In the year 2007, Chen-To Tai, Stuart A. Long, proposed design formula similar to [12] except slightly different current division formula for element spacing compared to the radius of the wired folded dipole antenna.

In the year 2007, J. K. Raines [11] developed a mathematical model of the wired folded antenna with arbitrary impedance loaded at both top and base which is applicable to both long $(L > \lambda_0)$ and short$(L < \lambda_0)$ antennas.

In the year 2010, H.J. Visser [5] modified the design formulas of asymmetric strip folded dipole in homogeneous medium proposed by R.W. Lampe [3, 4] which can be applied to antenna on dielectric substrate. They also employed correction factors for the dipole length and equivalent radius in homogeneous medium.

In the year 2013, Guang Hua, Chen Yang, Ping Lu, Hou-Xing Zhou, and Wei Hong [6] proposed an odd-even mode design procedure to calculate input impedance for asymmetric strip folded dipole with smaller width of center conductor.

Different authors [5-6, 9, 11-12] proposed current division factor (α) for wired folded dipole and strip dipole model. We transformed each model into corresponding strip dipole version necessary to compare the performance of the antenna with different values of α.

2. Design Considerations

In case of the free-space cylindrical dipole, the electric field between the gaps in the strip of a printed dipole is along the length of the dipole [7]. This distribution is different from that in a patch antenna in which the dominant electric field component is normal to the substrate [7]. Therefore, it is not possible to feed a printed dipole directly with a microstrip line where the major electric field component is normal to the substrate [7]. According to [7], the possible feed structure for printed dipole is coplanar strips (CPS), which is compatible, physically and electrically, with the coplanar strips printed dipole. The asymmetric strip folded dipole can be designed and can be mounted on a dielectric substrate of thickness **h**. The relative dielectric constant may be in the range of $2.32 \leq \epsilon_r \leq 6.15$. If the antenna is constructed without ground plane, its radiation pattern is likely to be similar to the dipole of the same length L. The structure provides almost four times lager input impedance than that of a single dipole for $L \leq \lambda/2$ [9]. The length of dipole antennas are generally in the range $\lambda/4 \leq L \leq \lambda/2$ for better performance [9]. Length L is slightly less than $\lambda/2$ to account for fringing length extension and to make the input impedance real [9]. The separation between fed-line

connecting the antenna should satisfy $d < 0.002\lambda$ [7]. The separation distance (**s**) between the two strip transmission lines of the folded dipole should not exceed 0.05λ [7].

3. The Model

The configuration of the proposed folded dipole antenna in asymmetric form is shown in Figure 1. The antenna is constructed by using microstrip folded dipoles connected with a feed line on a bottom substrate having a thickness **h**. The folded dipole has better BW characteristics than a single dipole of the same size [9]. Its geometrical arrangement is somewhat like a small side by side stub line which tries to nullify the reactance of a non-resonant lone dipole antenna [9]. According to the traditional analysis method [9], the excitation of a folded dipole is decomposed into two fundamental modes: (i) the transmission line mode and (ii) antenna radiation mode. The folded dipole for T-match can also be modeled by transmission line and antenna modes [9]. The total current at the input terminals is divided between the two conductors in a way that depends on the relative width of the two conductors and the spacing between them [9]. Since the two conductors are not in general of the same width, the antenna mode current division is not unity. So a current division factor is assigned which also applies to the voltage division of the transmission-line mode [9]. The design is performed in two steps. The first step is to calculate the input impedance of asymmetric strip line in transmission mode. The second step is to calculate the input impedance of folded dipole in antenna mode and then using the traditional method the equivalent input impedance is obtained [9].
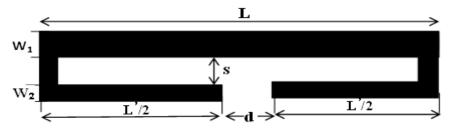

Figure 1. Top View of Asymmetric Strip Folded Dipole

3.1. Input Impedance

The feed port input impedance of folded dipole is given by [9]:

$$Z_{in} = \frac{2Z_t[(1+\alpha)^2 Z_A]}{2Z_t + (1+\alpha)^2 Z_A}$$

(1)

Where Z_A is the input impedance of strip dipole antenna with length L and width W_1 in antenna mode, $Z_t = jZ_c \tan(kL'/2)$ is input impedance in transmission line mode, Z_c is characteristic impedance of couple line defined in **eqn.(4)** or **eqn.(6)**, k is wave number and α is current division factor.

The current division factor for non-uniform dipole radius transformed into equivalent radius for very thin strip dipole can be expressed as [9]:

$$\alpha = \cosh^{-1}\left(\frac{v^2 - u^2 + 1}{2v}\right) \Big/ \cosh^{-1}\left(\frac{v^2 + u^2 - 1}{2vu}\right)$$

(1a)

With $u = W_1/W_2$, $v = 4S/W_2$

Current division factor reported in [6] is given by:

$$\alpha_1 = (\ln[4D + \sqrt{D_1}] - \ln W_1)/(\ln[4D + \sqrt{D_2}] - \ln W_2)$$
(1b)

With $D = s/2 + 0.25W_1 + 0.25W_2$, $D_1^2 = 4D^2 - 0.25W_1^2$, $D_2^2 = 4D^2 - 0.25W_2^2$

When W_1 and W_2 are small compared with the spacing (**s**), the current division factor proposed in [12] may be modified from circular cross section to strip folded dipole with the concept of equivalent radius given in [9] can be expressed as:

$$\alpha_2 = \ln(4s/W_2/\ln(4s/W_1))$$
(1c)

Another value of current division factor reported in [5] is given by:

$$\alpha_3 = (\ln(4C + 2\sqrt{A} - ln(W_2))/(\ln(4C + 2\sqrt{A_1} - ln(W_1))$$
(1d)

With $A = (2C)^2 - (W_2/2)^2$, $A_1 = (2C)^2 - (W_1/2)^2$ and $2C = s + W_1/2 + W_2/2$

Further current division factor proposed in [11] modified for strip folded dipole as:

$$\alpha_4 = ln(0.25W_2/(s + 0.25W_1)/ln(0.25W_1/(s + 0.25W_2)$$
(1e)

The input impedance Z_{in} of the asymmetric strip folded dipole of **eqn.(1)** can be expressed as [9]:

$$Z_{in} = R_{in} + jX_{in}$$
(2)

Where R_{in} and X_{in} are the real and imaginary part of input impedance of strip dipole antenna.

The reflection coefficient **Γ** and Voltage Standing Wave Ratio (**VSWR**) can be expressed as [9]:

$$\Gamma = (R_{in} - Z_c)/(R_{in} + Z_c)$$
(3)
$$VSWR = (1 + \Gamma)/(1 - \Gamma)$$
(3a)

3.2. Characteristic Impedance

At very high frequency operation, substrate height plays a crucial role in accurate formulation of effective dielectric constant. When substrate height is not very small compared with the in the dielectric, the quasi-static expressions may be inadequate [7]. In case of a digital signal with short rise time propagates along a microstrip line, the signal can be assumed to contain a number of high-frequency harmonics [10]. In such a situation, an accurate dispersion model for propagation along microstrip lines is required [10].The characteristic impedance can be determined by odd-even method to account for dispersion. An asymmetric folded dipole in antenna mode can be viewed as symmetric two-port microwave network. We have proposed: (a) Coplanar Waveguide models and (b) Coplanar Strip model for accurate determination of characteristics impedance and effective dielectric constant.

3.2.1. Coplanar Waveguide Model:
The Coplanar waveguide model (CPW), printed on a finite-thickness dielectric substrate is shown in Figure 2. The width of the dielectric substrate is assumed to be finite. The quasi-static expression for characteristic impedance and effective dielectric constant of this transmission line are given by [7]:
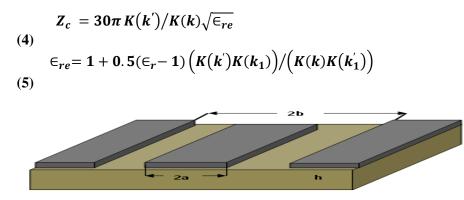
$$Z_c = 30\pi\, K(k')/K(k)\sqrt{\epsilon_{re}}$$

(4)

$$\epsilon_{re} = 1 + 0.5(\epsilon_r - 1)\left(K(k')K(k_1)\right)/\left(K(k)K(k_1')\right)$$

(5)

Figure 2. CPW Model of Transmission Lines with 2b= W_1+W_2+S separated by Distance S=2a Representing Equivalent Printed Folded Dipole

In the above expressions (**eqn.(4)** and **eqn.(5)**) **K** is complete elliptical integral of first kind. An approximate expression for $K(k)/K(k')$ which is accurate to 8 ppm can be written as [7]:

$$\frac{K(k)}{K(k')} = \frac{K(k)}{K'(k)}\begin{cases} ln\left(2\frac{1+\sqrt{k}}{1-\sqrt{k}}\right)/\pi & \text{for } 0.5 \le k^2 \le 1 \\ \pi/ln\left(2\frac{1+\sqrt{k'}}{1-\sqrt{k'}}\right) & \text{for } 0 \le k'^2 \le 0.5 \end{cases}$$

(5a)

Where $k = a/b,\, k' = \sqrt{1-k^2},\; k_1 = sinh(\pi a/2h)/sinh(\pi b/2h),\; k_1' = \sqrt{1-k_1^2}$

3.2.2. Coplanar Strips Model: Coplanar strips (CPS) are basically a coupled microstrip lines either symmetric or asymmetric, (two transmission lines) of width W_1 and W_2 on a dielectric substrate of finite thickness **h** separated by very small gap **s** as shown in Figure 3.
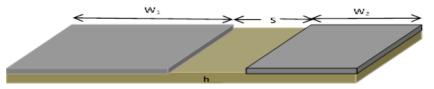

Figure 3. CPS Transmission Line Model of Width W_1 and W_2 Separated by Distance S Representing Equivalent Printed Folded Dipole Antenna

Characteristic impedance and effective dielectric constant of asymmetric CPS with finite substrate thickness is given by [7]:

$$Z_c = 60\pi K'(k_2')/(K(k_2')\sqrt{\epsilon_{re}}$$

(6)

$$\epsilon_{re} = 1 + q(\epsilon_r - 1)$$

(7)

With fill factor $= 0.5\left(K(k_4)K'(k_2')\right)/\left(K'(k_2')K(k_2')\right)$, and also

$$k_2' = \sqrt{(W_1 W_2)/(W_1+S)(W_2+S)}\;,\; k_4 = \sqrt{\frac{sinh(\pi W_1/2h)}{sinh(\pi(W_1+S)/2h)}\frac{sinh(\pi W_2/2h)}{sinh(\pi(W_2+S)/2h)}}$$

3.3. Effective Dielectric Constant of Even and Odd Mode

The zero frequency approximation of effective permittivity (ϵ_{re}) to account for the fringing can be expressed as [8]:

$$\epsilon_{re}(0) = 0.5(\epsilon_r + 1) + 0.5(\epsilon_r - 1)[1 + 10/u]^{-AB} \tag{8}$$

With **u=W/h, A**=$1 + ln\left[(u^4 + \left(\frac{u}{52}\right)^2)/(u^4 + 0.432)\right]/49 + \left[\ln\left\{1 + \left(\frac{u}{18.1}\right)^3\right\}\right]/18.7$ and
B=$0.564[(\epsilon_r - 0.9)/(\epsilon_r + 0.3)]^{0.053}$

The even-mode effective permittivity for coupled microstrip lines for **u= W/h, g= S/h** and ϵ_r in the range $0.1 \leq W/h \leq 10, 0.1 \leq S/h \leq 10$ and $1 \leq \epsilon_r \leq 18$ for zero conductor thickness is given by [7]:

$$\epsilon_{re}^{even}(0) = 0.5(\epsilon_r + 1) + 0.5(\epsilon_r - 1)[1 + 10/u]^{-A_e(v)B_e(\epsilon_r)} \tag{9}$$

Where **v**=$u(20-g^2)/(10 + g^2) + g.exp(-g)$,
$$A_e(v) = 1 + \ln\left[(v^4 + (v/52)^2)/(v^4 + 0.432)\right]/49 + ln\left[1 + (v/18.1)^3\right]/18.7$$
And $B_e(\epsilon_r) = 0.564[(\epsilon_r - 0.9)/(\epsilon_r + 3)]^{0.058}$

The odd-mode effective dielectric constant for coupled microstrip lines for zero conductor thickness is given by [7]:

$$\epsilon_{re}^{odd}(0) = [0.5(\epsilon_r + 1) + A_o(u, \epsilon_r) - \epsilon_{re}(0)] \cdot exp(-C_0 g D_0) + \epsilon_{re}(0) \tag{10}$$

$$A_o(u, \epsilon_r) = 0.7287[\epsilon_{re}(0) - 0.5(\epsilon_r + 1)] \cdot [1 - exp(-0.179u)]$$

$$B_o(\epsilon_r) = 0.747 \epsilon_r/(\epsilon_r + 0.15), \quad C_0 = B_o(\epsilon_r) - [B_o(\epsilon_r) - 0.207] \cdot exp(-0.414u)$$
$$D_0 = 0.593 + 0.694 \cdot exp(-0.562u)$$

3.4. Characteristic Impedance of Even and Odd Mode

The even-mode characteristic impedance of coupled microstrip lines is given by [7]:

$$Z_{ce}(0) = Z_0\sqrt{\epsilon_{re}(0)/\epsilon_{re}^{even}(0)}/\left(1 - [Z_0(0)/377][\epsilon_{re}(0)]^{0.5}Q_4\right) \tag{11}$$

With $Z_0(0) = 60/\sqrt{\epsilon_{re}} \, ln\left[f(u)/u + \sqrt{1 + (2/u)^2}\right]$, **u=W/h**
$f(u) = 6 + (2\pi - 6)exp\left[-(92/3u)^{0.7528}\right]$, Q_1=0.8695$\cdot u^{0.194}$, Q_2=1+0.7519 g+0.189$\cdot g^{2.31}$
$$Q_3 = 0.1975 + \left[16.6 + (8.4/g)^6\right]^{-0.387} + ln\left(g^{10}/\left[1 + (g/3.4)^{10}\right]\right)/243$$
$$Q_4 = (2Q_1/Q_2) \cdot \left\{exp(-g) \cdot u^{Q_3} + [2 - exp(-g)] \cdot u^{-Q_3}\right\}^{-1}$$

Similarly, the odd-mode characteristic impedance of coupled microstrip lines is [7]:

$$Z_{co}(0) = Z_0\sqrt{\epsilon_{re}(0)/\epsilon_{re}^{odd}(0)}/\left(1 - [Z_0(0)/377][\epsilon_{re}(0)]^{0.5}Q_{10}\right) \tag{12}$$

Q_5=1.794+1/14$\cdot ln\left[1 + 0.638/(g + 0.517g^{2.43})\right]$
$$Q_6 = 0.2305 + ln\left[(g^{10}/(1 + (g/5.8)^{10})\right]/281.3 + ln(1 + 0.598g^{1.154})/5.1$$
$Q_7 = \left(10 + 190g^2\right)/(1 + 2.3g^3)$ Q_8=$exp\left(-6.5 - 0.95ln(g) - (g/0.15)^5\right)$

$$Q_9 = ln(Q_7) \cdot (Q_8 + 1/16.5), \quad Q_{10} = \left[Q_2 Q_4 - Q_5 \cdot exp\left[ln(u) \cdot Q_6 \cdot u^{-Q_9} \right] \right] / Q_2$$

4. Simulation

Considering the input impedance of the model in **eqn. (1),** it is possible to simulate and analyze the behavior of the model using **eqn.(1a).-(1e),eqn.(2)-(3a)** with **eqn.(4) or eqn.(6)**. One of the important factors in the design of folded dipole antenna is its current division factor or impedance step up ratio **α** as given in **eqn. (1a), eqn.(1b),eqn.(1c), eqn.(1d)**and **eqn.(1e)**, as their values determine the step up of impedance, depending upon the width and spacing between the two arms of the folded dipole antenna. Further, due to the coupling of the electromagnetic field between the coupled lines, the lines can support two propagation modes namely: (a) even and (b) odd modes [7]. Even-mode propagation implies two signals of the same amplitude and zero phase difference passing through the coupled line, while odd-mode operation denotes the propagation of two signals of the same amplitude but 180^0 phase difference [7]. Due to the inhomogeneous dielectric medium, namely: (i) air and (ii) substrate material, the two modes have different effective dielectric constants and phase velocities that degrade the performance of the coupled lines [7]. When operating at different modes, the effective capacitance between the two transmission lines and the ground plane is different and contribute to two impedances namely: (a) even-mode Z_{co} **(eqn.(11))** and (b) odd-mode impedances Z_{ce} **(eqn.(12)).**The characteristic impedance of the coupled line dependents on Z_{ce} and Z_{co}. In order to evaluate the performance and accuracy of the model, we simulate it in MATLAB Platform. The Flow diagram of the simulation program is given in Figure 4.
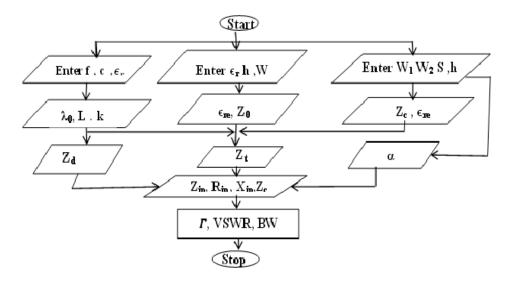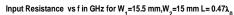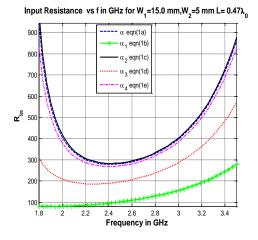

Figure 4. Flow Diagram of the Simulation Program

In the above simulations **eqn.(1)-eqn.(12)** are used to study various characteristics of the proposed asymmetric strip folded dipole antenna.

5. Result and Discussions

Real and imaginary part of input impedance as given in **eqn.(1)** of asymmetric and nearly symmetric strip folded dipole is simulated as a function of frequency with different values of

α obtained from **eqn.(1a)-eqn.(1e)** and the responses are shown in Figure 5–Figure 8 respectively. It is observed that the input impedance increases with frequency and the variation is uniform for nearly symmetric folded dipole antenna. At resonance frequency the input impedance is nearly four times that of single dipole. The current division factor α obtained from **eqn.(1a)-(1e)** for asymmetric and nearly symmetric folded dipole is simulated as a function of dipole spacing and the responses are shown in Figure 9 and Figure 10 respectively. It is observed that for nearly symmetric folded antenna step-up impedance ratio is nearly equal when spacing is very small. The VSWR of **eqn.(3a)** using **eqn.(1)-eqn.(3)** and **eqn.(6)** with different values of α, from **eqn.(1a) –eqn.(1e)** is simulated as a function of frequency and the responses are shown in Figure 11 and Figure 12 for asymmetric and nearly symmetric strip folded dipole antenna respectively. From the plot it is apparent that asymmetric folded dipole yield large Band Width (BW) with VSWR=2 compared to nearly symmetric folded dipole. We have simulated VSWR of **eqn.(3a)** using **eqn.(1),eqn.(1a), eqn.(3)** and **eqn.(4)** asymmetric folded dipole for waveguide mode while for CPS model we have used all the four equations but substituted value of characteristic impedance from **eqn.(6)** and the responses are shown in Figure 13 and Figure 14 respectively. The geometries such as , W_1, and W_2 are adjusted to tune the input impedance and to widen the BW. The VSWR of **eqn.(3a)** using **eqn.(1)- eqn.(3)** and **eqn.(6)** is simulated as function of line spacing s for asymmetric and nearly symmetric folded dipole with different values of α and responses are shown in Figure 15 and Figure 16 respectively. It is observed that for asymmetric folded dipole, current division factor α described in **eqn. (1b)** yields $VSWR > 2$ when the spacing (s) between the two arms of the folded dipole is increased, but other values of α of **eqn.(1a),(1c), (1d)** and **(1e)** shows decrease in $VSWR$, while for nearly symmetric folded dipole the variations of **VSWR** with spacing is almost linear**.** The values of design parameters are listed in Table 1-Table 5. The even-odd-mode effective dielectric constant and characteristic impedance as function of substrate height are simulated and the responses are depicted in Figure 17 and Figure 18 respectively. The even-mode effective dielectric constant and characteristic impedances are appeared to be more accurate within the substrate thickness range. The results show that the variation of characteristic impedance with substrate height is much sharper than the variation of an effective dielectric constant with substrate height. Further, it is seen that the even-mode parameters show a greater variation with substrate height than the odd mode parameters. The **α** values of **eqn.(1e)** shown in Table-1 collapse giving real and imaginary part for nearly symmetric case when the element spacing between the folded dipole strips are very small. Further, when spacing **s** between the lines is very small the characteristic impedance and dielectric constant yields real and imaginary part as can be seen in Table 3. According to [12] the spacing act like a slot and it fails to resonate when the slot width is very small compared to widths of the coupled line.
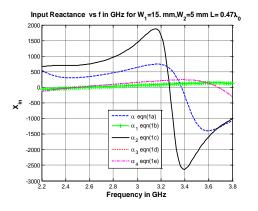
Input Resistance vs f in GHz for W_1=15.0 mm,W_2=5 mm L= 0.47λ_0

Figure 5. R_{in} as a Function of Frequency for an Asymmetric Folded Dipole

Input Resistance vs f in GHz for W_1=15.5 mm,W_2=15 mm L= 0.47λ_0

Figure 6. R_{in} as a Function of Frequency for a Nearly Symmetric Folded Dipole

Input Reactance vs f in GHz for W_1=15. mm,W_2=5 mm L= 0.47λ_0

Figure 7. X_{in} as a Function of Frequency for an Asymmetric Folded Dipole

Input Reactance vs f in GHz for W_1=15.5 mm,W_2=15 mm L= 0.47λ_0

Figure 8. X_{in} as a Function of Frequency for Nearly Symmetric Folded Dipole

Current Division Factot α vs Spacing W_1=5mm,$W2$=15 mm

Figure 9. Current Division Factor a Function of Spacing for an Asymmetric Folded Dipole

Current Division Factot α vs Spacing W_1=15mm,$W2$=10 mm
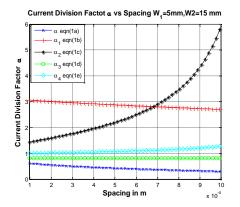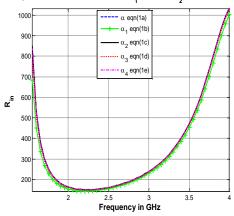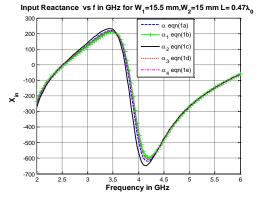
Figure 10. Current Division Factor as a Function of Spacing for a Nearly Symmetric Folded Dipole

Figure 11. VSWR as a Function of Frequency for an Asymmetric Folded Dipole
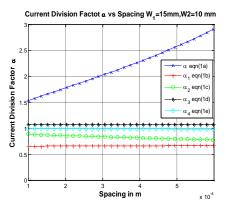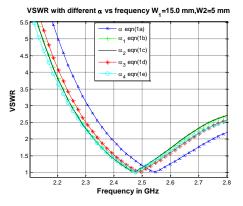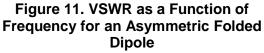

Figure 12. VSWR as a Function of Frequency for a Nearly Symmetric Folded Dipole
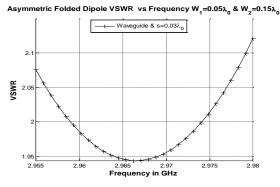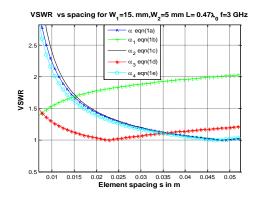

Figure 13. VSWR vs Frequency for a Modified Asymmetric Folded Dipole in Waveguide Model

Figure 14. VSWR as a Function of f (GHz) for an Asymmetric Folded Dipole in CPS Mode

Figure 15. VSWR as a Function of Spacing (s) with Different Values of α for an Asymmetric Folded Dipole at f=3 GHz

Figure 16. VSWR as a Function of s (s$> 0.05\lambda_0$) with Different Values of α for Nearly Symmetric Folded Dipole at f=GHz

Table 1. Evaluation of Current Division Factor for ϵ_r=2.32, h=3mm, ϵ_{re} =2.2 &d=0.2mm

s mm	W_1 mm	W_2 mm	α eqn.(1a)	α_1 eqn.(1b)	α_2 eqn.(1c)	α_3 eqn.(1d)	α_4 eqn.(1e)
6.25	15	5	2.5323	0.5016	3.1507	1.2170	2.4094
7.5	10	5	1.5655	0.6772	1.6309	1.1268	1.5129
8.75	15	10	1.3853	0.7733	1.4785	1.0800	1.3569
11.25	20.5	20	1.0233	0.9833	1.0314	1.0052	1.0226
20	15	5	1.6388	0.6165	1.6563	1.2160	1.5937
21	10.5	10	1.0229	0.9780	1.0235	1.0090	1.0215
2	15.5	15	1.0970	0.9707	0.9504	1.0065	0.9921+ 0.03i
0.25	5.1	5	1.1453	0.9807	0.9878	1.0032	0.9993 + .02i

Table 2. Evaluation of Even-odd ModeZ_{oe}, Z_{oo}, $\epsilon_{re}\epsilon_{re}^e$,$\epsilon_{re}^o$, Coupled Line

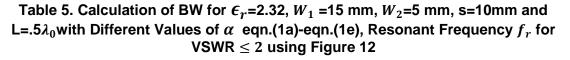| ϵ_r	h mm	s mm	W mm	Z_{oe} ohms	Z_{oo} ohms	ϵ_{re}	$\in_{re}^e$	$\in_{re}^o$
2.32	3.1	2	5	73.38	54.75	1.884	1.887	1.571
2.32	3.1	2	10	47.86	40.61	1.964	1.967	1.484
3.7	2.5	1	5	52.28	37.47	2.853	2.880	2.276
3.7	2.5	0.5	10	32.73	23.54	3.027	3.082	2.418
6.15	1.9	0.5	5	35.12	24.63	4.64	4.73	3.59
6.15	1.9	0.25	10	21.22	15.53	4.99	5.12	3.85

Table 3. Evaluation of Z_{oe}, Z_{oo}, ϵ_{re}, $\in_{re}^{cps}$ Asymmetric Coplanar Strip Model

ϵ_r	h mm	s mm	W_1 (mm)	W_2 (mm)	ϵ_{re}	ϵ_{reI}	Z_{ce}	Z_{co}
2.32	3.1	1	5	10	1.924	1.257	130.29	132.30
2.32	3.1	1	10	5	1.924	1.39 +0.5i	118.3 -2.1i	121.8+1.9i
2.32	3.1	20	10	5	1.924	1.260	290.74	307.25
3.7	2.5	20	5	10	2.943	1.517	265.09	301.62
3.7	2.5	20	10	5	2.943	1.522	264.69	296.15
6.15	1.9	20	5	10	4.823	1.984	231.79	289.87
6.15	1.9	20	10	5	4.823	1.986	231.68	283.43

Table 4. Evaluation of Z_{oe}, Z_{oo}, ϵ_{re}, ϵ_{re}^{WG} Coplanar Waveguide Model

ϵ_r	h mm	s mm	W_1 (mm)	W_2 (mm)	ϵ_{re}	ϵ_{reI}	Z_{ce}	Z_{co}
2.32	3.1	1	5	10	1.924	1.070	34.42	34.99
2.32	3.1	20	5	10	1.924	1.178	73.69	73.92
3.7	2.5	1	5	10	2.943	1.133	33.45	34.16
3.7	2.5	20	5	10	2.943	1.321	69.60	70.33
6.15	1.9	1	5	10	4.823	1.236	32.02	33.09
6.15	1.9	20	5	10	4.823	1.547	64.30	66.26

Table 5. Calculation of BW for ϵ_r=2.32, W_1 =15 mm, W_2=5 mm, s=10mm and L=.5λ_0 with Different Values of α eqn.(1a)-eqn.(1e), Resonant Frequency f_r for VSWR $\leq$ 2 using Figure 12

Eqn. No.	α value	f_r GHz	Z_c ohms eqn.(6)	Z_t ohms	R_{in} eqn.(2)	Xin eqn.(2)	BW MHz Fig.11	BW%
Eqn.(1a)	2.0000	2.55	219	-534j	219	-194.9j	360	14.1
Eqn.(1b)	0.5486	2.475	219	-534j	75.5	-46.8j	225	9.1
Eqn.(1c)	2.1201	2.475	219	-534j	229.9	-211.5j	300	12.1
Eqn.(1d)	1.2168	2.5	2.19	-534j	140.7	-101.7j	2.75	11
Eqn.(1e)	1.8995	2.475	2.19	-534j	209.5	-101.7j	300	12.1

Figure 17. Even Odd Mode ϵ_{re} as a Function of Height (h) for a Folded Dipole

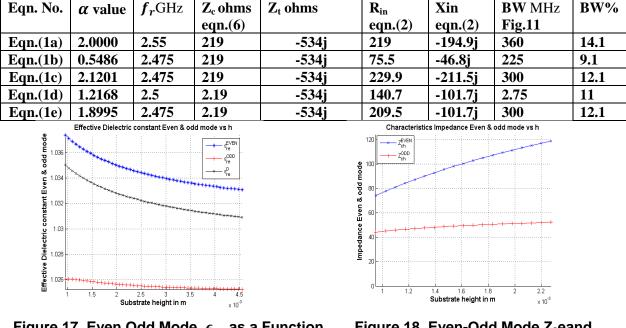**Figure 18. Even-Odd Mode Z_0eand Z_{oO} as a Function of h for a Folded Dipole**

6. Conclusion

A microstrip folded dipole antenna is modeled and simulated with center frequency of 3GHz and fractional BW is determined for **VSWR $\leq$ 2**. It is observed that the folded dipole design gives wide impedance BW with variation of spacing and width ratio of folded arms. The odd-even mode design is applied to calculate input impedance and effective dielectric constant for asymmetric strip folded dipole. The values of current division factor (α) proposed in five models are compared. It differs significantly from the original folded dipole antenna model **(eqn.1a)** of circular cross section transformed to corresponding strip dipole model. The simulation is performed with α of different models. The results closely agree for nearly symmetric folded dipole antenna and BW values are almost equal. In case of asymmetric folded dipole, the maximum value of BW is obtained; when α of **eqn. (1a)** is used, while **eqn. (1b)** yields minimum value of BW. However if the width of center conductor W_1 is made smaller than the width of folded arm W_2, **eqn. (1b)** yields large BW while all other values of α **(eqn. (1a), (1c)-(1e))** gives smaller BW when $W_1 < W_2$.

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Authors

Tulshi Bezboruah, he received the B.Sc. degree in physics with electronics under the University of Dibrugarh, Dibrugarh, India, in 1990, and the M.Sc. and Ph.D. degrees in electronics and radio physics from Gauhati University, Guwahati, India, in 1993 and 1999, respectively. In February 2000, he joined in the Department of Electronics Science, Gauhati University, as a Lecturer. He is currently the Professor & Head, Department of Electronics and Communication Technology, Gauhati University. His current research interest include web based instrumentation and control, web service, and communication systems. Professor Bezboruah is member of the IEEE, IEEE Geoscience and Remote Sensing Society as well as an Associate Member of the International Center for Theoretical Physics, Trieste, Italy.

Prabir Banerjee, he received the BSc degree with honors in Physics under Gauhati University, Guwahati, India in 1984, and M. Sc (Electronics) degree from Delhi University in 1988. In November 1989 he joined Department of Physics, Jagiroad College, Jagiroad, Morigaon. Assam, India as a Lecturer, he is currently holding the post of Associate Professor in Physics in the same college. His research interest includes Microstrip Antennas and communication technology