ECEN 5224 High Speed Digital Design
Homework 10: Current Distribution

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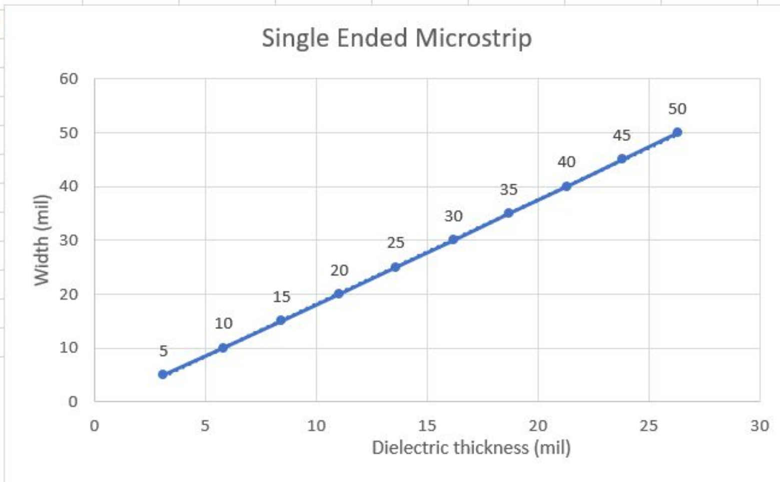
Q1) Show W/H plot for single-ended (50 ohms) and differential impedance (100 ohms) – both stripline and microstrip. Keep: ½ oz copper (0.7 mil) Stripline: h1=h2

Note: For a differential pair, tight coupling condition is considered.

For Single Ended Microstrip:

Microstrip

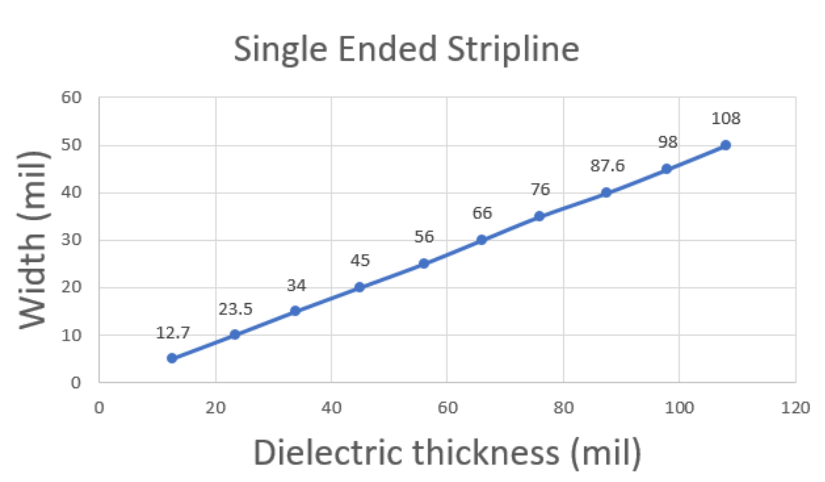
Dielectric thickness (mil)	Width (mil)
3.13	5
5.82	10
8.45	15
11.05	20
13.6	25
16.2	30
18.7	35
21.3	40
23.8	45
26.3	50
Slope	**1.944712**



For a Dk of **4.3**, as expected the width by dielectric thickness ratio (Aspect Ratio) is 1.94 (nearly **2)** for a Single ended characteristic impedance of **50 ohm.**

For Single Ended Stripline:

Dielectric thickness (mil)	Width (mil)
12.7	5
23.5	10
34	15
45	20
56	25
66	30
76	35
87.6	40
98	45
108	50
Slope	**0.471311**

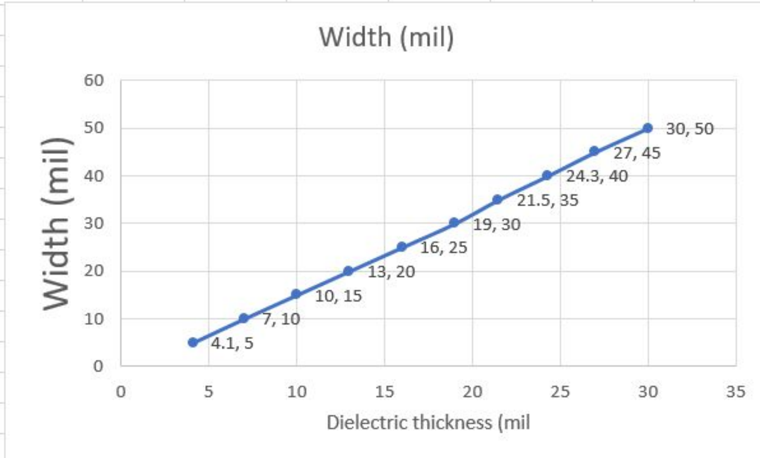


For a Dk of **4.3**, as expected the width by dielectric thickness ratio (Aspect Ratio) is 0.47 (nearly **0.5)** for a Single ended characteristic impedance of **50 ohm.**

For Differential Ended Microstrip:

Differential Microstrip

Dielectric thickness (mil)	Width (mil)
4.1	5
7	10
10	15
13	20
16	25
19	30
21.5	35
24.3	40
27	45
30	50
Slope	**1.742955**

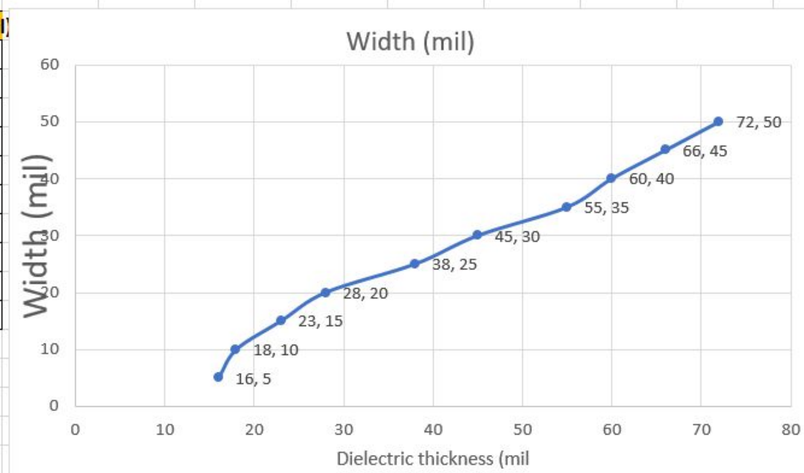


For a Dk of **4.3**, as expected the width by dielectric thickness ratio (Aspect Ratio) is 1.74 (nearly **2)** for a Differential pair Microstrip with a Differential impedance of **100 ohm.**

For Differential Ended Stripline:

Stripline

Dielectric thickness (mil)	Width (mil)
16	5
18	10
23	15
28	20
38	25
45	30
55	35
60	40
66	45
72	50
Slope	**0.731678**



For a Dk of **4.3**, the width by dielectric thickness ratio (Aspect Ratio) is 0.73 for a Differential pair Stripline with a Differential impedance of **100 ohm.**

Q2) Calculate analytically using IPC formulae for single ended impedance of 50 ohms and differential impedance of 80 ohms. Also, Calculate Inductance, capacitance, even and odd mode impedance.

For Single Ended Microstrip:

Here, the width value is assumed and the corresponding Dielectric thickness is calculated using the standard IPC formulae for a given Dk, t and Z0.

$$Z_0\,(\text{ohms}) = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

Solving for h, we get

$$Z_o = \frac{87}{\sqrt{\mathcal{E}_r + 1.41}} \ln\left[\frac{5.98h}{0.8w + t}\right]$$

$$e^{\frac{Z_o\sqrt{\mathcal{E}_r + 1.41}}{87}} = \frac{5.98h}{0.8w + t}$$

$$\boxed{\frac{(0.8w + t)\, e^{\frac{Z_o\sqrt{\mathcal{E}_r + 1.41}}{87}}}{5.98} = h}$$

Substituting all the known values, we get h to **be 3.1 mil for a width of 5mil.** The below excel table shows the values of h for 10 different of w. The Inductance and Capacitance formulae and values are also shown below.

IPC calculated Analytical Impedance		
Microstrip		
	Z0 (ohm)	50
	Dk	4.3
	t (mil)	0.7
	Length (in)	1
	Width (mil)	**Dielectric thickness (mil)**
	5	3.102816528
	10	5.743511445
	15	8.384206363
	20	11.02490128
	25	13.6655962
	30	16.30629111
	35	18.94698603
	40	21.58768095
	45	24.22837587
	50	26.86907078
	tpd (ps)	139.5804456
	C0(pF)	2.791608911
	L0(nF)	581.5851898

$$Z_0\,(\text{ohms}) = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

$$t_{pd}\,(\text{ps/inch}) = 84.75\sqrt{0.475\,\varepsilon_r + 0.67}$$

$$C_0\,(\text{pF/inch}) = \frac{t_{pd}\,(\text{ps/in})}{Z_0\,(\text{ohms})}$$

$$L_0\,(\text{nH/in}) = \frac{Z_0^2 C_0}{12}$$

As expected, the Aspect Ratio in a Microstrip is nearly **2.**

For Single Ended Stripline:

Here, the width value is assumed and the corresponding Dielectric thickness is calculated using the standard IPC formulae for a given Dk, t and Z0.

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \times \ln\left(\frac{4 \times h}{0.67\pi\,(0.8w + t)}\right)$$

Solving for h, we get

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{4h}{0.67\pi(0.8w+t)}\right)$$

$$\Rightarrow e^{\frac{Z_0\sqrt{\varepsilon_r}}{60}} = \frac{4h}{0.67\pi(0.8w+t)}$$

$$\frac{1}{4}\left[e^{\frac{Z_0\sqrt{\varepsilon_r}}{60}} \times 0.67\pi(0.8w+t)\right] = h$$

Substituting all the known values, we get h to **be 13.91 mil for a width of 5mil.** The below excel table shows the values of h for 10 different of w. The Inductance and Capacitance formulae and values are also shown below.

Stripline

Z0 (ohm)	50
Dk	4.3
t (mil)	0.7
Length (in)	1

Width (mil)	**Dielectric thickness (mil)**
5	13.91365859
10	25.75507016
15	37.59648173
20	49.43789329
25	61.27930486
30	73.12071643
35	84.96212799
40	96.80353956
45	108.6449511
50	120.4863627

tpd (ps)	175.7413405
C0(pF)	3.514826809
L0(nF)	8.787067023

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \times \ln\left(\frac{4 \times h}{0.67\pi\,(0.8w + t)}\right)$$

$$t_{pd}\ (\text{ps/in}) = 1000\left(\frac{1.017\sqrt{\varepsilon_r}}{12\ (\text{in})}\right)$$

$$C_0\ (\text{pF/in}) = \frac{T_{pd}\ (\text{ps/in})}{Z_0\ (\text{ohms})}$$

$$L_0\ (\text{nH/in}) = \frac{[Z_0\ (\text{ohms})]^2\ C_0\ (\text{pF/in})}{1000}$$

As expected, the Aspect Ratio in a Stripline is nearly **0.5.**

For Differential Ended Microstrip:

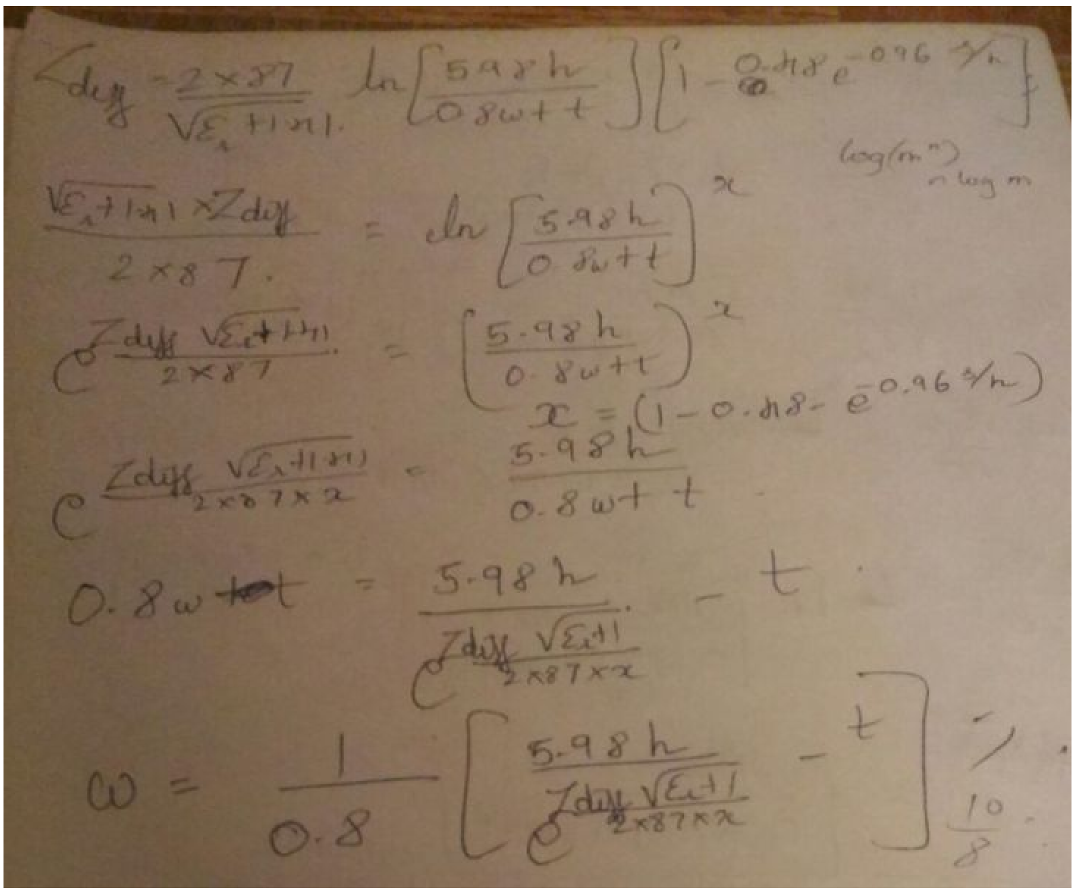
Here, the spacing and dielectric thickness values are assumed and the corresponding width is calculated using the standard IPC formulae for a given Dk, t and Z0.

$$Z_{diff,microstrip}\ (\text{ohms}) = 2Z_0\left(1 - 0.48e^{\left(-0.96\frac{s}{h'}\right)}\right)$$

IPC-2251: PG 36 Equation 0.64

$$Z_0\ (\text{ohms}) = \frac{87}{\sqrt{\varepsilon_r + 1.41}}\ln\left(\frac{5.98h}{0.8w + t}\right)$$

Assuming that we know s and h values,



$$Z_{diff} = \frac{2\times 87}{\sqrt{\varepsilon_r + 1.41}} \ln\left[\frac{5.98h}{0.8w+t}\right]\left[1 - 0.48e^{-0.96\, s/h}\right]$$

$\log(m^n) = n\log m$

$$\frac{\sqrt{\varepsilon_r+1.41}\times Z_{diff}}{2\times 87} = \ln\left[\frac{5.98h}{0.8w+t}\right]^x$$

$$e^{\frac{Z_{diff}\sqrt{\varepsilon_r+1.41}}{2\times 87}} = \left(\frac{5.98h}{0.8w+t}\right)^x$$

$$x = \left(1 - 0.48\, e^{-0.96\, s/h}\right)$$

$$e^{\frac{Z_{diff}\sqrt{\varepsilon_r+1.41}}{2\times 87\times x}} = \frac{5.98h}{0.8w+t}$$

$$0.8w \cancel{+t} = \frac{5.98h}{e^{\frac{Z_{diff}\sqrt{\varepsilon_r+1}}{2\times 87\times x}}} - t$$

$$w = \frac{1}{0.8}\left[\frac{5.98h}{e^{\frac{Z_{diff}\sqrt{\varepsilon_r+1}}{2\times 87\times x}}} - t\right] \quad \frac{1}{\cancel{0.8}}\ \frac{10}{8}$$

Differential Microstrip	
Zdiff (ohm)	80
Dk	4.3
t (mil)	0.7
Length (in)	1
Zodd (ohm)	40
Zeven(ohm)	45.68932502

$$Z_0\ (\text{ohms}) = \frac{87}{\sqrt{\varepsilon_r + 1.41}} \ln\left(\frac{5.98h}{0.8w + t}\right)$$

$$Z_{\text{diff,microstrip}}\ (\text{ohms}) = 2Z_0\left(1 - 0.48e^{\left(-0.96\frac{s}{h'}\right)}\right)$$

$$t_{pd}\ (\text{ps/inch}) = 84.75\sqrt{0.475\,\varepsilon_r + 0.67}$$

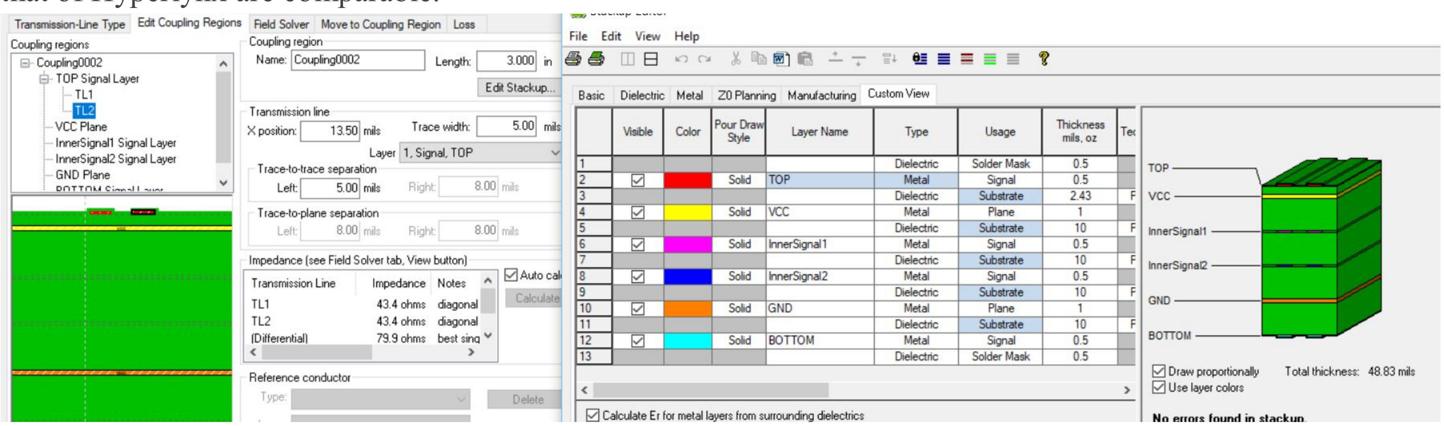
$$C_0\ (\text{pF/inch}) = \frac{t_{pd}\ (\text{ps/in})}{Z_0\ (\text{ohms})}$$

$$L_0\ (\text{nH/in}) = \frac{Z_0{}^2 C_0}{12}$$

Spacing (mil)	Dielectric thickness (mil)	x=1-0.48*exp(-0.96*s/h)	Zdiff(sqrt(Dk+1)	exp(Zdiff(sqrt(Dk+1))/2*87*x	Width (mil)	Zo (ohm)
5	2.55	0.926914621	184.1738309	3.13243349	5.001720201	42.84466
10	4.67	0.9385438		3.088428519	10.01079995	42.42976
15	6.8	0.942236412		3.074809959	15.02985884	42.30589
20	9	0.943135345		3.071519829	20.18672409	42.28656
25	11.1	0.944751117		3.065630595	25.14277827	42.22822
30	13.2	0.945826376		3.061728828	30.09781498	42.1897
35	15.3	0.946593345		3.058954192	35.0522668	42.16236
40	17.5	0.946497526		3.05930045	40.20859985	42.17094
45	19.5	0.947614429		3.055271108	44.9601909	42.12617
50	21.65	0.947703685		3.054949748	50.01530462	42.1251

tpd (ps)	139.5804456
C0(pF)	3.257825768
L0(nF)	1737.507076

For a spacing and dielectric thickness of 5 mil and 2.55 mil, width is found to be 5mil to have a Zdiff of 80 ohm. The values for 10 different combinations is as shown above. It is found through Hyperlynx that the calculated and practical values coincide. As it can be seen, the Single ended Impedance from calculations and that of Hyperlynx are comparable.



For Differential Ended Stripline:

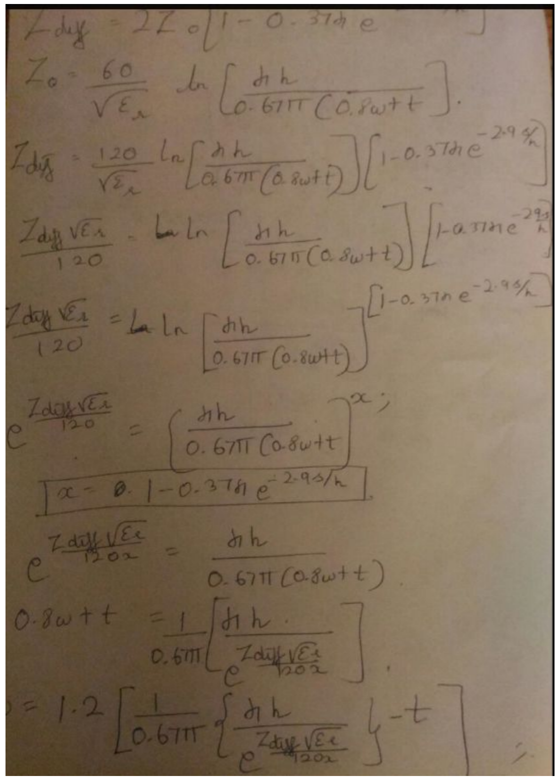
Here, the spacing and dielectric thickness values are assumed and the corresponding width is calculated using the standard IPC formulae for a given Dk, t and Z0.

$$Z_{\text{diff,stripline}}\ (\text{ohms}) = 2Z_0\left(1 - 0.374e^{\left(-2.9\frac{s}{h'}\right)}\right)$$

IPC-2251: PG 35 Equation 0.63

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \times \ln\left(\frac{4 \times h}{0.67\pi\,(0.8w + t)}\right)$$

Assuming that we know s and h values,



$$Z_{diff} = 2Z_0\left[1 - 0.374 e \ldots\right]$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right].$$

$$Z_{diff} = \frac{120}{\sqrt{\varepsilon_r}} \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]\left[1-0.374e^{-2.9s/h}\right]$$

$$\frac{Z_{diff}\sqrt{\varepsilon_r}}{120} = \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]\left[1-0.374e^{-2.9s/h}\right]$$

$$\frac{Z_{diff}\sqrt{\varepsilon_r}}{120} = \ln\left[\frac{4h}{0.67\pi(0.8w+t)}\right]^{\left[1-0.374e^{-2.9s/h}\right]}$$

$$e^{\frac{Z_{diff}\sqrt{\varepsilon_r}}{120}} = \left\{\frac{4h}{0.67\pi(0.8w+t)}\right\}^{x};$$

$$\boxed{x = 1-0.374e^{-2.9s/h}}$$

$$e^{\frac{Z_{diff}\sqrt{\varepsilon_r}}{120x}} = \frac{4h}{0.67\pi(0.8w+t)}$$

$$0.8w+t = \frac{1}{0.67\pi}\left[\frac{4h}{e^{\frac{Z_{diff}\sqrt{\varepsilon_r}}{120x}}}\right].$$

$$w = 1.2\left[\frac{1}{0.67\pi}\left\{\frac{4h}{e^{\frac{Z_{diff}\sqrt{\varepsilon_r}}{120x}}}\right\}-t\right]$$

Differential Stripline

Zdiff (ohm)	80
Dk	4.3
t (mil)	0.7
Length (in)	1
Zodd (ohm)	40
Zeven(ohm)	52.35905947

$$Z_{diff,stripline}\ (\text{ohms}) = 2Z_0\left(1 - 0.374e^{\left(-2.9\frac{s}{h}\right)}\right)$$

IPC-2251: PG 35 Equation 0.63

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \times \ln\left(\frac{4 \times h}{0.67\pi\,(0.8w+t)}\right)$$

$$t_{pd}\ (\text{ps/in}) = 1000\left(\frac{1.017\sqrt{\varepsilon_r}}{12\ (\text{in})}\right)$$

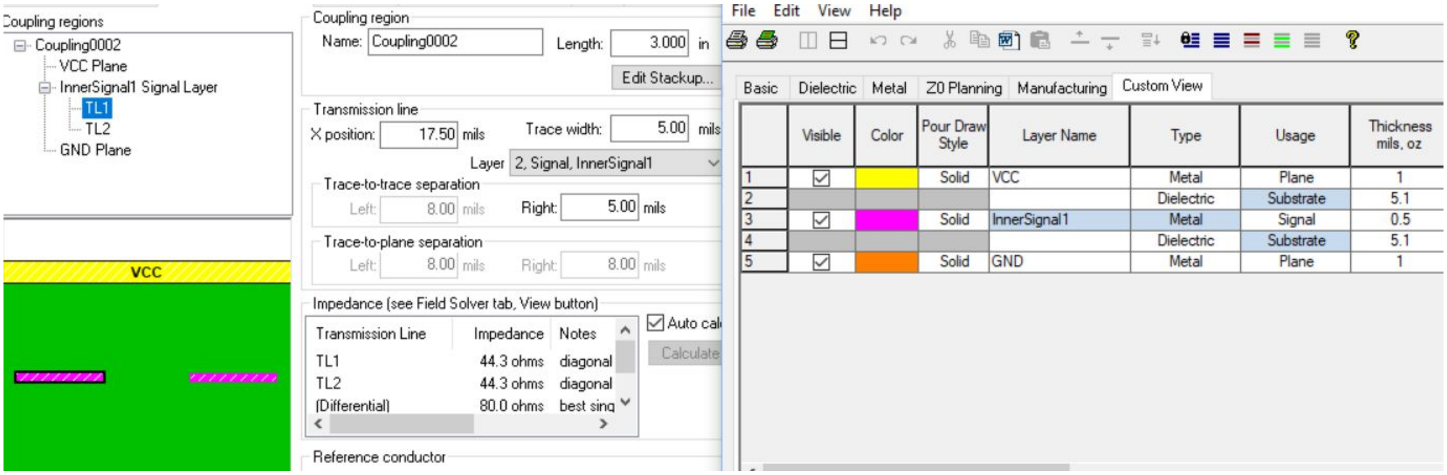
$$C_0\ (\text{pF/in}) = \frac{T_{pd}\ (\text{ps/in})}{Z_0\ (\text{ohms})}$$

$$L_0\ (\text{nH/in}) = \frac{[Z_0\ (\text{ohms})]^2\ C_0\ (\text{pF/in})}{1000}$$

Spacing (mil)	Dielectric thickness (mil)	x=1-0.374*exp(-2.9*s/h)	Zdiff(sqrt(Dk)	exp(Zdiff(sqrt(Dk+1))/2*87*x	Width (mil)	Zo (ohm)
5	12.2	0.88603921	165.8915308	4.759169932	5.003464533	46.17953
10	22.1	0.899297094		4.650961143	9.991568645	45.59344
15	32.1	0.903527681		4.617608154	15.00636846	45.41468
20	42	0.905985728		4.598481395	19.97980467	45.30981
25	52	0.907225707		4.58890202	24.99071053	45.25889
30	62	0.908056387		4.582510415	30.00111159	45.22491
35	72	0.908651694		4.57794253	35.01122123	45.20064
40	82	0.909099243		4.574515341	40.02114742	45.18243
45	92	0.909447969		4.571849025	45.03095066	45.16826
50	102	0.909727347		4.56971553	50.04066749	45.15693

tpd (ps)	175.7413405
C0(pF)	4.393533512
L0(nF)	7.029653619

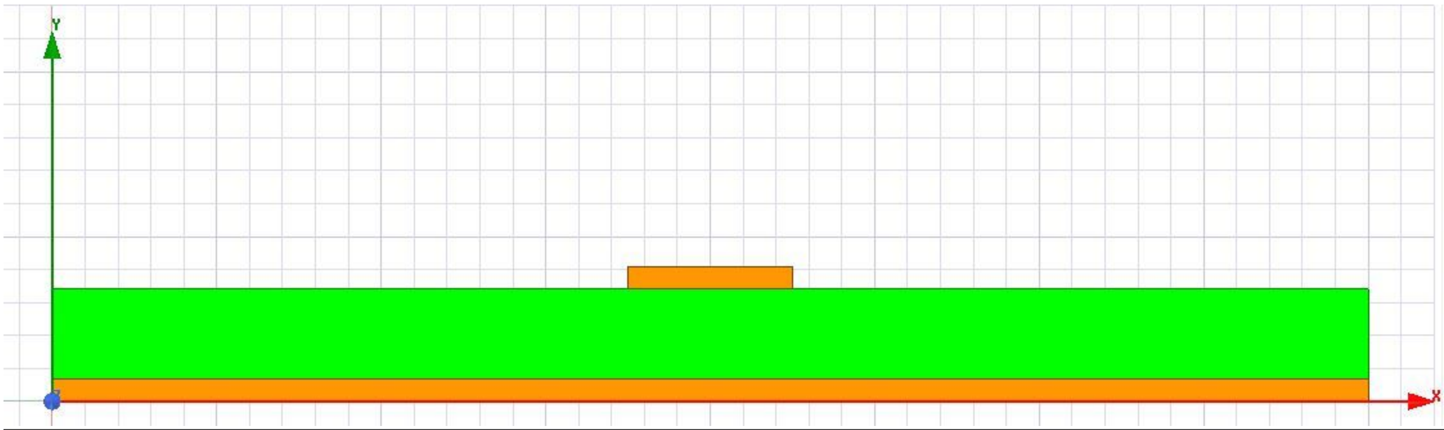
For a spacing and dielectric thickness of 5 mil and 12.2 mil, width is found to be 5mil to have a Zdiff of 80 ohm. The values for 10 different combinations is as shown above. It is found through Hyperlynx that the calculated and practical values co-inside. As it can be seen, the Single ended Impedance from calculations and that of Hyperlynx are comparable.



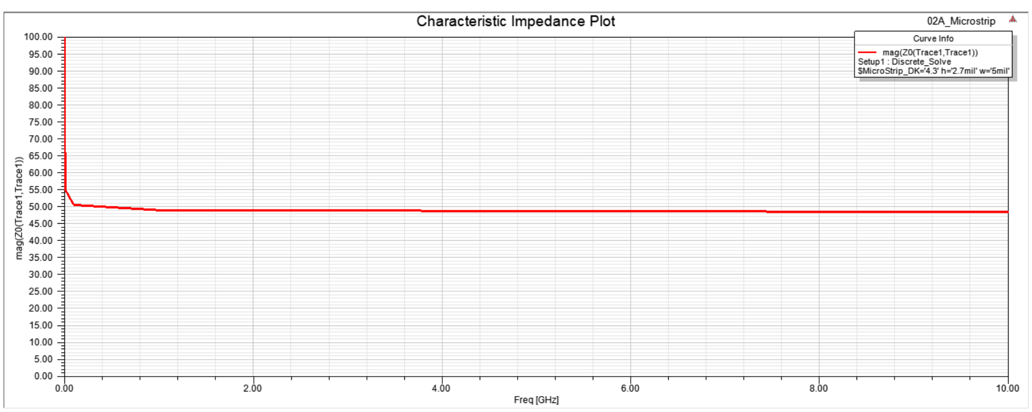
3) Create 50 ohm single ended impedance and also 80 ohm differential impedance in HFSS. Compare calculated with HFSS-simulated values

50 ohm single ended (microstrip)

From the numerically calculated values in Part 2, for a width of **5 mils**, the dielectric separation (h) is around **3.1 mils.** For these values, the model shown in figure below was simulated.



The port impedance vs. frequency plot below shows that for a single ended impedance of 50 ohms, HFSS computes the single ended impedance of the microstrip which very closely matches the analytically obtained value in Part 2.

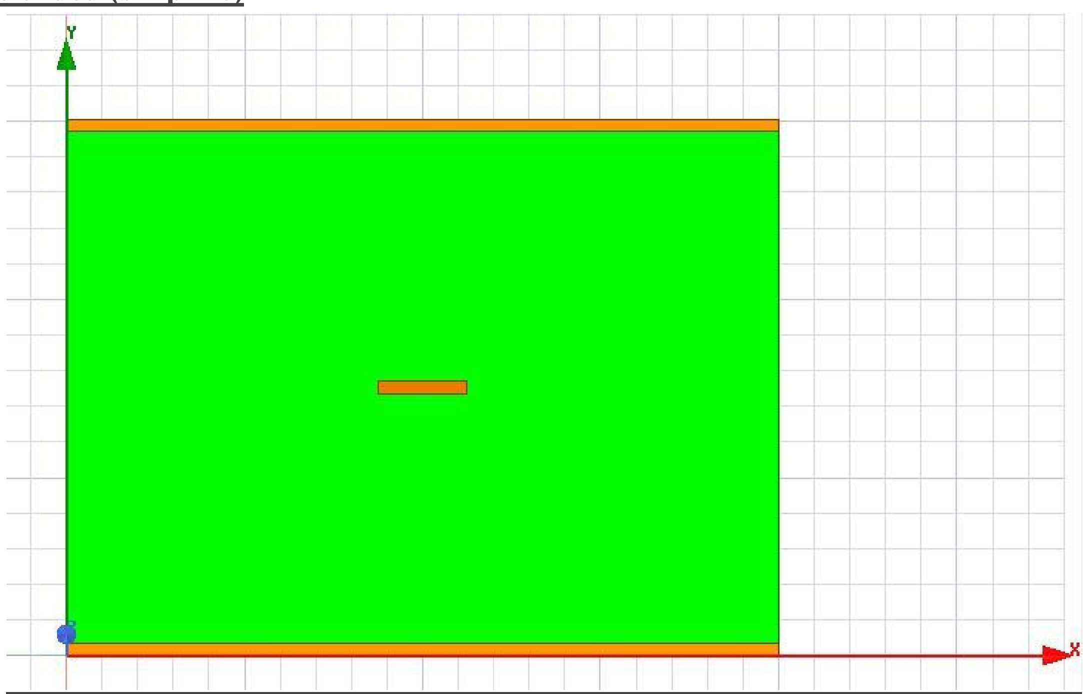


	Freq [GHz]	L(Trace1,Trace1) [nH] Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.7mil' w='5mil'
1	0.000001	410.080793
2	0.000100	409.870762
3	0.001000	394.096792
4	0.010000	338.014726
5	0.100000	313.111454
6	1.000000	295.421043
7	10.000000	288.864115

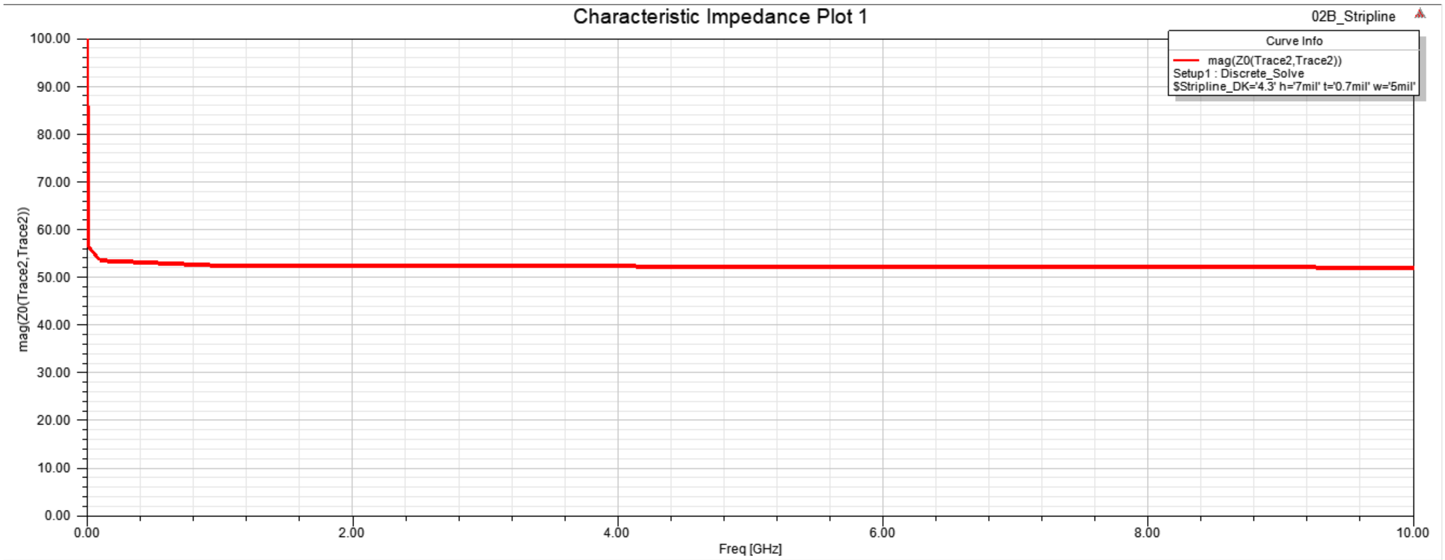
	Freq [GHz]	C(Trace1,Trace1) [pF] Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.7mil' w='5mil'
1	0.000001	122.892137
2	0.000100	122.892137
3	0.001000	122.892137
4	0.010000	122.892137
5	0.100000	122.892137
6	1.000000	122.892137
7	10.000000	122.892137

The above two tables show the single ended inductance (L) per unit length of the line, and the capacitance (C) per unit length of the line, as obtained from HFSS. The inductance matches the analytically obtained inductance per unit length obtained from the IPC formulae, and it decreases with increase in frequency, due to skin effect. As the capacitance (p.u.l.) of the line does not depend on the skin effect suffered by the line, it is not a function of frequency, as can be shown from the HFSS results. But there is a very large variation of ~50x in the capacitance value when compared to the analytical formula, suggesting that the IPC formulae for capacitance per unit length is at best, a bad approximation.

50 ohm single ended (stripline)



From the numerically calculated values in Part 2, for a width of **5 mils**, the dielectric separation (h) is around **3.1 mils.** For these values, the model shown in figure above was simulated.



The port impedance vs. frequency plot above shows that for a single ended impedance of 50 ohms, HFSS computes the single ended impedance of the microstrip which very closely matches the analytically obtained value in Part 2.

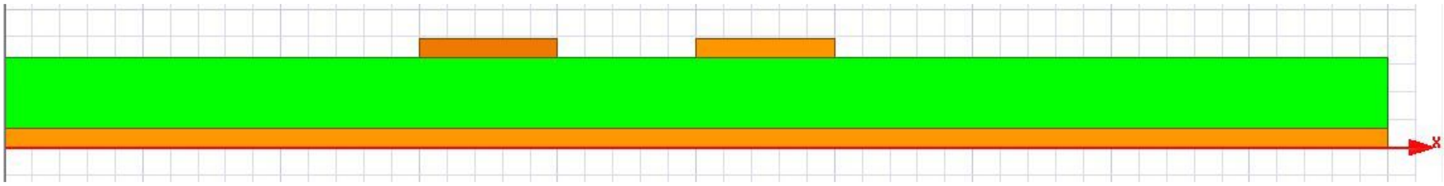
	Freq [GHz]	L(Trace2,Trace2) [nH] Setup1 : Discrete_Solve $Stripline_DK='4.3' h='7mil' t='0.7mil' w='5mil'
1	0.000001	439.422929
2	0.000100	439.295871
3	0.001000	430.336762
4	0.010000	404.678017
5	0.100000	383.973641
6	1.000000	369.642718
7	10.000000	364.134908

	Freq [GHz]	C(Trace2,Trace2) [pF] Setup1 : Discrete_Solve $Stripline_DK='4.3' h='7mil' t='0.7mil' w='5mil'
1	0.000001	134.067635
2	0.000100	134.067635
3	0.001000	134.067635
4	0.010000	134.067635
5	0.100000	134.067635
6	1.000000	134.067635
7	10.000000	134.067635

The above two tables show the single ended inductance (L) per unit length of the line, and the capacitance (C) per unit length of the line, as obtained from HFSS. The inductance obtained in HFSS does not match the analytically obtained inductance per unit length obtained from the IPC formulae, and it decreases with increase in frequency, due to skin effect. As the capacitance (p.u.l.) of the line does not depend on the skin effect suffered by the line, it is not a function of frequency, as can be shown from the HFSS results. But there is a very large variation of ~50x in the capacitance value when compared to the analytical formula, suggesting that the IPC formulae for capacitance per unit length and the inductance per unit length is at best, a bad approximation.

80 ohm Differential Pair (Microstrip)

As per results in Part 2, for a spacing and dielectric thickness of 5 mil and 2.55 mil, width is found to be 5mil to have a Zdiff of 80 ohm. The model below was created using the above dimensions.



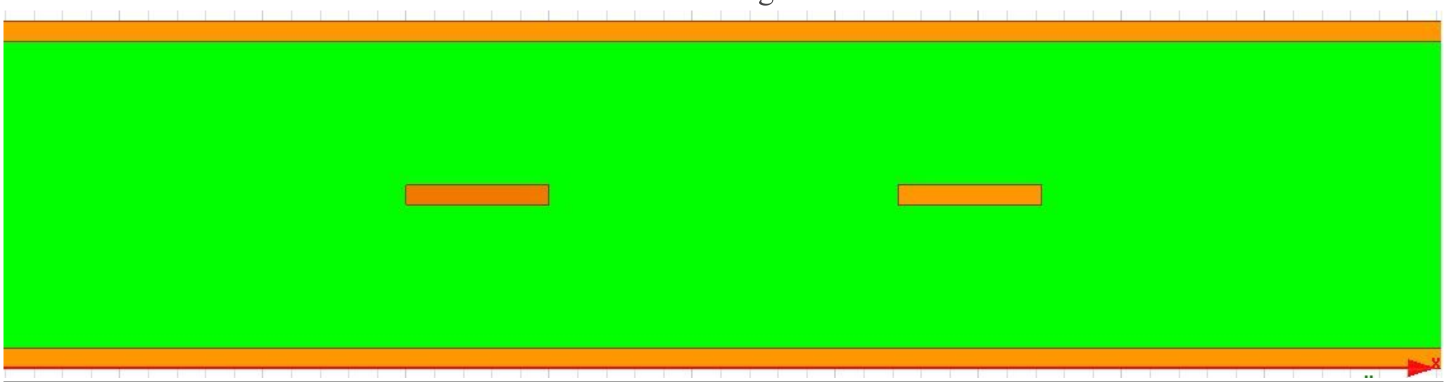
Characteristic Impedance Table 1 02C_Di

	Freq [GHz]	mag(Z0(Trace1,Trace1)) Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.55mil' s='5mil' w='5mil'	mag(Z0(Trace2,Trace1)) Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.55mil' s='5mil' w='5mil'	mag(Z0(Trace2,Trace2)) Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.55mil' s='5mil' w='5mil'	mag(Z0(Pair1:df,Pair1:df)) Setup1 : Discrete_Solve $MicroStrip_DK='4.3' h='2.55mil' s='5mil' w='5mil'
1	0.000001	3219.209181	201.212219	3217.008483	6033.793225
2	0.000100	322.132778	20.130127	321.912572	603.785432
3	0.001000	106.084103	6.789863	106.012201	198.525393
4	0.010000	53.389283	3.913605	53.354152	98.988195
5	0.100000	48.711021	3.929470	48.680236	89.533208
6	1.000000	47.135352	3.800304	47.099719	86.634517
7	10.000000	46.549095	3.755814	46.510501	85.547982

It can be seen from the table above that the differential impedance obtained for the above dimensions is ~ 85 ohms, which is very close to what we should obtain from the analytical calculations.

80 ohm Differential Pair (Stripline)

As per results in Part 2, for a spacing and dielectric thickness of 5 mil and 12.2 mil, width is found to be 5mil to have a Zdiff of 80 ohm. The model below was created using the above dimensions.



Characteristic Impedance Table 1 02D_Differential_Stripline

	Freq [GHz]	mag(Z0(Trace1,Trace1))_1 Setup1 : Discrete_Solve $Stripline_DK='4.3' h='12.5mil' s='5mil' w='5mil'	mag(Z0(Trace1,Trace2))_1 Setup1 : Discrete_Solve $Stripline_DK='4.3' h='12.5mil' s='5mil' w='5mil'	mag(Z0(Trace2,Trace2))_1 Setup1 : Discrete_Solve $Stripline_DK='4.3' h='12.5mil' s='5mil' w='5mil'	mag(Z0(Pair1:cm,Pair1:cm)) Setup1 : Discrete_Solve $Stripline_DK='4.3' h='12.5mil' s='5mil' w='5mil'	mag(Z0(Pair1:df,Pair1:... Setup1 : Discrete_Solve $Stripline_DK='4.3' h='...
1	0.000001	3480.224850	579.593079	3480.779757	2030.047683	5801.818492
2	0.000100	348.226590	58.062257	348.282107	203.150712	580.426692
3	0.001000	115.236575	21.311154	115.254779	68.109838	188.845573
4	0.010000	71.493461	18.850094	71.503872	45.133642	105.576286
5	0.100000	68.635454	19.006049	68.644379	43.821094	99.281079
6	1.000000	67.556926	18.957821	67.564910	43.259143	97.207806
7	10.000000	67.105356	18.968203	67.111976	43.038414	96.281073

It can be seen from the table above that the differential impedance obtained for the above dimensions is ~ 96 ohms, which is fairly close to what we should obtain from the analytical calculations.

Q4) Current distribution

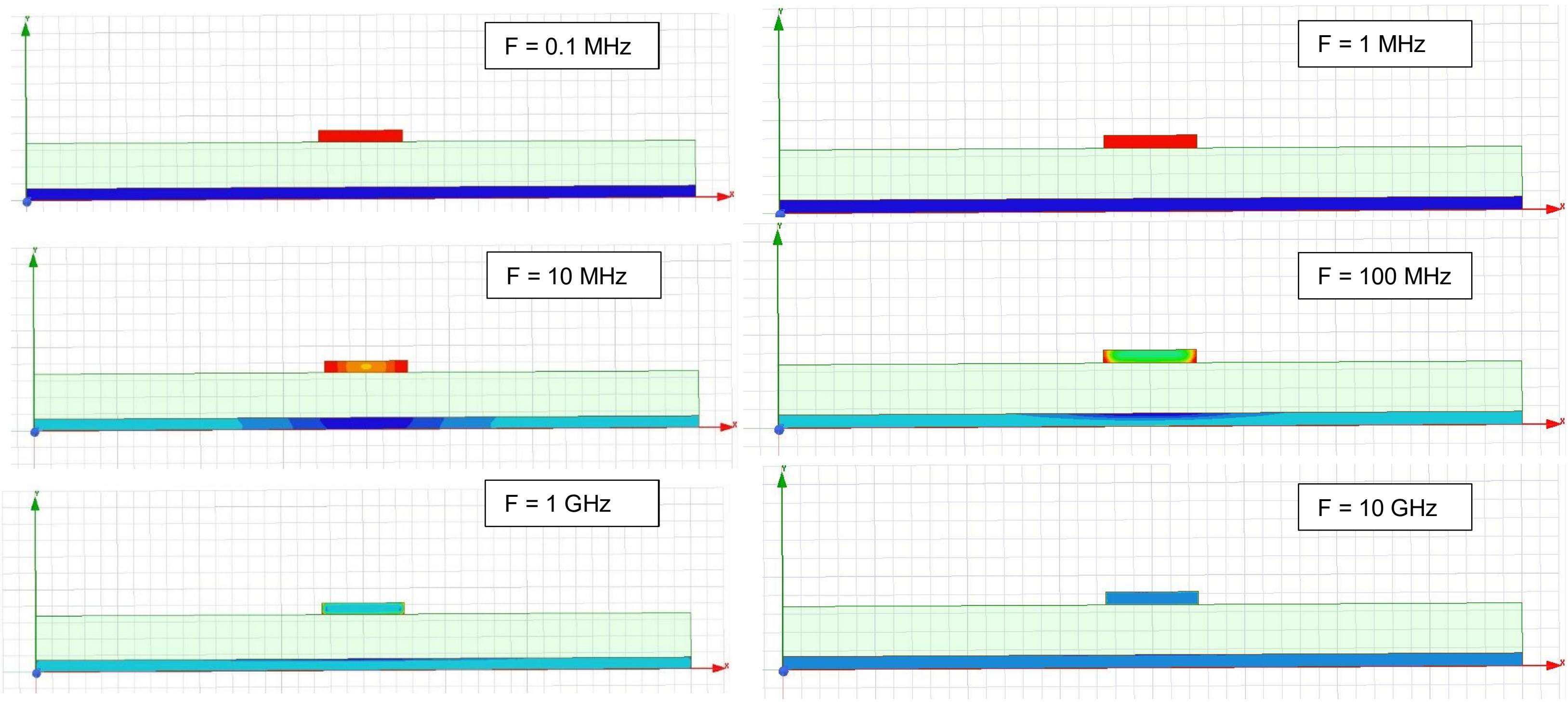
a) Freq effect (skin depth) –simulated skin depth and calculated.

b) Even and odd mode current distribution (for both signal trace and return plane)

- Effect of changing Separation of traces

- Effect of Dielectric thickness

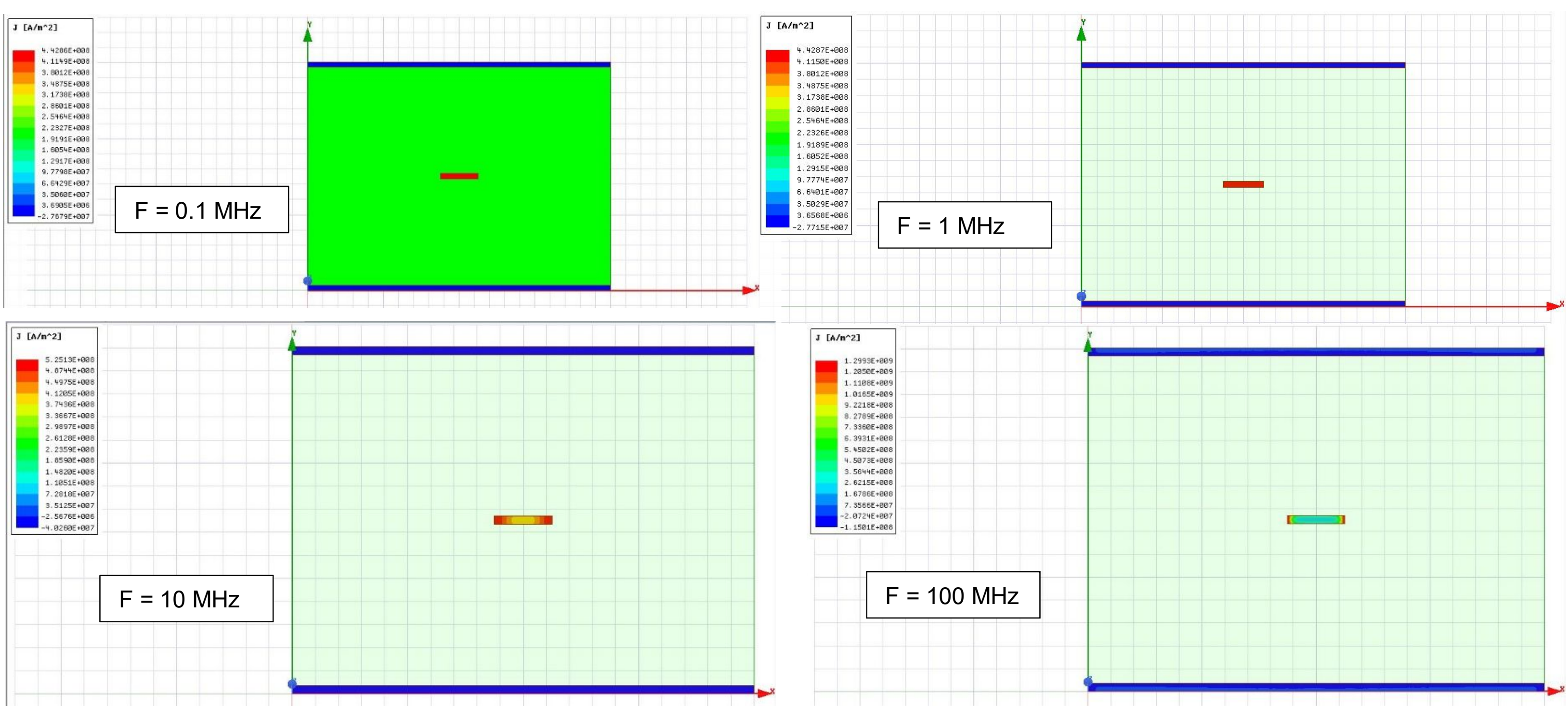
Single Ended Microstrip

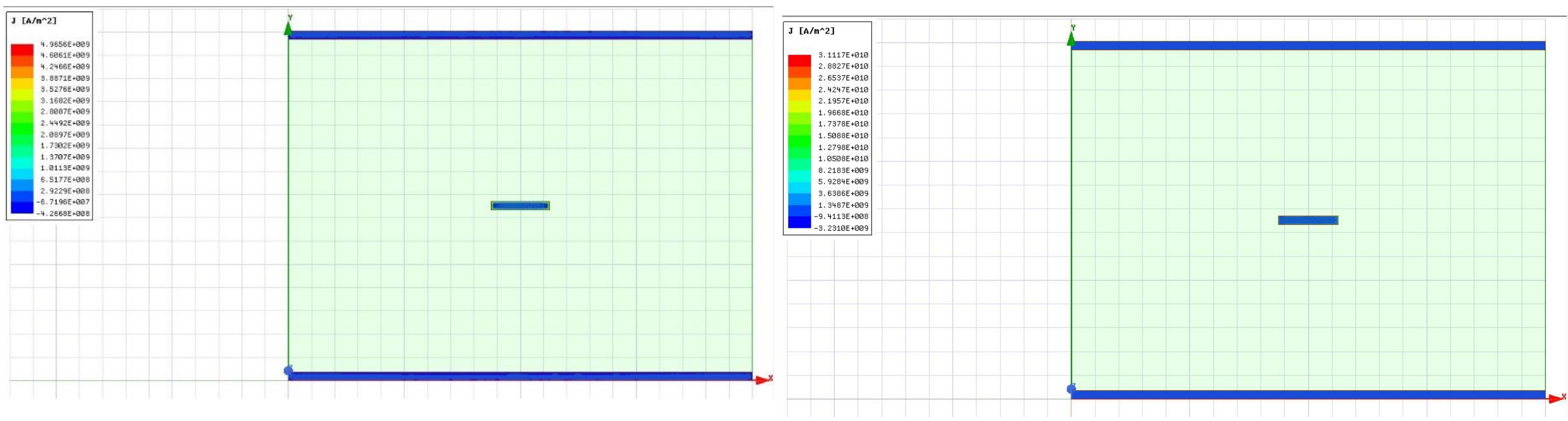


The above plots show the current distribution in a single ended microstrip line for different frequencies. At higher frequencies, the current distribution is limited only to the periphery of the trace owing to the skin depth, i.e., the penetration of the current distribution inside the trace, being inversely proportional to the square root of frequency. The skin-depth is a measure for attenuation due to the conductor. Lesser the skin depth (or higher the frequency), greater is the attenuation due to the conductor.

As the skin depth decreases, the return current can be seen to be centered about the conductor trace.

Single Ended Stripline

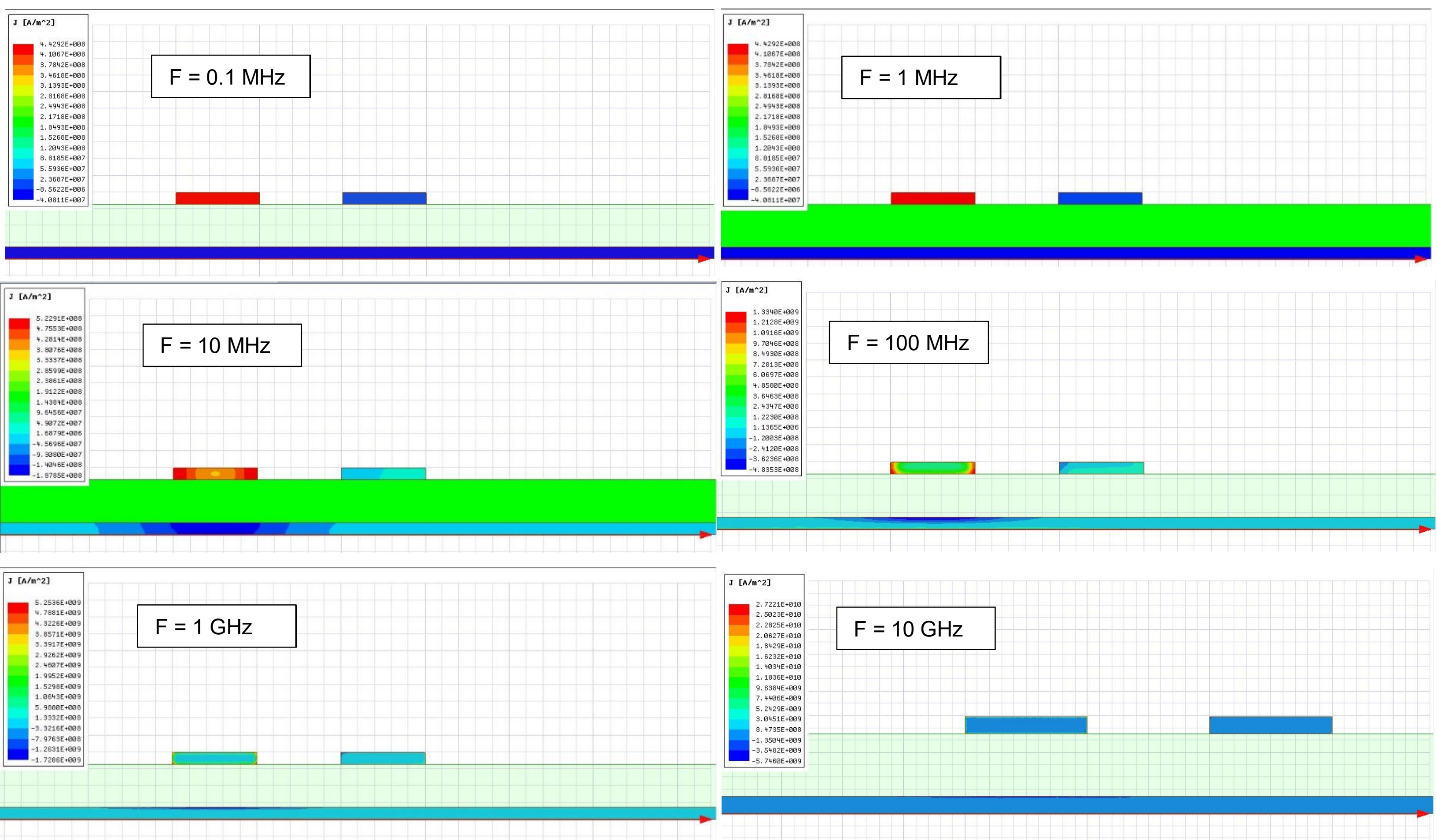




The above plots show the current distribution in a single ended stripline for different frequencies. At higher frequencies, the current distribution is limited only to the periphery of the trace owing to the skin depth, i.e., the penetration of the current distribution inside the trace, being inversely proportional to the square root of frequency. The skin-depth is a measure for attenuation due to the conductor. Lesser the skin depth (or higher the frequency), greater is the attenuation due to the conductor.

As the skin depth decreases, the return current can be seen to be centered about the conductor trace.

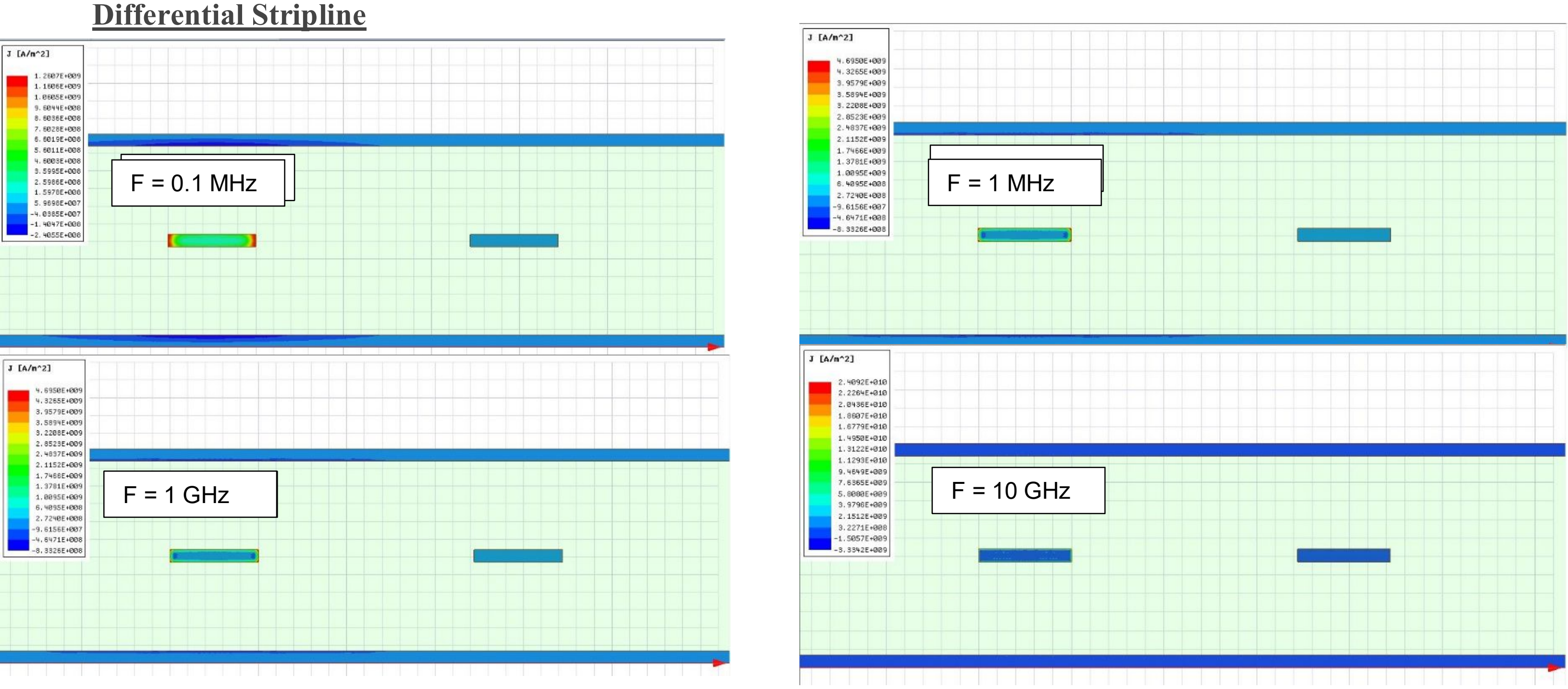
Differential Microstrip



The above plots show the current distribution in a differential microstrip for different frequencies. At higher frequencies, the current distribution is limited only to the periphery of the trace owing to the skin depth, i.e., the penetration of the current distribution inside the trace, being inversely proportional to the square root of frequency. The skin-depth is a measure for attenuation due to the conductor. Lesser the skin depth (or higher the frequency), greater is the attenuation due to the conductor.

As the skin depth decreases, the return current can be seen to be centered about the conductor trace. As the traces are tightly coupled, coupling effects cause the current distribution to be higher than that of the single ended microstrip.

Differential Stripline



The above plots show the current distribution in a differential stripline for different frequencies. At higher frequencies, the current distribution is limited only to the periphery of the trace owing to the skin depth, i.e., the penetration of the current distribution inside the trace, being inversely proportional to the square root of frequency. The skin-depth is a measure for attenuation due to the conductor. Lesser the skin depth (or higher the frequency), greater is the attenuation due to the conductor.

As the skin depth decreases, the return current can be seen to be centered about the conductor trace. As the traces are tightly coupled, coupling effects cause the current distribution to be higher than that of the single ended microstrip.

Effect of increasing trace separation (s)

Increasing the trace separation (s) causes the differential impedance (Z_{diff}) to increase, and when $s > 3w$, the differential impedance is constant thereafter and the two traces have been **uncoupled**. Here we have driven both the traces in opposite, and as a result increasing the trace separation will cause the single ended impedance (Z_0) of the line to increase till when $s > 3w$. Thereafter it remains constant.

Effect of increasing dielectric thickness (h)

Keeping the trace to trace separation (s) constant, if we increase the dielectric thickness (h), the differential as well as the single ended impedance of the line increases.