# Exemplu de proiectare de circuite pasive în structuri integrate

Tema de proiectare

Să se realizeze un filtru trece bandă, în tehnologie microstrip, cu frecvenţa centrală la 6.0 GHz. Se va utiliza programul Sonnet pentru simulare. Se poate realiza sinteza filtrului (rf-opto.etti.tuiasi.ro -> secţiunea Circuite pentru microunde) sau se poate adapta o structură cu rezultate cunoscute.

Se alege utilizarea unei structuri tipice de filtru interdigital. Un astfel de circuit este prezent între fişierele Sonnet, în secţiunea exemple, proiectul "filtwall.son". Acest filtru este realizat pe un substrat din alumină (Al$_2$O$_3$ - $\varepsilon_r$ = 9.8, tan $\delta$ = 10$^{-4}$) cu grosimea de 15 mil. Se folosesc 5 secţiuni de linie de transmisie (dimensiuni 22/24/26mil×214mil) spaţiate cu 30/32/38mil (pentru detalii deschideţi fişierul exemplu).

Caracteristicile acestui filtru sunt prezentate în figura următoare, banda obţinută fiind între 4.95GHz - 5.3GHz cu atenuare înafara benzii foarte bună (atenuare > 30dB la 4.75GHz şi 5.35GHz). Aceleaşi performanţe vor fi dificil de realizat pe un substrat de circuit integrat (se reaminteşte că alumina este un dielectric foarte bun utilizat în circuitele integrate în timp ce substratul în circuitele integrate monolitice este un material semiconductor)
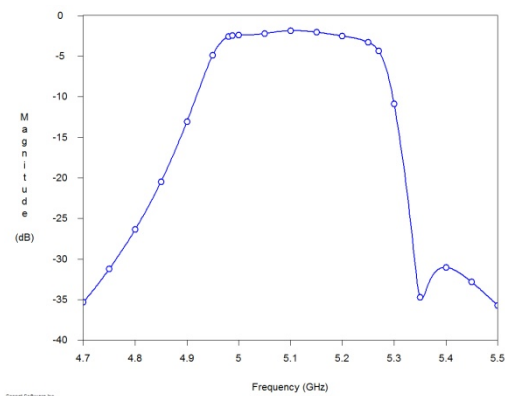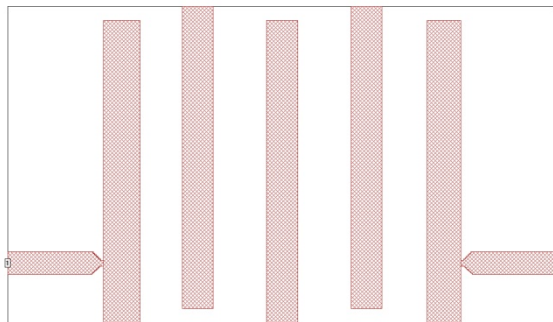


Trecerea la structura de circuit integrat aduce câteva deosebiri esenţiale care modifică total comportamentul şi forma circuitului:

- schimbarea unităţilor de măsură în sistemul internaţional (dacă în proiectarea pe substrat dielectric – alumină – se utilizează câteodată unităţile englezeşti datorită înălţimilor standard ale substratelor, în proiectarea circuitelor integrate se lucraează în SI)
  - 1 mil = 10$^{-3}$ inch = 25.4 μm

- Modificarea caracteristicilor substratului (Se poate utiliza materialul din biblioteca Sonnet standard: $\varepsilon_r = 12.9$, $\tan\delta = 6\times10^{-3}$, $\sigma \approx 0$) şi a înălţimii acestuia (h = 200μm)

- Modificarea liniilor microstrip. Caracteristicile care se modifică sunt $\varepsilon_{eff}$ şi $Z_0$. Pentru calcularea noilor valori există relaţii precise de calcul, dar se pot utiliza câteva metode mai rapide de proiectare:

  o tabele/grafice de proiectare (la sfârşitul acestui document).
  o programe de calcul (Exemplu Tools->Line Calc în ADS 2003)
  o pentru acces facil, cu riscurile de rigoare, calculatoare on-line
    ▪ http://www.microwaves101.com/encyclopedia/calmstrip.cfm – calcul aproximativ
    ▪ http://mcalc.sourceforge.net/ - calcul după relaţii mai precise

În general, regula de bază este modificarea lăţimii traseelor pentru a păstra nemodificată impedanţa caracteristică pe noul substrat, urmat de modificarea lungimii pentru a păstra lungimea electrică constantă.

Pentru scalarea lungimilor se reamintesc câteva relaţii de bază. Funcţionalitatea circuitului nu depinde în general de dimensiuni în mărimi absolute, ci de raportul între dimensiune şi lungimea de undă. Pentru a păstra funcţionalitatea la modificări de structură/material (cum este cazul în această temă) trebuie păstrat un raport $l/\lambda$ constant ţinând cont de lungimea de undă diferită, la aceeaşi frecvenţă. Dacă în plus trebuie modificate şi frecvenţele de lucru, se introduce o scalare suplimentară.

$$\lambda = \frac{\lambda_0}{n} = \frac{\lambda_0}{\sqrt{\varepsilon_r}} = \frac{c_0}{\sqrt{\varepsilon_r} \cdot f}$$

Pentru circuitul iniţial realizat pe Alumină:

$$k_{Al} = \frac{l_{Al}}{\lambda_{Al}} = \frac{l_{Al}}{c_0} \cdot \sqrt{\varepsilon_{rAl}} \cdot f_{Al}$$

Pentru circuitul realizat pe GaAs:

$$k_{GaAs} = \frac{l_{GaAs}}{\lambda_{GaAs}} = \frac{l_{GaAs}}{c_0} \cdot \sqrt{\varepsilon_{rGaAs}} \cdot f_{GaAs}$$

Păstrarea raportului constant introduce un coeficient de scalare a dimensiunilor:

$$k = \frac{l_{GaAs}}{l_{Al}} = \frac{\sqrt{\varepsilon_{rAl}} \cdot f_{Al}}{\sqrt{\varepsilon_{rGaAs}} \cdot f_{GaAs}}$$

În aceste relaţii $\varepsilon_r$ trebuie privit ca fiind $\varepsilon_{eff}$ pentru liniile microstrip corespunzătoare, dependent de materialul de substrat şi de lăţimea traseelor (ε şi w/h).

## **Exemplu**

Pentru prima secţiune de linie din filtrul interdigital: dimensiuni 26×214mil pe substrat alumină ($\varepsilon_r$ = 9.8, tan δ = $10^{-4}$) cu grosimea de 15 mil impedanţa caracteristică a liniei este (Line Calc din ADS):

$$Z_0 = 36.58\Omega, \qquad \varepsilon_{\text{eff}} = 7.025$$

Pentru obţinerea aceleiaşi impedanţe caracteristice pe noul substrat GaAs ($\varepsilon_r$ = 12.9, tan δ = 6×$10^{-3}$ , σ ≈ 0, h = 200μm) lăţimea liniei trebuie să fie 275.75μm condiţie în care se obţine $\varepsilon_{\text{eff}}$ = 8.853.

În aceste condiţii lungimea secţiunii de linie trebuie să fie:

$$l = \frac{(214 \cdot 25.4)\mu m \cdot \sqrt{7.025} \cdot 5.15 GHz}{\sqrt{8.853} \cdot 6 GHz} = 4156.06 \mu m$$

Celelalte secţiuni de linie au aceeaşi lungime, dar lăţimile sunt de 22mil (3 linii) şi 24mil (ultima linie) care devin prin aceeaşi metodă de proiectare 230.23μm(40.27Ω) şi 252.93μm(38.32Ω).

Pentru liniile de intrare/ieşire se obţine o impedanţă caracteristică $Z_0$ = 47.7Ω. Se remarcă adaptarea dorită cu porturile de 50Ω. Lăţimea corespunzătoare pe GaAs va fi de 162μm iar lungimea de 1320μm.

Spaţiile dintre "degete" (secţiuni de linie) sunt de 30/38/38/32mil devenind cu scalarea în distanţă menţionată anterior 582.62/737.99/737.99/621.47μm. Degetele 2 şi 4 sunt deplasate cu 10mil faţă de celelalte, distanţă care devine 194.21μm.

În aceste condiţii putem determina dimensiunile volumului de calcul (Box Size în Sonnet):

- X: 4156.06 + 194.21 = 4350.27μm
- Y: 2 · 1319.56 + 275.75 + 3 · 230.23 + 252.93 + 582.62 + 2 · 737.99 + 621.47
  = 6538.56μm

În acest moment se poate realiza desenarea schemei. E recomandat ca la desenarea poligoanelor să se incerce, pe cât posibil, ca fiecare poligon să acopere un număr întreg de celule. Acest lucru se poate asigura alegând o anumită discretizare a cutiei, urmând ca fiecare dimensiune să fie modificată la cel mai apropiat multiplu al dimensiunei celulei. Estimarea unui număr suficient de celule în acest pas este dificilă, dar din nou putem face apel la caracteristicile structurii exemplu. Aici întreaga structură cu dimensiunile 390×224mil a fost discretizată cu celule 2×2mil (195×112 celule) de unde şi dimensiunile "întregi şi pare" ale structurii iniţiale. La alegerea dimensiunii celulelor trebuie să se ţină seama şi de caracteristicile tehnologice. În cazul de faţă, considerăm Plessey Foundry F20 utilizat şi la

curs, caz în care liniile vor fi implementate în stratul de metalizare M3, cu dimensiunea minimă implementabilă 10μm şi un control al lăţimii (precizie) de 1μm. In aceste condiţii nu se obţin avantaje decisive din utilizarea a prea multe zecimale în determinarea caracteristicilor celulei. Vom alege ca dimensiuni iniţiale ale celulei $C_x \times C_y$ = 25.54μm×33.99μm care asigură o diviziune iniţială 256×128 celule apropiată de cea din proiect.

| | Iniţial (alumină) [mil] | Calculat (GaAs) [μm] | Număr celule X×Y | Dimensiuni proiect [μm] |
|---|---|---|---|---|
| Cutie | 390×224 | 6538.56×4350.27 | 256×128 | 6538.24×4350.72 |
| Linii in/out | 16/68 | 162/1320 | 52×5 | 169.95/1328.08 |
| Distanţă Y intrare | 34 | 660.31 | -×19 | 645.81 |
| Distanţă Y degete | 10 | 194.21 | -×6 | 203.94 |
| Deget1 | 26/214 | 275.75/4156 | 11×122 | 280.94/4146.78 |
| Deget2-4 | 22/214 | 230.23/4156 | 9×122 | 229.86/4146.78 |
| Deget5 | 24/214 | 252.93/4156 | 10×122 | 255.4/4146.78 |
| Spaţiu1-2 | 30 | 582.62 | 23×- | 587.42 |
| Spatiu2-4 | 38 | 737.99 | 29×- | 740.66 |
| Spaţiu4-5 | 32 | 621.47 | 24×- | 612.47 |
| Suma | | | 257×128 | 6563.78×4350.72 |

Se constată că suma de control a numărului de celule pe distanţa X este 257 datorită rotunjirilor ceea ce va implica faptul că una dintre liniile de intrare/ieşire va fi reprezentată pe 51 de celule lungime în loc de 52.

Se realizează noul proiect completând datele corespunzătoare ale unităţilor (Circuit→Units), cutiei (Circuit→Box) şi straturilor de dielectric (Circuit→Dielectric Layers).
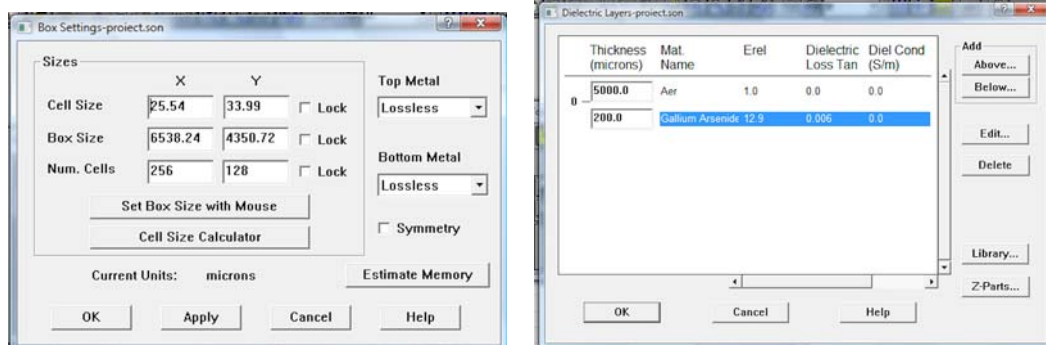


Urmează desenarea efectivă a circuitului. În acest pas se vor folosi indicaţiile Sonnet în bara de stare (dimensiunile curente ale poligoanelor desenate) şi se va folosi **intens** facilitatea de măsurare pusă la dispoziţie (View→Measuring Tool) pentru a poziţiona corect poligoanele. Se recomandă desenarea iniţială a unor dreptunghiuri urmând ca unde este

nevoie (în acest caz la liniile de intrare/ieşire care se îngustează treptat la atingerea primului/ultimului deget) să se adauge puncte care apoi să fie deplasate unde este nevoie. E obligatoriu ca opţiunea de fixare în nodurile grilei să fie selectată la nodurile reţelei (Tools→Snap Setup) pentru a avea o precizie mai bună de calcul.
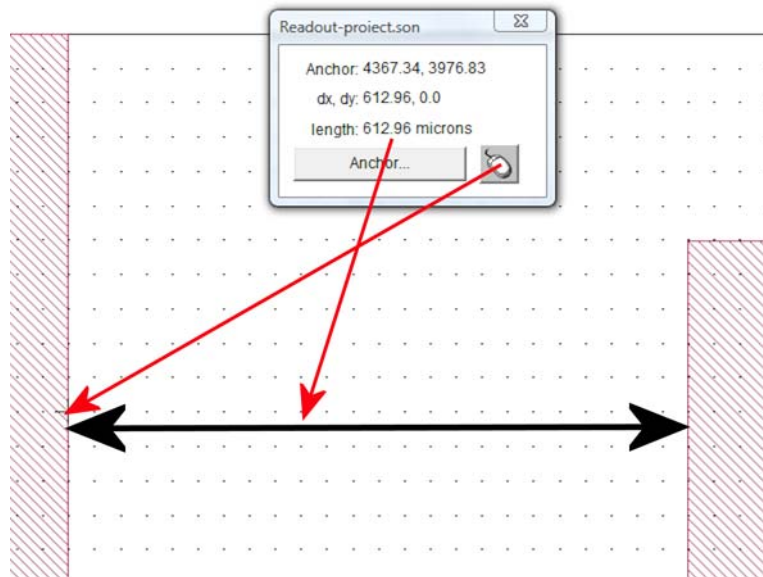


Pe desenul realizat se observă faptul că liniile sunt mai subţiri decât în cazul precedent şi de asemenea la distanţe mai mari (datorită în primul rând modificărilor substratului).
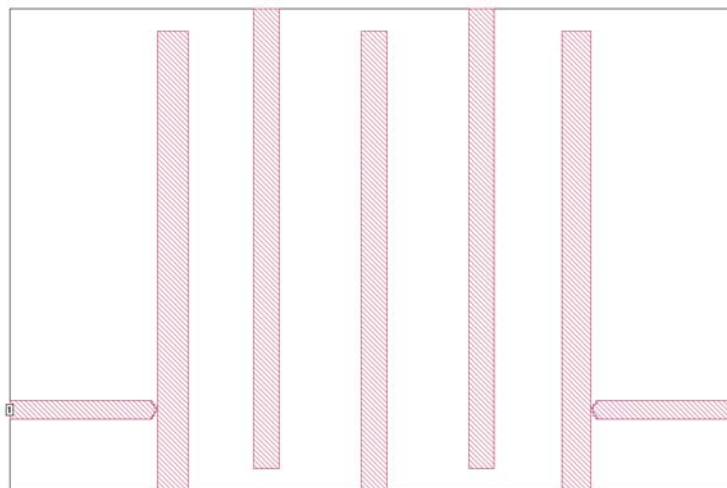


Se realizează o primă analiză (recomandat Analysis→Setup→Adaptive Sweep pentru o viteză de calcul mai mare) pentru verificarea corectitudinii calculelor geometrice.
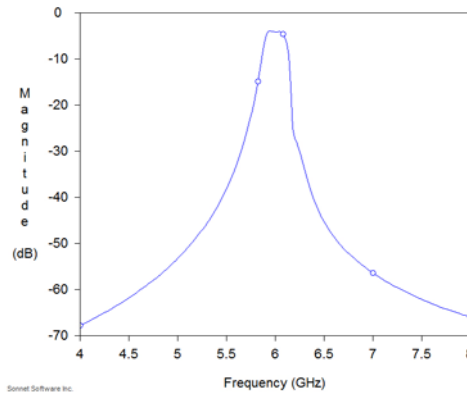
Daca rezultatul arata îndeplinirea cerințelor (cum e cazul aici) se poate efectua o analiza mai precisa Analysis→Setup→Linear Frequency Sweep care efectuează calculul în mai multe puncte.
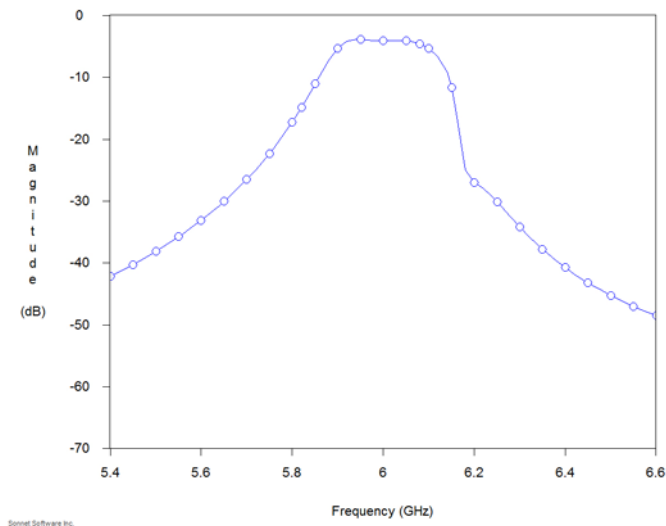
Este obligatorie în continuare efectuarea unei analize de convergență prin micșorarea dimensiunilor celulelor, cu scopul de a observa dacă analiza realizată este destul de fină. Se realizează relativ ușor o înjumătăţire a celulelor pe ambele dimensiuni (mărire de 4 ori a numărului de celule) în secțiunea Circuit→Box selectând Lock în secțiunea Box Size și mărind (dublare sau eventual mai mult dacă este nevoie) numărul de celule. În cazul acestui circuit, calculul cu 512×256 celule nu aduce un spor de precizie lucru care se poate observa prin suprapunerea celor două grafice (ţinând cont că estimarea inițială a fost "împrumutată" e a fost suficient de bună).
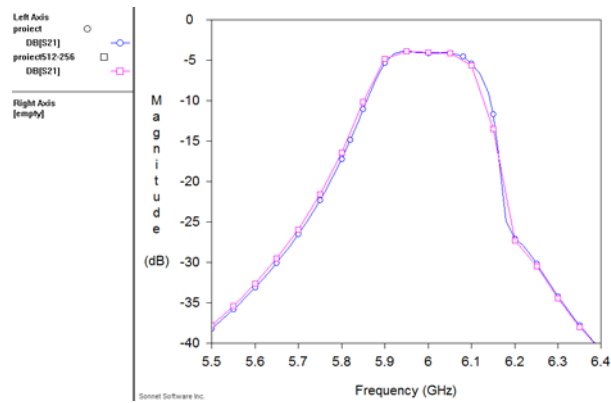
În sfârşit se prezintă posibilitatea de a afecta (în anumite limite!!!) funcţionarea filtrului prin modificarea lăţimii degetelor şi a distanţelor dintre ele pentru a afecta cuplajul. Se prezintă situaţia obţinută pentru linii mai late, cu efectul măririi benzii de trecere după cum se observă la comparaţia cu cazul anterior. Totuşi, mărirea lăţimii liniilor ar trebui însoţită de o mărire corespunzătoare a cutiei, pentru a păstra frecvenţa centrală dorită.
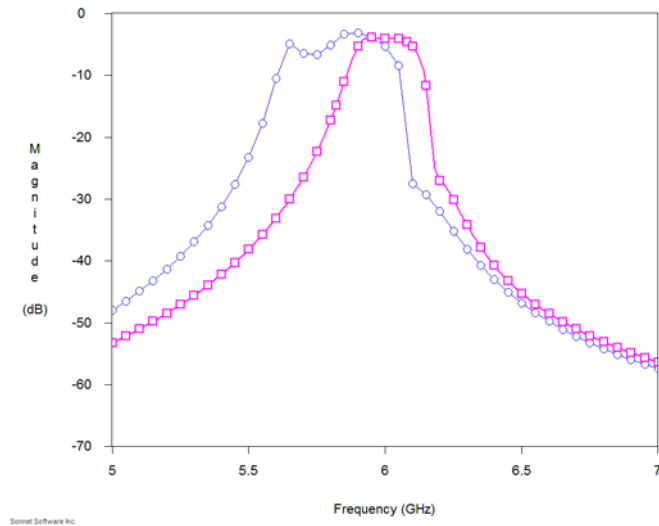
# Microstrip Impedances



**FIGURE 12**

**TABLE 12a**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 2.2

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 250.3363 | 2.1861 | 49.3192 | 0.0493 | 57 | 2.5199 | 1.8500 | 0.7959 | 2.5860 |
| 2 | 123.5739 | 2.1728 | 24.5846 | 0.0983 | 58 | 2.4514 | 1.8471 | 0.7816 | 2.6294 |
| 3 | 81.4007 | 2.1601 | 16.3417 | 0.1471 | 59 | 2.3854 | 1.8443 | 0.7678 | 2.6727 |
| 4 | 60.3537 | 2.1480 | 12.2218 | 0.1955 | 60 | 2.3218 | 1.8416 | 0.7544 | 2.7160 |
| 5 | 47.7490 | 2.1364 | 9.7510 | 0.2438 | 61 | 2.2603 | 1.8389 | 0.7415 | 2.7592 |
| 6 | 39.3615 | 2.1253 | 8.1046 | 0.2918 | 62 | 2.2010 | 1.8362 | 0.7290 | 2.8024 |
| 7 | 33.3816 | 2.1146 | 6.9294 | 0.3395 | 63 | 2.1437 | 1.8336 | 0.7170 | 2.8456 |
| 8 | 28.9051 | 2.1044 | 6.0485 | 0.3871 | 64 | 2.0883 | 1.8310 | 0.7053 | 2.8887 |
| 9 | 25.4299 | 2.0946 | 5.3639 | 0.4345 | 65 | 2.0347 | 1.8285 | 0.6939 | 2.9318 |
| 10 | 22.6550 | 2.0851 | 4.8166 | 0.4817 | 66 | 1.9829 | 1.8259 | 0.6829 | 2.9749 |
| 11 | 20.3889 | 2.0760 | 4.3692 | 0.5287 | 67 | 1.9327 | 1.8235 | 0.6723 | 3.0179 |
| 12 | 18.5040 | 2.0673 | 3.9967 | 0.5755 | 68 | 1.8919 | 1.8214 | 0.6620 | 3.0612 |
| 13 | 16.9121 | 2.0589 | 3.6817 | 0.6222 | 69 | 1.8447 | 1.8190 | 0.6520 | 3.1042 |
| 14 | 15.5503 | 2.0508 | 3.4120 | 0.6688 | 70 | 1.7990 | 1.8166 | 0.6423 | 3.1471 |
| 15 | 14.3723 | 2.0429 | 3.1784 | 0.7152 | 71 | 1.7548 | 1.8143 | 0.6328 | 3.1900 |
| 16 | 13.3435 | 2.0354 | 2.9743 | 0.7614 | 72 | 1.7119 | 1.8120 | 0.6236 | 3.2329 |
| 17 | 12.4375 | 2.0280 | 2.7943 | 0.8075 | 73 | 1.6704 | 1.8097 | 0.6147 | 3.2757 |
| 18 | 11.6337 | 2.0210 | 2.6344 | 0.8536 | 74 | 1.6301 | 1.8075 | 0.6060 | 3.3186 |
| 19 | 10.9159 | 2.0141 | 2.4915 | 0.8994 | 75 | 1.5910 | 1.8053 | 0.5976 | 3.3614 |
| 20 | 10.2711 | 2.0075 | 2.3631 | 0.9452 | 76 | 1.5531 | 1.8031 | 0.5894 | 3.4041 |
| 21 | 9.6889 | 2.0010 | 2.2469 | 0.9909 | 77 | 1.5163 | 1.8010 | 0.5814 | 3.4469 |
| 22 | 9.1607 | 1.9948 | 2.1414 | 1.0365 | 78 | 1.4806 | 1.7988 | 0.5736 | 3.4896 |
| 23 | 8.6793 | 1.9887 | 2.0452 | 1.0819 | 79 | 1.4458 | 1.7968 | 0.5660 | 3.5322 |
| 24 | 8.2389 | 1.9828 | 1.9571 | 1.1273 | 80 | 1.4121 | 1.7947 | 0.5586 | 3.5749 |
| 25 | 7.8346 | 1.9771 | 1.8761 | 1.1726 | 81 | 1.3793 | 1.7926 | 0.5514 | 3.6175 |
| 26 | 7.4621 | 1.9715 | 1.8014 | 1.2177 | 82 | 1.3474 | 1.7906 | 0.5443 | 3.6601 |
| 27 | 7.1178 | 1.9661 | 1.7323 | 1.2628 | 83 | 1.3164 | 1.7886 | 0.5375 | 3.7027 |
| 28 | 6.7988 | 1.9608 | 1.6682 | 1.3078 | 84 | 1.2862 | 1.7867 | 0.5308 | 3.7453 |
| 29 | 6.5024 | 1.9557 | 1.6085 | 1.3528 | 85 | 1.2568 | 1.7847 | 0.5243 | 3.7878 |

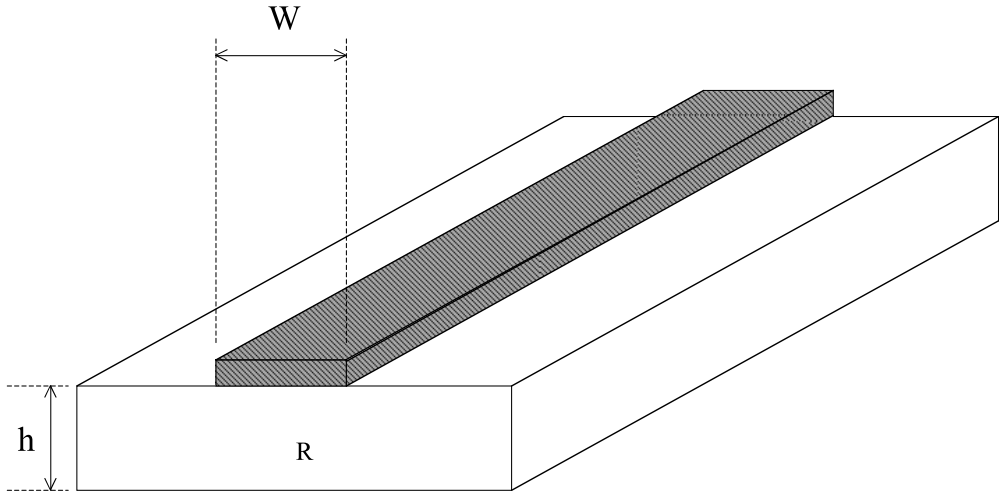**TABLE 12a (continued)**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 2.2

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 30 | 6.2263 | 1.9507 | 1.5529 | 1.3976 | 86 | 1.2282 | 1.7828 | 0.5179 | 3.8303 |
| 31 | 5.9686 | 1.9458 | 1.5010 | 1.4424 | 87 | 1.2003 | 1.7809 | 0.5117 | 3.8728 |
| 32 | 5.7274 | 1.9410 | 1.4523 | 1.4871 | 88 | 1.1732 | 1.7791 | 0.5056 | 3.9152 |
| 33 | 5.5013 | 1.9364 | 1.4066 | 1.5318 | 89 | 1.1467 | 1.7772 | 0.4996 | 3.9577 |
| 34 | 5.2890 | 1.9319 | 1.3636 | 1.5763 | 90 | 1.1210 | 1.7754 | 0.4938 | 4.0001 |
| 35 | 5.0892 | 1.9274 | 1.3231 | 1.6208 | 91 | 1.0959 | 1.7736 | 0.4882 | 4.0424 |
| 36 | 4.9009 | 1.9231 | 1.2849 | 1.6653 | 92 | 1.0714 | 1.7718 | 0.4826 | 4.0848 |
| 37 | 4.7231 | 1.9189 | 1.2488 | 1.7096 | 93 | 1.0476 | 1.7700 | 0.4772 | 4.1272 |
| 38 | 4.5550 | 1.9147 | 1.2146 | 1.7539 | 94 | 1.0243 | 1.7683 | 0.4719 | 4.1695 |
| 39 | 4.3959 | 1.9107 | 1.1822 | 1.7982 | 95 | 1.0016 | 1.7665 | 0.4667 | 4.2118 |
| 40 | 4.2450 | 1.9067 | 1.1515 | 1.8424 | 96 | 0.9795 | 1.7658 | 0.4617 | 4.2552 |
| 41 | 4.1018 | 1.9028 | 1.1223 | 1.8865 | 97 | 0.9579 | 1.7651 | 0.4569 | 4.2987 |
| 42 | 3.9658 | 1.8990 | 1.0945 | 1.9306 | 98 | 0.9369 | 1.7644 | 0.4521 | 4.3421 |
| 43 | 3.8363 | 1.8953 | 1.0680 | 1.9746 | 99 | 0.9163 | 1.7637 | 0.4475 | 4.3855 |
| 44 | 3.7129 | 1.8917 | 1.0427 | 2.0186 | 100 | 0.8962 | 1.7629 | 0.4429 | 4.4289 |
| 45 | 3.5953 | 1.8881 | 1.0185 | 2.0625 | 101 | 0.8767 | 1.7621 | 0.4384 | 4.4722 |
| 46 | 3.4831 | 1.8846 | 0.9955 | 2.1064 | 102 | 0.8575 | 1.7613 | 0.4340 | 4.5154 |
| 47 | 3.3758 | 1.8811 | 0.9734 | 2.1502 | 103 | 0.8389 | 1.7605 | 0.4297 | 4.5586 |
| 48 | 3.2733 | 1.8778 | 0.9523 | 2.1940 | 104 | 0.8206 | 1.7596 | 0.4255 | 4.6018 |
| 49 | 3.1751 | 1.8745 | 0.9320 | 2.2378 | 105 | 0.8028 | 1.7588 | 0.4213 | 4.6449 |
| 50 | 3.0811 | 1.8712 | 0.9126 | 2.2814 | 106 | 0.7855 | 1.7579 | 0.4172 | 4.6880 |
| 51 | 2.9909 | 1.8680 | 0.8939 | 2.3251 | 107 | 0.7685 | 1.7570 | 0.4132 | 4.7310 |
| 52 | 2.9044 | 1.8649 | 0.8760 | 2.3687 | 108 | 0.7519 | 1.7561 | 0.4093 | 4.7740 |
| 53 | 2.8214 | 1.8618 | 0.8588 | 2.4122 | 109 | 0.7357 | 1.7552 | 0.4054 | 4.8169 |
| 54 | 2.7416 | 1.8587 | 0.8422 | 2.4557 | 110 | 0.7198 | 1.7543 | 0.4016 | 4.8599 |
| 55 | 2.6648 | 1.8558 | 0.8262 | 2.4992 | 111 | 0.7043 | 1.7534 | 0.3979 | 4.9027 |
| 56 | 2.5910 | 1.8528 | 0.8108 | 2.5426 | 112 | 0.6892 | 1.7524 | 0.3943 | 4.9456 |
| 113 | 0.6744 | 1.7515 | 0.3907 | 4.9884 | 132 | 0.4484 | 1.7330 | 0.3327 | 5.7964 |
| 114 | 0.6600 | 1.7505 | 0.3871 | 5.0312 | 133 | 0.4389 | 1.7321 | 0.3301 | 5.8387 |
| 115 | 0.6459 | 1.7496 | 0.3837 | 5.0739 | 134 | 0.4296 | 1.7311 | 0.3275 | 5.8810 |
| 116 | 0.6320 | 1.7486 | 0.3803 | 5.1166 | 135 | 0.4206 | 1.7302 | 0.3250 | 5.9232 |
| 117 | 0.6185 | 1.7477 | 0.3769 | 5.1593 | 136 | 0.4117 | 1.7292 | 0.3225 | 5.9654 |
| 118 | 0.6053 | 1.7467 | 0.3736 | 5.2020 | 137 | 0.4030 | 1.7283 | 0.3201 | 6.0076 |
| 119 | 0.5924 | 1.7457 | 0.3704 | 5.2446 | 138 | 0.3945 | 1.7273 | 0.3177 | 6.0498 |
| 120 | 0.5798 | 1.7447 | 0.3672 | 5.2872 | 139 | 0.3862 | 1.7264 | 0.3153 | 6.0920 |
| 121 | 0.5675 | 1.7438 | 0.3640 | 5.3298 | 140 | 0.3781 | 1.7254 | 0.3130 | 6.1342 |
| 122 | 0.5554 | 1.7428 | 0.3609 | 5.3723 | 141 | 0.3702 | 1.7245 | 0.3107 | 6.1763 |
| 123 | 0.5436 | 1.7418 | 0.3579 | 5.4148 | 142 | 0.3624 | 1.7236 | 0.3084 | 6.2185 |
| 124 | 0.5321 | 1.7408 | 0.3549 | 5.4573 | 143 | 0.3547 | 1.7226 | 0.3062 | 6.2606 |
| 125 | 0.5208 | 1.7399 | 0.3520 | 5.4998 | 144 | 0.3473 | 1.7217 | 0.3039 | 6.3027 |
| 126 | 0.5097 | 1.7389 | 0.3491 | 5.5422 | 145 | 0.3400 | 1.7208 | 0.3018 | 6.3448 |
| 127 | 0.4989 | 1.7379 | 0.3462 | 5.5846 | 146 | 0.3328 | 1.7199 | 0.2996 | 6.3868 |
| 128 | 0.4884 | 1.7369 | 0.3434 | 5.6270 | 147 | 0.3259 | 1.7190 | 0.2975 | 6.4289 |
| 129 | 0.4780 | 1.7360 | 0.3407 | 5.6694 | 148 | 0.3190 | 1.7181 | 0.2954 | 6.4709 |
| 130 | 0.4679 | 1.7350 | 0.3380 | 5.7118 | 149 | 0.3123 | 1.7172 | 0.2934 | 6.5130 |
| 131 | 0.4580 | 1.7340 | 0.3353 | 5.7541 | 150 | 0.3058 | 1.7163 | 0.2913 | 6.5550 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12b**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =3.78

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 190.5772 | 3.7382 | 64.4927 | 0.0645 | 26 | 5.4498 | 3.1668 | 2.2831 | 1.5433 |
| 2 | 93.9049 | 3.6989 | 32.0763 | 0.1283 | 27 | 5.1890 | 3.1537 | 2.1940 | 1.5994 |
| 3 | 61.7511 | 3.6619 | 21.2770 | 0.1915 | 28 | 4.9474 | 3.1410 | 2.1113 | 1.6553 |
| 4 | 45.7086 | 3.6271 | 15.8817 | 0.2541 | 29 | 4.7230 | 3.1287 | 2.0345 | 1.7110 |
| 5 | 36.1035 | 3.5942 | 12.6477 | 0.3162 | 30 | 4.5140 | 3.1167 | 1.9629 | 1.7666 |
| 6 | 29.7137 | 3.5632 | 10.4941 | 0.3778 | 31 | 4.3190 | 3.1051 | 1.8961 | 1.8221 |
| 7 | 25.1593 | 3.5337 | 8.9578 | 0.4389 | 32 | 4.1365 | 3.0938 | 1.8335 | 1.8775 |
| 8 | 21.7508 | 3.5059 | 7.8070 | 0.4997 | 33 | 3.9655 | 3.0827 | 1.7747 | 1.9327 |
| 9 | 19.1053 | 3.4794 | 6.9133 | 0.5600 | 34 | 3.8050 | 3.0720 | 1.7195 | 1.9878 |
| 10 | 16.9935 | 3.4542 | 6.1994 | 0.6199 | 35 | 3.6539 | 3.0616 | 1.6676 | 2.0428 |
| 11 | 15.2694 | 3.4301 | 5.6162 | 0.6796 | 36 | 3.5116 | 3.0514 | 1.6185 | 2.0976 |
| 12 | 13.8357 | 3.4072 | 5.1309 | 0.7389 | 37 | 3.3773 | 3.0414 | 1.5722 | 2.1524 |
| 13 | 12.6252 | 3.3853 | 4.7210 | 0.7978 | 38 | 3.2504 | 3.0317 | 1.5284 | 2.2070 |
| 14 | 11.5899 | 3.3643 | 4.3702 | 0.8566 | 39 | 3.1302 | 3.0222 | 1.4869 | 2.2616 |
| 15 | 10.6946 | 3.3442 | 4.0666 | 0.9150 | 40 | 3.0164 | 3.0130 | 1.4475 | 2.3160 |
| 16 | 9.9129 | 3.3249 | 3.8014 | 0.9732 | 41 | 2.9083 | 3.0039 | 1.4101 | 2.3703 |
| 17 | 9.2247 | 3.3064 | 3.5678 | 1.0311 | 42 | 2.8056 | 2.9951 | 1.3745 | 2.4246 |
| 18 | 8.6143 | 3.2885 | 3.3605 | 1.0888 | 43 | 2.7080 | 2.9864 | 1.3406 | 2.4787 |
| 19 | 8.0694 | 3.2714 | 3.1754 | 1.1463 | 44 | 2.6150 | 2.9780 | 1.3082 | 2.5327 |
| 20 | 7.5800 | 3.2549 | 3.0090 | 1.2036 | 45 | 2.5263 | 2.9697 | 1.2774 | 2.5867 |
| 21 | 7.1382 | 3.2389 | 2.8586 | 1.2607 | 46 | 2.4417 | 2.9615 | 1.2479 | 2.6406 |
| 22 | 6.7375 | 3.2235 | 2.7222 | 1.3175 | 47 | 2.3609 | 2.9536 | 1.2197 | 2.6943 |
| 23 | 6.3724 | 3.2086 | 2.5978 | 1.3743 | 48 | 2.2836 | 2.9458 | 1.1927 | 2.7480 |
| 24 | 6.0386 | 3.1942 | 2.4840 | 1.4308 | 49 | 2.2097 | 2.9381 | 1.1669 | 2.8016 |
| 25 | 5.7321 | 3.1803 | 2.3794 | 1.4871 | 50 | 2.1389 | 2.9306 | 1.1421 | 2.8552 |
| 51 | 2.0711 | 2.9233 | 1.1183 | 2.9086 | 101 | 0.5140 | 2.7126 | 0.5439 | 5.5488 |
| 52 | 2.0060 | 2.9160 | 1.0954 | 2.9620 | 102 | 0.5008 | 2.7099 | 0.5383 | 5.6008 |
| 53 | 1.9435 | 2.9089 | 1.0734 | 3.0152 | 103 | 0.4878 | 2.7071 | 0.5328 | 5.6529 |
| 54 | 1.8840 | 2.9020 | 1.0523 | 3.0685 | 104 | 0.4752 | 2.7043 | 0.5274 | 5.7048 |
| 55 | 1.8268 | 2.8952 | 1.0320 | 3.1217 | 105 | 0.4630 | 2.7016 | 0.5222 | 5.7568 |
| 56 | 1.7719 | 2.8886 | 1.0124 | 3.1748 | 106 | 0.4511 | 2.6989 | 0.5170 | 5.8086 |
| 57 | 1.7190 | 2.8820 | 0.9935 | 3.2278 | 107 | 0.4394 | 2.6961 | 0.5119 | 5.8605 |
| 58 | 1.6682 | 2.8756 | 0.9752 | 3.2807 | 108 | 0.4281 | 2.6934 | 0.5069 | 5.9123 |
| 59 | 1.6192 | 2.8693 | 0.9577 | 3.3336 | 109 | 0.4171 | 2.6907 | 0.5020 | 5.9640 |
| 60 | 1.5720 | 2.8631 | 0.9407 | 3.3865 | 110 | 0.4064 | 2.6880 | 0.4972 | 6.0157 |
| 61 | 1.5265 | 2.8569 | 0.9243 | 3.4392 | 111 | 0.3960 | 2.6853 | 0.4924 | 6.0674 |
| 62 | 1.4826 | 2.8509 | 0.9084 | 3.4919 | 112 | 0.3858 | 2.6826 | 0.4878 | 6.1190 |
| 63 | 1.4402 | 2.8450 | 0.8931 | 3.5446 | 113 | 0.3759 | 2.6800 | 0.4832 | 6.1706 |
| 64 | 1.3993 | 2.8392 | 0.8782 | 3.5971 | 114 | 0.3663 | 2.6774 | 0.4788 | 6.2221 |
| 65 | 1.3597 | 2.8334 | 0.8638 | 3.6496 | 115 | 0.3569 | 2.6747 | 0.4744 | 6.2736 |
| 66 | 1.3215 | 2.8278 | 0.8499 | 3.7021 | 116 | 0.3477 | 2.6721 | 0.4701 | 6.3251 |
| 67 | 1.2845 | 2.8222 | 0.8364 | 3.7545 | 117 | 0.3388 | 2.6696 | 0.4658 | 6.3765 |
| 68 | 1.2488 | 2.8167 | 0.8233 | 3.8068 | 118 | 0.3301 | 2.6670 | 0.4616 | 6.4279 |
| 69 | 1.2142 | 2.8113 | 0.8106 | 3.8591 | 119 | 0.3217 | 2.6644 | 0.4575 | 6.4793 |
| 70 | 1.1807 | 2.8060 | 0.7982 | 3.9113 | 120 | 0.3134 | 2.6619 | 0.4535 | 6.5307 |
| 71 | 1.1482 | 2.8008 | 0.7862 | 3.9635 | 121 | 0.3054 | 2.6594 | 0.4496 | 6.5820 |
| 72 | 1.1168 | 2.7956 | 0.7746 | 4.0156 | 122 | 0.2976 | 2.6569 | 0.4457 | 6.6333 |
| 73 | 1.0863 | 2.7905 | 0.7633 | 4.0676 | 123 | 0.2900 | 2.6544 | 0.4418 | 6.6845 |
| 74 | 1.0568 | 2.7855 | 0.7523 | 4.1196 | 124 | 0.2826 | 2.6520 | 0.4381 | 6.7358 |
| 75 | 1.0282 | 2.7805 | 0.7416 | 4.1716 | 125 | 0.2754 | 2.6496 | 0.4344 | 6.7870 |
| 76 | 1.0004 | 2.7756 | 0.7312 | 4.2235 | 126 | 0.2683 | 2.6472 | 0.4307 | 6.8382 |
| 77 | 0.9735 | 2.7737 | 0.7215 | 4.2776 | 127 | 0.2615 | 2.6448 | 0.4271 | 6.8893 |
| 78 | 0.9474 | 2.7717 | 0.7120 | 4.3316 | 128 | 0.2548 | 2.6424 | 0.4236 | 6.9405 |
| 79 | 0.9220 | 2.7696 | 0.7027 | 4.3855 | 129 | 0.2483 | 2.6401 | 0.4201 | 6.9916 |

**TABLE 12b (continued)**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =3.78

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 0.8974 | 2.7675 | 0.6936 | 4.4393 | 130 | 0.2420 | 2.6378 | 0.4167 | 7.0427 |
| 81 | 0.8735 | 2.7653 | 0.6848 | 4.4929 | 131 | 0.2358 | 2.6355 | 0.4134 | 7.0938 |
| 82 | 0.8503 | 2.7630 | 0.6762 | 4.5465 | 132 | 0.2298 | 2.6332 | 0.4101 | 7.1449 |
| 83 | 0.8277 | 2.7606 | 0.6677 | 4.6000 | 133 | 0.2239 | 2.6309 | 0.4068 | 7.1959 |
| 84 | 0.8058 | 2.7582 | 0.6595 | 4.6534 | 134 | 0.2182 | 2.6287 | 0.4036 | 7.2469 |
| 85 | 0.7845 | 2.7557 | 0.6514 | 4.7067 | 135 | 0.2126 | 2.6265 | 0.4004 | 7.2980 |
| 86 | 0.7639 | 2.7532 | 0.6436 | 4.7599 | 136 | 0.2072 | 2.6243 | 0.3973 | 7.3490 |
| 87 | 0.7438 | 2.7506 | 0.6359 | 4.8130 | 137 | 0.2019 | 2.6221 | 0.3943 | 7.3999 |
| 88 | 0.7242 | 2.7481 | 0.6284 | 4.8660 | 138 | 0.1968 | 2.6200 | 0.3912 | 7.4509 |
| 89 | 0.7052 | 2.7454 | 0.6210 | 4.9190 | 139 | 0.1917 | 2.6179 | 0.3883 | 7.5019 |
| 90 | 0.6868 | 2.7428 | 0.6138 | 4.9718 | 140 | 0.1869 | 2.6158 | 0.3853 | 7.5528 |
| 91 | 0.6688 | 2.7401 | 0.6068 | 5.0246 | 141 | 0.1821 | 2.6137 | 0.3825 | 7.6037 |
| 92 | 0.6513 | 2.7374 | 0.5999 | 5.0773 | 142 | 0.1775 | 2.6116 | 0.3796 | 7.6546 |
| 93 | 0.6344 | 2.7347 | 0.5931 | 5.1300 | 143 | 0.1729 | 2.6096 | 0.3768 | 7.7055 |
| 94 | 0.6178 | 2.7320 | 0.5865 | 5.1826 | 144 | 0.1685 | 2.6076 | 0.3741 | 7.7564 |
| 95 | 0.6018 | 2.7292 | 0.5801 | 5.2351 | 145 | 0.1642 | 2.6056 | 0.3713 | 7.8073 |
| 96 | 0.5861 | 2.7265 | 0.5737 | 5.2875 | 146 | 0.1600 | 2.6036 | 0.3687 | 7.8582 |
| 97 | 0.5709 | 2.7237 | 0.5675 | 5.3399 | 147 | 0.1560 | 2.6017 | 0.3660 | 7.9091 |
| 98 | 0.5561 | 2.7209 | 0.5615 | 5.3922 | 148 | 0.1520 | 2.5998 | 0.3634 | 7.9599 |
| 99 | 0.5417 | 2.7182 | 0.5555 | 5.4444 | 149 | 0.1481 | 2.5979 | 0.3608 | 8.0108 |
| 100 | 0.5277 | 2.7154 | 0.5497 | 5.4966 | 150 | 0.1444 | 2.5960 | 0.3583 | 8.0616 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12c**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =5.75

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 154.1545 | 5.6626 | 79.3758 | 0.0794 | 55 | 1.3098 | 4.1200 | 1.2310 | 3.7239 |
| 2 | 75.8057 | 5.5818 | 39.4035 | 0.1576 | 56 | 1.2664 | 4.1088 | 1.2074 | 3.7864 |
| 3 | 49.7547 | 5.5068 | 26.0920 | 0.2348 | 57 | 1.2248 | 4.0978 | 1.1846 | 3.8488 |
| 4 | 36.7611 | 5.4372 | 19.4449 | 0.3111 | 58 | 1.1847 | 4.0869 | 1.1627 | 3.9112 |
| 5 | 28.9839 | 5.3723 | 15.4628 | 0.3866 | 59 | 1.1461 | 4.0763 | 1.1415 | 3.9734 |
| 6 | 23.8117 | 5.3116 | 12.8127 | 0.4613 | 60 | 1.1089 | 4.0658 | 1.1210 | 4.0355 |
| 7 | 20.1263 | 5.2548 | 10.9235 | 0.5352 | 61 | 1.0731 | 4.0555 | 1.1012 | 4.0976 |
| 8 | 17.3689 | 5.2014 | 9.5094 | 0.6086 | 62 | 1.0386 | 4.0453 | 1.0821 | 4.1596 |
| 9 | 15.2296 | 5.1512 | 8.4118 | 0.6814 | 63 | 1.0054 | 4.0353 | 1.0636 | 4.2214 |
| 10 | 13.5223 | 5.1037 | 7.5357 | 0.7536 | 64 | 0.9733 | 4.0305 | 1.0464 | 4.2859 |
| 11 | 12.1289 | 5.0589 | 6.8204 | 0.8253 | 65 | 0.9423 | 4.0265 | 1.0297 | 4.3507 |
| 12 | 10.9706 | 5.0163 | 6.2257 | 0.8965 | 66 | 0.9124 | 4.0222 | 1.0136 | 4.4153 |
| 13 | 9.9929 | 4.9759 | 5.7236 | 0.9673 | 67 | 0.8836 | 4.0178 | 0.9979 | 4.4797 |
| 14 | 9.1570 | 4.9375 | 5.2942 | 1.0377 | 68 | 0.8557 | 4.0132 | 0.9827 | 4.5439 |
| 15 | 8.4343 | 4.9008 | 4.9229 | 1.1077 | 69 | 0.8288 | 4.0084 | 0.9679 | 4.6080 |
| 16 | 7.8035 | 4.8659 | 4.5987 | 1.1773 | 70 | 0.8028 | 4.0035 | 0.9535 | 4.6719 |
| 17 | 7.2484 | 4.8324 | 4.3133 | 1.2466 | 71 | 0.7777 | 3.9985 | 0.9394 | 4.7357 |
| 18 | 6.7562 | 4.8004 | 4.0602 | 1.3155 | 72 | 0.7534 | 3.9933 | 0.9258 | 4.7993 |
| 19 | 6.3169 | 4.7697 | 3.8342 | 1.3841 | 73 | 0.7299 | 3.9881 | 0.9125 | 4.8628 |
| 20 | 5.9225 | 4.7403 | 3.6312 | 1.4525 | 74 | 0.7072 | 3.9828 | 0.8996 | 4.9261 |
| 21 | 5.5666 | 4.7119 | 3.4479 | 1.5205 | 75 | 0.6853 | 3.9774 | 0.8870 | 4.9893 |
| 22 | 5.2438 | 4.6847 | 3.2817 | 1.5883 | 76 | 0.6641 | 3.9720 | 0.8747 | 5.0524 |
| 23 | 4.9499 | 4.6584 | 3.1302 | 1.6559 | 77 | 0.6435 | 3.9665 | 0.8628 | 5.1153 |
| 24 | 4.6812 | 4.6331 | 2.9916 | 1.7232 | 78 | 0.6236 | 3.9609 | 0.8511 | 5.1781 |
| 25 | 4.4346 | 4.6087 | 2.8644 | 1.7902 | 79 | 0.6044 | 3.9554 | 0.8397 | 5.2408 |

**TABLE 12c (continued)**    Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =5.75

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 26 | 4.2075 | 4.5851 | 2.7471 | 1.8571 | 80 | 0.5858 | 3.9498 | 0.8287 | 5.3034 |
| 27 | 3.9979 | 4.5623 | 2.6388 | 1.9237 | 81 | 0.5678 | 3.9442 | 0.8178 | 5.3659 |
| 28 | 3.8037 | 4.5402 | 2.5384 | 1.9901 | 82 | 0.5503 | 3.9386 | 0.8073 | 5.4283 |
| 29 | 3.6233 | 4.5187 | 2.4451 | 2.0563 | 83 | 0.5334 | 3.9329 | 0.7970 | 5.4905 |
| 30 | 3.4554 | 4.4980 | 2.3581 | 2.1223 | 84 | 0.5171 | 3.9273 | 0.7870 | 5.5527 |
| 31 | 3.2988 | 4.4778 | 2.2769 | 2.1881 | 85 | 0.5012 | 3.9217 | 0.7771 | 5.6148 |
| 32 | 3.1523 | 4.4583 | 2.2010 | 2.2538 | 86 | 0.4859 | 3.9161 | 0.7676 | 5.6768 |
| 33 | 3.0151 | 4.4393 | 2.1297 | 2.3193 | 87 | 0.4710 | 3.9105 | 0.7582 | 5.7387 |
| 34 | 2.8863 | 4.4208 | 2.0628 | 2.3846 | 88 | 0.4566 | 3.9049 | 0.7490 | 5.8005 |
| 35 | 2.7652 | 4.4028 | 1.9997 | 2.4497 | 89 | 0.4427 | 3.8994 | 0.7401 | 5.8623 |
| 36 | 2.6511 | 4.3853 | 1.9403 | 2.5147 | 90 | 0.4292 | 3.8938 | 0.7314 | 5.9239 |
| 37 | 2.5434 | 4.3682 | 1.8842 | 2.5795 | 91 | 0.4161 | 3.8883 | 0.7228 | 5.9855 |
| 38 | 2.4417 | 4.3516 | 1.8311 | 2.6441 | 92 | 0.4034 | 3.8829 | 0.7144 | 6.0470 |
| 39 | 2.3455 | 4.3353 | 1.7808 | 2.7087 | 93 | 0.3912 | 3.8774 | 0.7063 | 6.1085 |
| 40 | 2.2543 | 4.3195 | 1.7331 | 2.7730 | 94 | 0.3793 | 3.8720 | 0.6983 | 6.1699 |
| 41 | 2.1678 | 4.3040 | 1.6878 | 2.8373 | 95 | 0.3677 | 3.8667 | 0.6904 | 6.2312 |
| 42 | 2.0856 | 4.2889 | 1.6448 | 2.9014 | 96 | 0.3565 | 3.8614 | 0.6828 | 6.2925 |
| 43 | 2.0075 | 4.2741 | 1.6037 | 2.9653 | 97 | 0.3457 | 3.8561 | 0.6753 | 6.3537 |
| 44 | 1.9289 | 4.2588 | 1.5645 | 3.0288 | 98 | 0.3352 | 3.8508 | 0.6679 | 6.4148 |
| 45 | 1.8591 | 4.2449 | 1.5272 | 3.0926 | 99 | 0.3250 | 3.8456 | 0.6607 | 6.4759 |
| 46 | 1.7926 | 4.2312 | 1.4916 | 3.1562 | 100 | 0.3152 | 3.8405 | 0.6537 | 6.5369 |
| 47 | 1.7291 | 4.2178 | 1.4576 | 3.2198 | 101 | 0.3056 | 3.8354 | 0.6468 | 6.5979 |
| 48 | 1.6684 | 4.2048 | 1.4250 | 3.2832 | 102 | 0.2963 | 3.8304 | 0.6400 | 6.6588 |
| 49 | 1.6104 | 4.1919 | 1.3938 | 3.3464 | 103 | 0.2874 | 3.8254 | 0.6334 | 6.7197 |
| 50 | 1.5549 | 4.1794 | 1.3638 | 3.4096 | 104 | 0.2787 | 3.8204 | 0.6269 | 6.7806 |
| 51 | 1.5017 | 4.1671 | 1.3351 | 3.4727 | 105 | 0.2702 | 3.8155 | 0.6205 | 6.8414 |
| 52 | 1.4507 | 4.1550 | 1.3076 | 3.5356 | 106 | 0.2620 | 3.8107 | 0.6143 | 6.9022 |
| 53 | 1.4018 | 4.1431 | 1.2811 | 3.5985 | 107 | 0.2541 | 3.8059 | 0.6082 | 6.9629 |
| 54 | 1.3549 | 4.1315 | 1.2556 | 3.6612 | 108 | 0.2464 | 3.8011 | 0.6022 | 7.0236 |
| 109 | 0.2389 | 3.7964 | 0.5963 | 7.0842 | 130 | 0.1255 | 3.7101 | 0.4942 | 8.3525 |
| 110 | 0.2317 | 3.7918 | 0.5905 | 7.1449 | 131 | 0.1217 | 3.7065 | 0.4902 | 8.4127 |
| 111 | 0.2247 | 3.7872 | 0.5848 | 7.2055 | 132 | 0.1180 | 3.7030 | 0.4863 | 8.4729 |
| 112 | 0.2179 | 3.7827 | 0.5792 | 7.2660 | 133 | 0.1144 | 3.6996 | 0.4824 | 8.5331 |
| 113 | 0.2113 | 3.7782 | 0.5738 | 7.3265 | 134 | 0.1110 | 3.6962 | 0.4786 | 8.5933 |
| 114 | 0.2049 | 3.7738 | 0.5684 | 7.3871 | 135 | 0.1076 | 3.6928 | 0.4748 | 8.6535 |
| 115 | 0.1987 | 3.7694 | 0.5631 | 7.4475 | 136 | 0.1044 | 3.6895 | 0.4711 | 8.7137 |
| 116 | 0.1927 | 3.7651 | 0.5580 | 7.5080 | 137 | 0.1012 | 3.6863 | 0.4675 | 8.7739 |
| 117 | 0.1869 | 3.7608 | 0.5529 | 7.5684 | 138 | 0.0982 | 3.6830 | 0.4639 | 8.8341 |
| 118 | 0.1813 | 3.7566 | 0.5479 | 7.6288 | 139 | 0.0952 | 3.6799 | 0.4603 | 8.8943 |
| 119 | 0.1758 | 3.7524 | 0.5430 | 7.6892 | 140 | 0.0923 | 3.6767 | 0.4569 | 8.9544 |
| 120 | 0.1705 | 3.7483 | 0.5382 | 7.7496 | 141 | 0.0896 | 3.6737 | 0.4534 | 9.0146 |
| 121 | 0.1653 | 3.7443 | 0.5334 | 7.8099 | 142 | 0.0869 | 3.6706 | 0.4500 | 9.0748 |
| 122 | 0.1603 | 3.7403 | 0.5288 | 7.8703 | 143 | 0.0842 | 3.6676 | 0.4467 | 9.1350 |
| 123 | 0.1555 | 3.7363 | 0.5242 | 7.9306 | 144 | 0.0817 | 3.6647 | 0.4434 | 9.1952 |
| 124 | 0.1508 | 3.7324 | 0.5197 | 7.9909 | 145 | 0.0792 | 3.6618 | 0.4402 | 9.2553 |
| 125 | 0.1462 | 3.7286 | 0.5153 | 8.0512 | 146 | 0.0768 | 3.6589 | 0.4370 | 9.3155 |
| 126 | 0.1418 | 3.7248 | 0.5109 | 8.1115 | 147 | 0.0745 | 3.6561 | 0.4339 | 9.3757 |
| 127 | 0.1375 | 3.7210 | 0.5066 | 8.1717 | 148 | 0.0723 | 3.6533 | 0.4308 | 9.4359 |
| 128 | 0.1334 | 3.7173 | 0.5024 | 8.2320 | 149 | 0.0701 | 3.6505 | 0.4277 | 9.4961 |
| 129 | 0.1294 | 3.7137 | 0.4983 | 8.2922 | 150 | 0.0680 | 3.6478 | 0.4247 | 9.5562 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:*  Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12d** Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 9.4

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 120.1221 | 9.2047 | 101.2010 | 0.1012 | 24 | 3.4066 | 7.1750 | 3.7229 | 2.1444 |
| 2 | 58.8859 | 9.0280 | 50.1125 | 0.2004 | 25 | 3.2161 | 7.1309 | 3.5630 | 2.2269 |
| 3 | 38.5353 | 8.8676 | 33.1101 | 0.2980 | 26 | 3.0409 | 7.0885 | 3.4157 | 2.3090 |
| 4 | 28.3901 | 8.7212 | 24.6268 | 0.3940 | 27 | 2.8791 | 7.0475 | 3.2797 | 2.3909 |
| 5 | 22.3208 | 8.5871 | 19.5493 | 0.4887 | 28 | 2.7293 | 7.0079 | 3.1537 | 2.4725 |
| 6 | 18.2864 | 8.4635 | 16.1735 | 0.5822 | 29 | 2.5902 | 6.9697 | 3.0366 | 2.5538 |
| 7 | 15.4132 | 8.3493 | 13.7691 | 0.6747 | 30 | 2.4609 | 6.9326 | 2.9276 | 2.6348 |
| 8 | 13.2647 | 8.2433 | 11.9712 | 0.7662 | 31 | 2.3403 | 6.8967 | 2.8258 | 2.7156 |
| 9 | 11.5985 | 8.1445 | 10.5771 | 0.8567 | 32 | 2.2275 | 6.8619 | 2.7306 | 2.7961 |
| 10 | 10.2695 | 8.0521 | 9.4653 | 0.9465 | 33 | 2.1220 | 6.8281 | 2.6413 | 2.8764 |
| 11 | 9.1854 | 7.9655 | 8.5584 | 1.0356 | 34 | 2.0229 | 6.7952 | 2.5574 | 2.9564 |
| 12 | 8.2846 | 7.8841 | 7.8050 | 1.1239 | 35 | 1.9221 | 6.7606 | 2.4780 | 3.0356 |
| 13 | 7.5248 | 7.8074 | 7.1695 | 1.2116 | 36 | 1.8364 | 6.7301 | 2.4037 | 3.1152 |
| 14 | 6.8754 | 7.7348 | 6.6264 | 1.2988 | 37 | 1.7556 | 6.7004 | 2.3336 | 3.1947 |
| 15 | 6.3143 | 7.6661 | 6.1571 | 1.3853 | 38 | 1.6792 | 6.6715 | 2.2673 | 3.2740 |
| 16 | 5.8248 | 7.6009 | 5.7477 | 1.4714 | 39 | 1.6070 | 6.6434 | 2.2045 | 3.3530 |
| 17 | 5.3942 | 7.5389 | 5.3875 | 1.5570 | 40 | 1.5386 | 6.6159 | 2.1449 | 3.4319 |
| 18 | 5.0126 | 7.4798 | 5.0682 | 1.6421 | 41 | 1.4738 | 6.5891 | 2.0884 | 3.5105 |
| 19 | 4.6722 | 7.4234 | 4.7833 | 1.7268 | 42 | 1.4122 | 6.5629 | 2.0346 | 3.5890 |
| 20 | 4.3668 | 7.3694 | 4.5276 | 1.8110 | 43 | 1.3537 | 6.5373 | 1.9834 | 3.6673 |
| 21 | 4.0913 | 7.3178 | 4.2968 | 1.8949 | 44 | 1.2981 | 6.5122 | 1.9346 | 3.7454 |
| 22 | 3.8416 | 7.2683 | 4.0876 | 1.9784 | 45 | 1.2451 | 6.4877 | 1.8880 | 3.8233 |
| 23 | 3.6143 | 7.2207 | 3.8971 | 2.0616 | 46 | 1.1946 | 6.4638 | 1.8436 | 3.9010 |
| 47 | 1.1465 | 6.4403 | 1.8011 | 3.9786 | 99 | 0.1530 | 5.8352 | 0.8139 | 7.9771 |
| 48 | 1.1005 | 6.4173 | 1.7604 | 4.0560 | 100 | 0.1472 | 5.8268 | 0.8052 | 8.0518 |
| 49 | 1.0567 | 6.3948 | 1.7215 | 4.1332 | 101 | 0.1417 | 5.8184 | 0.7966 | 8.1265 |
| 50 | 1.0148 | 6.3728 | 1.6841 | 4.2103 | 102 | 0.1365 | 5.8102 | 0.7883 | 8.2012 |
| 51 | 0.9747 | 6.3596 | 1.6494 | 4.2901 | 103 | 0.1314 | 5.8021 | 0.7801 | 8.2758 |
| 52 | 0.9364 | 6.3507 | 1.6165 | 4.3711 | 104 | 0.1265 | 5.7942 | 0.7720 | 8.3504 |
| 53 | 0.8997 | 6.3412 | 1.5849 | 4.4519 | 105 | 0.1217 | 5.7864 | 0.7642 | 8.4251 |
| 54 | 0.8646 | 6.3312 | 1.5543 | 4.5323 | 106 | 0.1172 | 5.7787 | 0.7565 | 8.4997 |
| 55 | 0.8309 | 6.3208 | 1.5248 | 4.6124 | 107 | 0.1128 | 5.7712 | 0.7489 | 8.5742 |
| 56 | 0.7987 | 6.3100 | 1.4963 | 4.6923 | 108 | 0.1086 | 5.7638 | 0.7415 | 8.6488 |
| 57 | 0.7678 | 6.2989 | 1.4687 | 4.7719 | 109 | 0.1046 | 5.7565 | 0.7342 | 8.7234 |
| 58 | 0.7382 | 6.2875 | 1.4421 | 4.8512 | 110 | 0.1006 | 5.7493 | 0.7271 | 8.7979 |
| 59 | 0.7098 | 6.2759 | 1.4163 | 4.9303 | 111 | 0.0969 | 5.7423 | 0.7201 | 8.8725 |
| 60 | 0.6826 | 6.2641 | 1.3914 | 5.0091 | 112 | 0.0933 | 5.7354 | 0.7133 | 8.9470 |
| 61 | 0.6564 | 6.2521 | 1.3673 | 5.0877 | 113 | 0.0898 | 5.7286 | 0.7065 | 9.0216 |
| 62 | 0.6313 | 6.2400 | 1.3439 | 5.1661 | 114 | 0.0864 | 5.7219 | 0.6999 | 9.0961 |
| 63 | 0.6072 | 6.2278 | 1.3213 | 5.2443 | 115 | 0.0832 | 5.7154 | 0.6934 | 9.1707 |
| 64 | 0.5841 | 6.2156 | 1.2994 | 5.3223 | 116 | 0.0801 | 5.7090 | 0.6871 | 9.2452 |
| 65 | 0.5619 | 6.2032 | 1.2781 | 5.4001 | 117 | 0.0771 | 5.7026 | 0.6808 | 9.3197 |
| 66 | 0.5406 | 6.1909 | 1.2575 | 5.4777 | 118 | 0.0743 | 5.6964 | 0.6747 | 9.3943 |
| 67 | 0.5201 | 6.1786 | 1.2375 | 5.5552 | 119 | 0.0715 | 5.6903 | 0.6687 | 9.4688 |
| 68 | 0.5004 | 6.1662 | 1.2181 | 5.6325 | 120 | 0.0688 | 5.6843 | 0.6627 | 9.5434 |
| 69 | 0.4814 | 6.1539 | 1.1992 | 5.7096 | 121 | 0.0662 | 5.6785 | 0.6569 | 9.6179 |
| 70 | 0.4632 | 6.1417 | 1.1809 | 5.7866 | 122 | 0.0638 | 5.6727 | 0.6512 | 9.6925 |
| 71 | 0.4457 | 6.1295 | 1.1631 | 5.8634 | 123 | 0.0614 | 5.6670 | 0.6456 | 9.7670 |
| 72 | 0.4289 | 6.1173 | 1.1458 | 5.9401 | 124 | 0.0591 | 5.6615 | 0.6401 | 9.8416 |
| 73 | 0.4127 | 6.1053 | 1.1290 | 6.0166 | 125 | 0.0569 | 5.6560 | 0.6346 | 9.9162 |
| 74 | 0.3972 | 6.0933 | 1.1127 | 6.0931 | 126 | 0.0548 | 5.6506 | 0.6293 | 9.9907 |
| 75 | 0.3822 | 6.0814 | 1.0968 | 6.1694 | 127 | 0.0527 | 5.6454 | 0.6241 | 10.0653 |
| 76 | 0.3679 | 6.0696 | 1.0813 | 6.2456 | 128 | 0.0508 | 5.6402 | 0.6189 | 10.1399 |
| 77 | 0.3540 | 6.0579 | 1.0662 | 6.3217 | 129 | 0.0489 | 5.6351 | 0.6138 | 10.2146 |
| 78 | 0.3407 | 6.0464 | 1.0516 | 6.3977 | 130 | 0.0471 | 5.6301 | 0.6088 | 10.2892 |
| 79 | 0.3279 | 6.0350 | 1.0373 | 6.4736 | 131 | 0.0453 | 5.6252 | 0.6039 | 10.3638 |

TABLE 12d (continued)  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL
Capacitance and Inductance for Er = 9.4

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 0.3156 | 6.0236 | 1.0233 | 6.5494 | 132 | 0.0436 | 5.6204 | 0.5991 | 10.4385 |
| 81 | 0.3038 | 6.0125 | 1.0098 | 6.6251 | 133 | 0.0420 | 5.6157 | 0.5943 | 10.5131 |
| 82 | 0.2924 | 6.0014 | 0.9965 | 6.7007 | 134 | 0.0404 | 5.6111 | 0.5897 | 10.5878 |
| 83 | 0.2815 | 5.9905 | 0.9836 | 6.7762 | 135 | 0.0389 | 5.6065 | 0.5850 | 10.6625 |
| 84 | 0.2709 | 5.9797 | 0.9710 | 6.8517 | 136 | 0.0375 | 5.6021 | 0.5805 | 10.7372 |
| 85 | 0.2608 | 5.9691 | 0.9588 | 6.9271 | 137 | 0.0361 | 5.5977 | 0.5761 | 10.8119 |
| 86 | 0.2510 | 5.9586 | 0.9468 | 7.0024 | 138 | 0.0347 | 5.5934 | 0.5717 | 10.8867 |
| 87 | 0.2416 | 5.9482 | 0.9351 | 7.0777 | 139 | 0.0334 | 5.5892 | 0.5673 | 10.9614 |
| 88 | 0.2326 | 5.9380 | 0.9237 | 7.1529 | 140 | 0.0322 | 5.5850 | 0.5631 | 11.0362 |
| 89 | 0.2239 | 5.9280 | 0.9125 | 7.2281 | 141 | 0.0310 | 5.5809 | 0.5589 | 11.1110 |
| 90 | 0.2155 | 5.9180 | 0.9016 | 7.3032 | 142 | 0.0298 | 5.5770 | 0.5547 | 11.1858 |
| 91 | 0.2074 | 5.9083 | 0.8910 | 7.3782 | 143 | 0.0287 | 5.5730 | 0.5507 | 11.2606 |
| 92 | 0.1997 | 5.8986 | 0.8806 | 7.4532 | 144 | 0.0276 | 5.5692 | 0.5467 | 11.3354 |
| 93 | 0.1922 | 5.8891 | 0.8704 | 7.5281 | 145 | 0.0266 | 5.5654 | 0.5427 | 11.4103 |
| 94 | 0.1850 | 5.8798 | 0.8605 | 7.6031 | 146 | 0.0256 | 5.5617 | 0.5388 | 11.4852 |
| 95 | 0.1781 | 5.8706 | 0.8507 | 7.6779 | 147 | 0.0247 | 5.5581 | 0.5350 | 11.5600 |
| 96 | 0.1715 | 5.8616 | 0.8412 | 7.7528 | 148 | 0.0237 | 5.5545 | 0.5312 | 11.6350 |
| 97 | 0.1651 | 5.8526 | 0.8319 | 7.8276 | 149 | 0.0229 | 5.5510 | 0.5274 | 11.7099 |
| 98 | 0.1589 | 5.8439 | 0.8228 | 7.9023 | 150 | 0.0220 | 5.5476 | 0.5238 | 11.7848 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P.*, Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

TABLE 12e  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance
and Inductance for Er = 9.8

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 117.6023 | 9.5914 | 103.3045 | 0.1033 | 57 | 0.7347 | 6.5379 | 1.4963 | 4.8615 |
| 2 | 57.6329 | 9.4030 | 51.1424 | 0.2046 | 58 | 0.7059 | 6.5254 | 1.4691 | 4.9421 |
| 3 | 37.7044 | 9.2322 | 33.7840 | 0.3041 | 59 | 0.6783 | 6.5128 | 1.4428 | 5.0224 |
| 4 | 27.7700 | 9.0767 | 25.1237 | 0.4020 | 60 | 0.6519 | 6.5000 | 1.4174 | 5.1025 |
| 5 | 21.8272 | 8.9344 | 19.9408 | 0.4985 | 61 | 0.6265 | 6.4870 | 1.3927 | 5.1824 |
| 6 | 17.8771 | 8.8035 | 16.4952 | 0.5938 | 62 | 0.6022 | 6.4740 | 1.3689 | 5.2621 |
| 7 | 15.0641 | 8.6827 | 14.0413 | 0.6880 | 63 | 0.5788 | 6.4609 | 1.3458 | 5.3415 |
| 8 | 12.9606 | 8.5706 | 12.2066 | 0.7812 | 64 | 0.5564 | 6.4477 | 1.3234 | 5.4208 |
| 9 | 11.3295 | 8.4662 | 10.7841 | 0.8735 | 65 | 0.5349 | 6.4346 | 1.3017 | 5.4999 |
| 10 | 10.0285 | 8.3688 | 9.6496 | 0.9650 | 66 | 0.5142 | 6.4214 | 1.2807 | 5.5788 |
| 11 | 8.9673 | 8.2775 | 8.7244 | 1.0557 | 67 | 0.4944 | 6.4082 | 1.2603 | 5.6575 |
| 12 | 8.0857 | 8.1917 | 7.9558 | 1.1456 | 68 | 0.4753 | 6.3951 | 1.2405 | 5.7360 |
| 13 | 7.3419 | 8.1109 | 7.3075 | 1.2350 | 69 | 0.4570 | 6.3820 | 1.2213 | 5.8144 |
| 14 | 6.7063 | 8.0345 | 6.7535 | 1.3237 | 70 | 0.4395 | 6.3690 | 1.2026 | 5.8927 |
| 15 | 6.1572 | 7.9622 | 6.2749 | 1.4118 | 71 | 0.4226 | 6.3561 | 1.1844 | 5.9708 |
| 16 | 5.6782 | 7.8937 | 5.8573 | 1.4995 | 72 | 0.4064 | 6.3432 | 1.1668 | 6.0488 |
| 17 | 5.2568 | 7.8285 | 5.4900 | 1.5866 | 73 | 0.3908 | 6.3305 | 1.1497 | 6.1266 |
| 18 | 4.8834 | 7.7664 | 5.1644 | 1.6733 | 74 | 0.3758 | 6.3179 | 1.1330 | 6.2043 |
| 19 | 4.5503 | 7.7071 | 4.8738 | 1.7595 | 75 | 0.3614 | 6.3053 | 1.1168 | 6.2820 |
| 20 | 4.2515 | 7.6505 | 4.6131 | 1.8452 | 76 | 0.3476 | 6.2929 | 1.1010 | 6.3595 |
| 21 | 3.9820 | 7.5963 | 4.3778 | 1.9306 | 77 | 0.3343 | 6.2807 | 1.0857 | 6.4368 |
| 22 | 3.7377 | 7.5443 | 4.1645 | 2.0156 | 78 | 0.3215 | 6.2685 | 1.0707 | 6.5141 |
| 23 | 3.5154 | 7.4944 | 3.9703 | 2.1003 | 79 | 0.3092 | 6.2565 | 1.0561 | 6.5913 |
| 24 | 3.3122 | 7.4464 | 3.7926 | 2.1846 | 80 | 0.2974 | 6.2447 | 1.0419 | 6.6684 |
| 25 | 3.1259 | 7.4002 | 3.6296 | 2.2685 | 81 | 0.2860 | 6.2329 | 1.0281 | 6.7455 |

**TABLE 12e (continued)**   Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 9.8

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 26 | 2.9545 | 7.3557 | 3.4795 | 2.3522 | 82 | 0.2751 | 6.2214 | 1.0146 | 6.8224 |
| 27 | 2.7962 | 7.3128 | 3.3408 | 2.4355 | 83 | 0.2646 | 6.2100 | 1.0015 | 6.8993 |
| 28 | 2.6497 | 7.2713 | 3.2124 | 2.5185 | 84 | 0.2545 | 6.1987 | 0.9887 | 6.9760 |
| 29 | 2.5138 | 7.2312 | 3.0930 | 2.6012 | 85 | 0.2448 | 6.1876 | 0.9762 | 7.0528 |
| 30 | 2.3873 | 7.1923 | 2.9819 | 2.6837 | 86 | 0.2355 | 6.1766 | 0.9640 | 7.1294 |
| 31 | 2.2693 | 7.1547 | 2.8781 | 2.7659 | 87 | 0.2265 | 6.1658 | 0.9520 | 7.2060 |
| 32 | 2.1591 | 7.1182 | 2.7811 | 2.8478 | 88 | 0.2179 | 6.1552 | 0.9404 | 7.2825 |
| 33 | 2.0558 | 7.0827 | 2.6901 | 2.9295 | 89 | 0.2096 | 6.1447 | 0.9291 | 7.3590 |
| 34 | 1.9590 | 7.0483 | 2.6046 | 3.0109 | 90 | 0.2016 | 6.1344 | 0.9180 | 7.4355 |
| 35 | 1.8614 | 7.0124 | 2.5237 | 3.0916 | 91 | 0.1939 | 6.1242 | 0.9071 | 7.5118 |
| 36 | 1.7777 | 6.9805 | 2.4480 | 3.1727 | 92 | 0.1865 | 6.1142 | 0.8965 | 7.5882 |
| 37 | 1.6987 | 6.9494 | 2.3766 | 3.2535 | 93 | 0.1794 | 6.1044 | 0.8862 | 7.6645 |
| 38 | 1.6241 | 6.9191 | 2.3090 | 3.3342 | 94 | 0.1726 | 6.0947 | 0.8760 | 7.7408 |
| 39 | 1.5535 | 6.8896 | 2.2450 | 3.4146 | 95 | 0.1660 | 6.0852 | 0.8661 | 7.8170 |
| 40 | 1.4867 | 6.8609 | 2.1843 | 3.4948 | 96 | 0.1597 | 6.0758 | 0.8565 | 7.8932 |
| 41 | 1.4233 | 6.8328 | 2.1266 | 3.5749 | 97 | 0.1536 | 6.0666 | 0.8470 | 7.9693 |
| 42 | 1.3632 | 6.8053 | 2.0718 | 3.6547 | 98 | 0.1478 | 6.0575 | 0.8377 | 8.0455 |
| 43 | 1.3060 | 6.7785 | 2.0197 | 3.7343 | 99 | 0.1422 | 6.0486 | 0.8286 | 8.1216 |
| 44 | 1.2517 | 6.7523 | 1.9699 | 3.8138 | 100 | 0.1368 | 6.0398 | 0.8198 | 8.1977 |
| 45 | 1.1999 | 6.7266 | 1.9225 | 3.8931 | 101 | 0.1316 | 6.0312 | 0.8111 | 8.2737 |
| 46 | 1.1507 | 6.7015 | 1.8772 | 3.9721 | 102 | 0.1266 | 6.0227 | 0.8026 | 8.3498 |
| 47 | 1.1037 | 6.6770 | 1.8339 | 4.0510 | 103 | 0.1217 | 6.0143 | 0.7942 | 8.4258 |
| 48 | 1.0588 | 6.6529 | 1.7924 | 4.1298 | 104 | 0.1171 | 6.0062 | 0.7860 | 8.5018 |
| 49 | 1.0161 | 6.6293 | 1.7527 | 4.2083 | 105 | 0.1127 | 5.9981 | 0.7780 | 8.5778 |
| 50 | 0.9752 | 6.6149 | 1.7158 | 4.2895 | 106 | 0.1084 | 5.9902 | 0.7702 | 8.6538 |
| 51 | 0.9361 | 6.6054 | 1.6810 | 4.3722 | 107 | 0.1043 | 5.9824 | 0.7625 | 8.7298 |
| 52 | 0.8988 | 6.5953 | 1.6474 | 4.4545 | 108 | 0.1003 | 5.9748 | 0.7549 | 8.8057 |
| 53 | 0.8630 | 6.5846 | 1.6150 | 4.5365 | 109 | 0.0965 | 5.9673 | 0.7476 | 8.8817 |
| 54 | 0.8289 | 6.5735 | 1.5837 | 4.6182 | 110 | 0.0928 | 5.9600 | 0.7403 | 8.9576 |
| 55 | 0.7961 | 6.5619 | 1.5536 | 4.6996 | 111 | 0.0893 | 5.9527 | 0.7332 | 9.0336 |
| 56 | 0.7648 | 6.5501 | 1.5245 | 4.7807 | 112 | 0.0859 | 5.9456 | 0.7262 | 9.1095 |
| 113 | 0.0826 | 5.9387 | 0.7194 | 9.1855 | 132 | 0.0396 | 5.8280 | 0.6101 | 10.6295 |
| 114 | 0.0795 | 5.9318 | 0.7126 | 9.2614 | 133 | 0.0381 | 5.8232 | 0.6052 | 10.7056 |
| 115 | 0.0765 | 5.9251 | 0.7060 | 9.3374 | 134 | 0.0366 | 5.8185 | 0.6005 | 10.7818 |
| 116 | 0.0736 | 5.9185 | 0.6996 | 9.4133 | 135 | 0.0352 | 5.8139 | 0.5958 | 10.8579 |
| 117 | 0.0708 | 5.9120 | 0.6932 | 9.4893 | 136 | 0.0339 | 5.8093 | 0.5912 | 10.9341 |
| 118 | 0.0681 | 5.9057 | 0.6870 | 9.5652 | 137 | 0.0326 | 5.8049 | 0.5866 | 11.0102 |
| 119 | 0.0655 | 5.8994 | 0.6808 | 9.6412 | 138 | 0.0314 | 5.8005 | 0.5821 | 11.0864 |
| 120 | 0.0630 | 5.8933 | 0.6748 | 9.7172 | 139 | 0.0302 | 5.7962 | 0.5777 | 11.1626 |
| 121 | 0.0606 | 5.8873 | 0.6689 | 9.7931 | 140 | 0.0290 | 5.7920 | 0.5734 | 11.2389 |
| 122 | 0.0583 | 5.8814 | 0.6631 | 9.8691 | 141 | 0.0279 | 5.7879 | 0.5691 | 11.3151 |
| 123 | 0.0561 | 5.8756 | 0.6574 | 9.9451 | 142 | 0.0269 | 5.7838 | 0.5649 | 11.3914 |
| 124 | 0.0540 | 5.8699 | 0.6517 | 10.0211 | 143 | 0.0258 | 5.7799 | 0.5608 | 11.4677 |
| 125 | 0.0519 | 5.8643 | 0.6462 | 10.0971 | 144 | 0.0249 | 5.7760 | 0.5567 | 11.5440 |
| 126 | 0.0499 | 5.8588 | 0.6408 | 10.1731 | 145 | 0.0239 | 5.7722 | 0.5527 | 11.6203 |
| 127 | 0.0480 | 5.8534 | 0.6354 | 10.2492 | 146 | 0.0230 | 5.7684 | 0.5487 | 11.6966 |
| 128 | 0.0462 | 5.8482 | 0.6302 | 10.3252 | 147 | 0.0221 | 5.7647 | 0.5448 | 11.7730 |
| 129 | 0.0445 | 5.8430 | 0.6250 | 10.4013 | 148 | 0.0213 | 5.7611 | 0.5410 | 11.8494 |
| 130 | 0.0428 | 5.8379 | 0.6200 | 10.4773 | 149 | 0.0205 | 5.7576 | 0.5372 | 11.9258 |
| 131 | 0.0411 | 5.8329 | 0.6150 | 10.5534 | 150 | 0.0197 | 5.7541 | 0.5334 | 12.0022 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12f**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 11.6

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 107.9253 | 11.3278 | 112.2672 | 0.1123 | 26 | 2.6229 | 8.5446 | 3.7502 | 2.5351 |
| 2 | 52.8209 | 11.0843 | 55.5270 | 0.2221 | 27 | 2.4782 | 8.4928 | 3.6003 | 2.6246 |
| 3 | 34.5132 | 10.8654 | 36.6506 | 0.3299 | 28 | 2.3444 | 8.4426 | 3.4615 | 2.7138 |
| 4 | 25.3888 | 10.6674 | 27.2364 | 0.4358 | 29 | 2.2202 | 8.3942 | 3.3325 | 2.8026 |
| 5 | 19.9316 | 10.4873 | 21.6044 | 0.5401 | 30 | 2.1047 | 8.3473 | 3.2124 | 2.8912 |
| 6 | 16.3052 | 10.3226 | 17.8617 | 0.6430 | 31 | 1.9970 | 8.3019 | 3.1003 | 2.9794 |
| 7 | 13.7232 | 10.1712 | 15.1973 | 0.7447 | 32 | 1.8884 | 8.2543 | 2.9948 | 3.0667 |
| 8 | 11.7929 | 10.0313 | 13.2059 | 0.8452 | 33 | 1.7964 | 8.2125 | 2.8967 | 3.1545 |
| 9 | 10.2964 | 9.9016 | 11.6625 | 0.9447 | 34 | 1.7101 | 8.1718 | 2.8045 | 3.2420 |
| 10 | 9.1031 | 9.7809 | 10.4321 | 1.0432 | 35 | 1.6291 | 8.1324 | 2.7178 | 3.3293 |
| 11 | 8.1299 | 9.6682 | 9.4289 | 1.1409 | 36 | 1.5527 | 8.0939 | 2.6361 | 3.4163 |
| 12 | 7.3215 | 9.5625 | 8.5958 | 1.2378 | 37 | 1.4807 | 8.0565 | 2.5589 | 3.5031 |
| 13 | 6.6397 | 9.4632 | 7.8932 | 1.3340 | 38 | 1.4128 | 8.0201 | 2.4859 | 3.5897 |
| 14 | 6.0573 | 9.3696 | 7.2931 | 1.4294 | 39 | 1.3485 | 7.9846 | 2.4168 | 3.6759 |
| 15 | 5.5541 | 9.2812 | 6.7747 | 1.5243 | 40 | 1.2877 | 7.9499 | 2.3513 | 3.7620 |
| 16 | 5.1153 | 9.1975 | 6.3226 | 1.6186 | 41 | 1.2301 | 7.9161 | 2.2890 | 3.8478 |
| 17 | 4.7294 | 9.1180 | 5.9249 | 1.7123 | 42 | 1.1754 | 7.8830 | 2.2299 | 3.9335 |
| 18 | 4.3875 | 9.0424 | 5.5725 | 1.8055 | 43 | 1.1235 | 7.8507 | 2.1735 | 4.0189 |
| 19 | 4.0826 | 8.9703 | 5.2581 | 1.8982 | 44 | 1.0742 | 7.8192 | 2.1199 | 4.1041 |
| 20 | 3.8091 | 8.9016 | 4.9760 | 1.9904 | 45 | 1.0273 | 7.7883 | 2.0687 | 4.1890 |
| 21 | 3.5625 | 8.8358 | 4.7215 | 2.0822 | 46 | 0.9827 | 7.7654 | 2.0207 | 4.2758 |
| 22 | 3.3390 | 8.7728 | 4.4908 | 2.1736 | 47 | 0.9402 | 7.7532 | 1.9762 | 4.3653 |
| 23 | 3.1357 | 8.7124 | 4.2807 | 2.2645 | 48 | 0.8998 | 7.7401 | 1.9334 | 4.4545 |
| 24 | 2.9499 | 8.6543 | 4.0887 | 2.3551 | 49 | 0.8612 | 7.7262 | 1.8922 | 4.5432 |
| 25 | 2.7796 | 8.5984 | 3.9125 | 2.4453 | 50 | 0.8244 | 7.7117 | 1.8526 | 4.6315 |
| 51 | 0.7893 | 7.6966 | 1.8145 | 4.7195 | 101 | 0.0957 | 6.9814 | 0.8726 | 8.9017 |
| 52 | 0.7558 | 7.6810 | 1.7778 | 4.8072 | 102 | 0.0917 | 6.9719 | 0.8635 | 8.9837 |
| 53 | 0.7238 | 7.6650 | 1.7425 | 4.8945 | 103 | 0.0880 | 6.9625 | 0.8545 | 9.0657 |
| 54 | 0.6933 | 7.6487 | 1.7084 | 4.9816 | 104 | 0.0844 | 6.9534 | 0.8458 | 9.1477 |
| 55 | 0.6641 | 7.6322 | 1.6755 | 5.0683 | 105 | 0.0809 | 6.9444 | 0.8372 | 9.2297 |
| 56 | 0.6362 | 7.6154 | 1.6438 | 5.1548 | 106 | 0.0776 | 6.9356 | 0.8287 | 9.3116 |
| 57 | 0.6095 | 7.5985 | 1.6131 | 5.2410 | 107 | 0.0744 | 6.9269 | 0.8205 | 9.3936 |
| 58 | 0.5840 | 7.5815 | 1.5835 | 5.3270 | 108 | 0.0714 | 6.9185 | 0.8124 | 9.4756 |
| 59 | 0.5596 | 7.5643 | 1.5549 | 5.4127 | 109 | 0.0684 | 6.9102 | 0.8044 | 9.5576 |
| 60 | 0.5363 | 7.5472 | 1.5273 | 5.4982 | 110 | 0.0656 | 6.9020 | 0.7967 | 9.6396 |
| 61 | 0.5139 | 7.5301 | 1.5005 | 5.5835 | 111 | 0.0630 | 6.8940 | 0.7890 | 9.7216 |
| 62 | 0.4925 | 7.5129 | 1.4747 | 5.6686 | 112 | 0.0604 | 6.8862 | 0.7815 | 9.8036 |
| 63 | 0.4721 | 7.4959 | 1.4496 | 5.7535 | 113 | 0.0579 | 6.8786 | 0.7742 | 9.8857 |
| 64 | 0.4525 | 7.4789 | 1.4253 | 5.8382 | 114 | 0.0555 | 6.8710 | 0.7670 | 9.9677 |
| 65 | 0.4337 | 7.4620 | 1.4018 | 5.9227 | 115 | 0.0533 | 6.8637 | 0.7599 | 10.0498 |
| 66 | 0.4158 | 7.4452 | 1.3790 | 6.0071 | 116 | 0.0511 | 6.8565 | 0.7530 | 10.1318 |
| 67 | 0.3986 | 7.4286 | 1.3569 | 6.0913 | 117 | 0.0490 | 6.8494 | 0.7461 | 10.2139 |
| 68 | 0.3821 | 7.4121 | 1.3355 | 6.1753 | 118 | 0.0470 | 6.8425 | 0.7394 | 10.2960 |
| 69 | 0.3663 | 7.3957 | 1.3147 | 6.2592 | 119 | 0.0450 | 6.8357 | 0.7329 | 10.3781 |
| 70 | 0.3512 | 7.3795 | 1.2945 | 6.3430 | 120 | 0.0432 | 6.8290 | 0.7264 | 10.4602 |
| 71 | 0.3367 | 7.3635 | 1.2749 | 6.4266 | 121 | 0.0414 | 6.8225 | 0.7201 | 10.5423 |
| 72 | 0.3228 | 7.3477 | 1.2558 | 6.5101 | 122 | 0.0397 | 6.8161 | 0.7138 | 10.6245 |
| 73 | 0.3095 | 7.3321 | 1.2373 | 6.5935 | 123 | 0.0381 | 6.8099 | 0.7077 | 10.7067 |
| 74 | 0.2967 | 7.3166 | 1.2193 | 6.6768 | 124 | 0.0365 | 6.8037 | 0.7017 | 10.7888 |
| 75 | 0.2845 | 7.3014 | 1.2018 | 6.7600 | 125 | 0.0350 | 6.7977 | 0.6957 | 10.8711 |
| 76 | 0.2728 | 7.2864 | 1.1847 | 6.8430 | 126 | 0.0336 | 6.7919 | 0.6899 | 10.9533 |
| 77 | 0.2616 | 7.2716 | 1.1682 | 6.9260 | 127 | 0.0322 | 6.7861 | 0.6842 | 11.0355 |
| 78 | 0.2508 | 7.2570 | 1.1520 | 7.0089 | 128 | 0.0309 | 6.7804 | 0.6786 | 11.1178 |
| 79 | 0.2405 | 7.2426 | 1.1363 | 7.0918 | 129 | 0.0296 | 6.7749 | 0.6730 | 11.2001 |
| 80 | 0.2306 | 7.2285 | 1.1210 | 7.1745 | 130 | 0.0284 | 6.7695 | 0.6676 | 11.2824 |

**TABLE 12f**   Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er = 11.6

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 81 | 0.2211 | 7.2146 | 1.1061 | 7.2572 | 131 | 0.0273 | 6.7642 | 0.6622 | 11.3647 |
| 82 | 0.2121 | 7.2009 | 1.0916 | 7.3398 | 132 | 0.0261 | 6.7590 | 0.6570 | 11.4471 |
| 83 | 0.2033 | 7.1874 | 1.0774 | 7.4224 | 133 | 0.0251 | 6.7539 | 0.6518 | 11.5294 |
| 84 | 0.1950 | 7.1741 | 1.0636 | 7.5049 | 134 | 0.0240 | 6.7489 | 0.6467 | 11.6118 |
| 85 | 0.1870 | 7.1611 | 1.0501 | 7.5873 | 135 | 0.0231 | 6.7440 | 0.6417 | 11.6943 |
| 86 | 0.1793 | 7.1483 | 1.0370 | 7.6697 | 136 | 0.0221 | 6.7392 | 0.6367 | 11.7767 |
| 87 | 0.1719 | 7.1357 | 1.0242 | 7.7520 | 137 | 0.0212 | 6.7345 | 0.6318 | 11.8592 |
| 88 | 0.1649 | 7.1233 | 1.0117 | 7.8343 | 138 | 0.0203 | 6.7300 | 0.6271 | 11.9417 |
| 89 | 0.1581 | 7.1111 | 0.9994 | 7.9166 | 139 | 0.0195 | 6.7255 | 0.6223 | 12.0242 |
| 90 | 0.1516 | 7.0992 | 0.9875 | 7.9988 | 140 | 0.0187 | 6.7210 | 0.6177 | 12.1067 |
| 91 | 0.1454 | 7.0874 | 0.9758 | 8.0810 | 141 | 0.0179 | 6.7167 | 0.6131 | 12.1893 |
| 92 | 0.1394 | 7.0759 | 0.9645 | 8.1632 | 142 | 0.0172 | 6.7125 | 0.6086 | 12.2718 |
| 93 | 0.1337 | 7.0646 | 0.9533 | 8.2453 | 143 | 0.0165 | 6.7084 | 0.6042 | 12.3545 |
| 94 | 0.1282 | 7.0535 | 0.9424 | 8.3274 | 144 | 0.0158 | 6.7043 | 0.5998 | 12.4371 |
| 95 | 0.1230 | 7.0426 | 0.9318 | 8.4095 | 145 | 0.0152 | 6.7003 | 0.5955 | 12.5197 |
| 96 | 0.1179 | 7.0319 | 0.9214 | 8.4916 | 146 | 0.0146 | 6.6964 | 0.5912 | 12.6024 |
| 97 | 0.1131 | 7.0214 | 0.9112 | 8.5736 | 147 | 0.0140 | 6.6926 | 0.5870 | 12.6851 |
| 98 | 0.1085 | 7.0111 | 0.9013 | 8.6556 | 148 | 0.0134 | 6.6889 | 0.5829 | 12.7679 |
| 99 | 0.1040 | 7.0010 | 0.8915 | 8.7377 | 149 | 0.0128 | 6.6852 | 0.5788 | 12.8506 |
| 100 | 0.0998 | 6.9911 | 0.8820 | 8.8197 | 150 | 0.0123 | 6.6817 | 0.5748 | 12.9334 |

*Notes:* Calculation of W/H has an error of less than 1%.
*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12g**   Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =11.9

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 106.5298 | 11.6168 | 113.6899 | 0.1137 | 55 | 0.6453 | 7.8084 | 1.6947 | 5.1265 |
| 2 | 52.1270 | 11.3637 | 56.2223 | 0.2249 | 56 | 0.6179 | 7.7908 | 1.6626 | 5.2139 |
| 3 | 34.0530 | 11.1365 | 37.1049 | 0.3339 | 57 | 0.5918 | 7.7731 | 1.6316 | 5.3009 |
| 4 | 25.0454 | 10.9312 | 27.5710 | 0.4411 | 58 | 0.5667 | 7.7554 | 1.6016 | 5.3878 |
| 5 | 19.6583 | 10.7446 | 21.8678 | 0.5467 | 59 | 0.5428 | 7.7375 | 1.5726 | 5.4744 |
| 6 | 16.0785 | 10.5741 | 18.0780 | 0.6508 | 60 | 0.5199 | 7.7197 | 1.5446 | 5.5607 |
| 7 | 13.5298 | 10.4175 | 15.3802 | 0.7536 | 61 | 0.4980 | 7.7019 | 1.5176 | 5.6469 |
| 8 | 11.6245 | 10.2730 | 13.3640 | 0.8553 | 62 | 0.4771 | 7.6841 | 1.4914 | 5.7328 |
| 9 | 10.1474 | 10.1390 | 11.8014 | 0.9559 | 63 | 0.4571 | 7.6664 | 1.4660 | 5.8186 |
| 10 | 8.9696 | 10.0144 | 10.5558 | 1.0556 | 64 | 0.4379 | 7.6488 | 1.4414 | 5.9041 |
| 11 | 8.0091 | 9.8981 | 9.5403 | 1.1544 | 65 | 0.4195 | 7.6313 | 1.4176 | 5.9895 |
| 12 | 7.2113 | 9.7891 | 8.6970 | 1.2524 | 66 | 0.4020 | 7.6140 | 1.3946 | 6.0748 |
| 13 | 6.5385 | 9.6867 | 7.9859 | 1.3496 | 67 | 0.3852 | 7.5968 | 1.3722 | 6.1598 |
| 14 | 5.9637 | 9.5902 | 7.3784 | 1.4462 | 68 | 0.3691 | 7.5797 | 1.3505 | 6.2447 |
| 15 | 5.4672 | 9.4991 | 6.8538 | 1.5421 | 69 | 0.3536 | 7.5628 | 1.3295 | 6.3295 |
| 16 | 5.0342 | 9.4128 | 6.3961 | 1.6374 | 70 | 0.3389 | 7.5462 | 1.3090 | 6.4142 |
| 17 | 4.6534 | 9.3309 | 5.9937 | 1.7322 | 71 | 0.3247 | 7.5297 | 1.2892 | 6.4987 |
| 18 | 4.3160 | 9.2531 | 5.6370 | 1.8264 | 72 | 0.3112 | 7.5134 | 1.2699 | 6.5831 |
| 19 | 4.0152 | 9.1789 | 5.3189 | 1.9201 | 73 | 0.2982 | 7.4973 | 1.2511 | 6.6674 |
| 20 | 3.7454 | 9.1081 | 5.0334 | 2.0134 | 74 | 0.2858 | 7.4814 | 1.2329 | 6.7516 |
| 21 | 3.5020 | 9.0404 | 4.7759 | 2.1062 | 75 | 0.2739 | 7.4658 | 1.2152 | 6.8356 |
| 22 | 3.2816 | 8.9755 | 4.5424 | 2.1985 | 76 | 0.2625 | 7.4504 | 1.1980 | 6.9196 |
| 23 | 3.0810 | 8.9134 | 4.3298 | 2.2905 | 77 | 0.2516 | 7.4352 | 1.1812 | 7.0035 |
| 24 | 2.8977 | 8.8536 | 4.1355 | 2.3820 | 78 | 0.2411 | 7.4202 | 1.1649 | 7.0873 |
| 25 | 2.7297 | 8.7961 | 3.9572 | 2.4732 | 79 | 0.2311 | 7.4055 | 1.1490 | 7.1711 |

**TABLE 12g (continued)** Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =11.9

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 26 | 2.5751 | 8.7408 | 3.7930 | 2.5641 | 80 | 0.2215 | 7.3910 | 1.1335 | 7.2547 |
| 27 | 2.4324 | 8.6874 | 3.6413 | 2.6545 | 81 | 0.2123 | 7.3767 | 1.1185 | 7.3383 |
| 28 | 2.3004 | 8.6359 | 3.5009 | 2.7447 | 82 | 0.2035 | 7.3627 | 1.1038 | 7.4218 |
| 29 | 2.1779 | 8.5861 | 3.3704 | 2.8345 | 83 | 0.1950 | 7.3489 | 1.0895 | 7.5053 |
| 30 | 2.0640 | 8.5378 | 3.2489 | 2.9240 | 84 | 0.1869 | 7.3353 | 1.0755 | 7.5887 |
| 31 | 1.9578 | 8.4911 | 3.1355 | 3.0132 | 85 | 0.1791 | 7.3220 | 1.0619 | 7.6721 |
| 32 | 1.8513 | 8.4425 | 3.0288 | 3.1014 | 86 | 0.1717 | 7.3089 | 1.0486 | 7.7554 |
| 33 | 1.7607 | 8.3995 | 2.9295 | 3.1902 | 87 | 0.1646 | 7.2960 | 1.0356 | 7.8386 |
| 34 | 1.6756 | 8.3577 | 2.8362 | 3.2787 | 88 | 0.1577 | 7.2834 | 1.0230 | 7.9219 |
| 35 | 1.5956 | 8.3171 | 2.7485 | 3.3669 | 89 | 0.1512 | 7.2709 | 1.0106 | 8.0051 |
| 36 | 1.5204 | 8.2776 | 2.6658 | 3.4549 | 90 | 0.1449 | 7.2588 | 0.9985 | 8.0882 |
| 37 | 1.4494 | 8.2391 | 2.5877 | 3.5426 | 91 | 0.1389 | 7.2468 | 0.9868 | 8.1713 |
| 38 | 1.3824 | 8.2016 | 2.5139 | 3.6301 | 92 | 0.1331 | 7.2350 | 0.9752 | 8.2544 |
| 39 | 1.3190 | 8.1651 | 2.4440 | 3.7173 | 93 | 0.1276 | 7.2235 | 0.9640 | 8.3375 |
| 40 | 1.2591 | 8.1295 | 2.3777 | 3.8043 | 94 | 0.1223 | 7.2122 | 0.9530 | 8.4206 |
| 41 | 1.2023 | 8.0947 | 2.3147 | 3.8910 | 95 | 0.1172 | 7.2011 | 0.9422 | 8.5036 |
| 42 | 1.1484 | 8.0607 | 2.2548 | 3.9775 | 96 | 0.1124 | 7.1902 | 0.9317 | 8.5866 |
| 43 | 1.0973 | 8.0275 | 2.1979 | 4.0639 | 97 | 0.1077 | 7.1795 | 0.9214 | 8.6696 |
| 44 | 1.0487 | 7.9951 | 2.1436 | 4.1499 | 98 | 0.1033 | 7.1691 | 0.9113 | 8.7526 |
| 45 | 1.0026 | 7.9633 | 2.0918 | 4.2358 | 99 | 0.0990 | 7.1588 | 0.9015 | 8.8356 |
| 46 | 0.9586 | 7.9500 | 2.0446 | 4.3263 | 100 | 0.0949 | 7.1487 | 0.8919 | 8.9185 |
| 47 | 0.9168 | 7.9367 | 1.9994 | 4.4167 | 101 | 0.0909 | 7.1388 | 0.8824 | 9.0015 |
| 48 | 0.8770 | 7.9226 | 1.9560 | 4.5067 | 102 | 0.0872 | 7.1292 | 0.8732 | 9.0845 |
| 49 | 0.8391 | 7.9078 | 1.9143 | 4.5962 | 103 | 0.0836 | 7.1197 | 0.8641 | 9.1674 |
| 50 | 0.8029 | 7.8923 | 1.8742 | 4.6854 | 104 | 0.0801 | 7.1104 | 0.8552 | 9.2504 |
| 51 | 0.7684 | 7.8762 | 1.8356 | 4.7743 | 105 | 0.0768 | 7.1012 | 0.8466 | 9.3333 |
| 52 | 0.7354 | 7.8598 | 1.7984 | 4.8628 | 106 | 0.0736 | 7.0923 | 0.8380 | 9.4163 |
| 53 | 0.7040 | 7.8429 | 1.7626 | 4.9510 | 107 | 0.0705 | 7.0835 | 0.8297 | 9.4992 |
| 54 | 0.6740 | 7.8258 | 1.7280 | 5.0389 | 108 | 0.0676 | 7.0749 | 0.8215 | 9.5822 |
| 109 | 0.0648 | 7.0665 | 0.8135 | 9.6652 | 130 | 0.0266 | 6.9243 | 0.6752 | 11.4107 |
| 110 | 0.0621 | 7.0583 | 0.8056 | 9.7481 | 131 | 0.0255 | 6.9190 | 0.6698 | 11.4940 |
| 111 | 0.0595 | 7.0502 | 0.7979 | 9.8311 | 132 | 0.0245 | 6.9138 | 0.6645 | 11.5774 |
| 112 | 0.0571 | 7.0423 | 0.7903 | 9.9141 | 133 | 0.0235 | 6.9086 | 0.6592 | 11.6608 |
| 113 | 0.0547 | 7.0345 | 0.7829 | 9.9971 | 134 | 0.0225 | 6.9036 | 0.6541 | 11.7442 |
| 114 | 0.0524 | 7.0269 | 0.7756 | 10.0801 | 135 | 0.0216 | 6.8987 | 0.6490 | 11.8276 |
| 115 | 0.0503 | 7.0195 | 0.7685 | 10.1632 | 136 | 0.0207 | 6.8939 | 0.6440 | 11.9110 |
| 116 | 0.0482 | 7.0122 | 0.7615 | 10.2462 | 137 | 0.0198 | 6.8892 | 0.6391 | 11.9945 |
| 117 | 0.0462 | 7.0050 | 0.7546 | 10.3293 | 138 | 0.0190 | 6.8845 | 0.6342 | 12.0780 |
| 118 | 0.0443 | 6.9980 | 0.7478 | 10.4123 | 139 | 0.0182 | 6.8800 | 0.6294 | 12.1615 |
| 119 | 0.0424 | 6.9911 | 0.7412 | 10.4954 | 140 | 0.0174 | 6.8756 | 0.6247 | 12.2451 |
| 120 | 0.0407 | 6.9844 | 0.7346 | 10.5785 | 141 | 0.0167 | 6.8713 | 0.6201 | 12.3287 |
| 121 | 0.0390 | 6.9778 | 0.7282 | 10.6617 | 142 | 0.0160 | 6.8670 | 0.6156 | 12.4123 |
| 122 | 0.0374 | 6.9714 | 0.7219 | 10.7448 | 143 | 0.0154 | 6.8628 | 0.6111 | 12.4959 |
| 123 | 0.0358 | 6.9651 | 0.7157 | 10.8280 | 144 | 0.0147 | 6.8588 | 0.6067 | 12.5795 |
| 124 | 0.0343 | 6.9589 | 0.7096 | 10.9112 | 145 | 0.0141 | 6.8548 | 0.6023 | 12.6632 |
| 125 | 0.0329 | 6.9528 | 0.7036 | 10.9944 | 146 | 0.0135 | 6.8509 | 0.5980 | 12.7469 |
| 126 | 0.0316 | 6.9469 | 0.6978 | 11.0776 | 147 | 0.0130 | 6.8471 | 0.5938 | 12.8306 |
| 127 | 0.0302 | 6.9411 | 0.6920 | 11.1608 | 148 | 0.0124 | 6.8433 | 0.5896 | 12.9144 |
| 128 | 0.0290 | 6.9354 | 0.6863 | 11.2441 | 149 | 0.0119 | 6.8396 | 0.5855 | 12.9982 |
| 129 | 0.0278 | 6.9298 | 0.6807 | 11.3274 | 150 | 0.0114 | 6.8361 | 0.5814 | 13.0820 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12h** Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =12.88

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 102.3159 | 12.5596 | 118.2135 | 0.1182 | 24 | 2.7402 | 9.5011 | 4.2841 | 2.4676 |
| 2 | 50.0315 | 12.2746 | 58.4323 | 0.2337 | 25 | 2.5791 | 9.4384 | 4.0991 | 2.5619 |
| 3 | 32.6633 | 12.0197 | 38.5483 | 0.3469 | 26 | 2.4309 | 9.3779 | 3.9288 | 2.6559 |
| 4 | 24.0084 | 11.7903 | 28.6339 | 0.4581 | 27 | 2.2942 | 9.3197 | 3.7715 | 2.7494 |
| 5 | 18.8329 | 11.5823 | 22.7043 | 0.5676 | 28 | 2.1677 | 9.2635 | 3.6258 | 2.8427 |
| 6 | 15.3941 | 11.3928 | 18.7648 | 0.6755 | 29 | 2.0503 | 9.2091 | 3.4905 | 2.9355 |
| 7 | 12.9460 | 11.2191 | 15.9610 | 0.7821 | 30 | 1.9316 | 9.1518 | 3.3637 | 3.0273 |
| 8 | 11.1161 | 11.0591 | 13.8660 | 0.8874 | 31 | 1.8324 | 9.1020 | 3.2463 | 3.1197 |
| 9 | 9.6977 | 10.9111 | 12.2425 | 0.9916 | 32 | 1.7397 | 9.0536 | 3.1365 | 3.2117 |
| 10 | 8.5668 | 10.7736 | 10.9487 | 1.0949 | 33 | 1.6528 | 9.0068 | 3.0335 | 3.3035 |
| 11 | 7.6446 | 10.6455 | 9.8939 | 1.1972 | 34 | 1.5714 | 8.9612 | 2.9369 | 3.3950 |
| 12 | 6.8787 | 10.5255 | 9.0182 | 1.2986 | 35 | 1.4948 | 8.9170 | 2.8459 | 3.4862 |
| 13 | 6.2329 | 10.4130 | 8.2799 | 1.3993 | 36 | 1.4228 | 8.8739 | 2.7602 | 3.5772 |
| 14 | 5.6812 | 10.3071 | 7.6492 | 1.4993 | 37 | 1.3549 | 8.8320 | 2.6792 | 3.6678 |
| 15 | 5.2048 | 10.2071 | 7.1046 | 1.5985 | 38 | 1.2908 | 8.7911 | 2.6027 | 3.7582 |
| 16 | 4.7893 | 10.1125 | 6.6296 | 1.6972 | 39 | 1.2302 | 8.7513 | 2.5302 | 3.8484 |
| 17 | 4.4239 | 10.0228 | 6.2119 | 1.7952 | 40 | 1.1729 | 8.7125 | 2.4614 | 3.9383 |
| 18 | 4.1003 | 9.9376 | 5.8418 | 1.8927 | 41 | 1.1186 | 8.6745 | 2.3962 | 4.0280 |
| 19 | 3.8117 | 9.8565 | 5.5117 | 1.9897 | 42 | 1.0672 | 8.6375 | 2.3341 | 4.1174 |
| 20 | 3.5529 | 9.7791 | 5.2155 | 2.0862 | 43 | 1.0184 | 8.6014 | 2.2751 | 4.2066 |
| 21 | 3.3196 | 9.7051 | 4.9483 | 2.1822 | 44 | 0.9721 | 8.5791 | 2.2205 | 4.2989 |
| 22 | 3.1082 | 9.6342 | 4.7061 | 2.2778 | 45 | 0.9281 | 8.5645 | 2.1693 | 4.3928 |
| 23 | 2.9159 | 9.5663 | 4.4856 | 2.3729 | 46 | 0.8863 | 8.5487 | 2.1202 | 4.4863 |
| 47 | 0.8465 | 8.5321 | 2.0731 | 4.5794 | 99 | 0.0845 | 7.6726 | 0.9333 | 9.1471 |
| 48 | 0.8086 | 8.5147 | 2.0278 | 4.6720 | 100 | 0.0808 | 7.6620 | 0.9233 | 9.2331 |
| 49 | 0.7726 | 8.4967 | 1.9843 | 4.7643 | 101 | 0.0774 | 7.6516 | 0.9136 | 9.3192 |
| 50 | 0.7383 | 8.4781 | 1.9425 | 4.8562 | 102 | 0.0740 | 7.6415 | 0.9040 | 9.4052 |
| 51 | 0.7056 | 8.4591 | 1.9023 | 4.9478 | 103 | 0.0709 | 7.6315 | 0.8946 | 9.4912 |
| 52 | 0.6744 | 8.4397 | 1.8635 | 5.0390 | 104 | 0.0678 | 7.6218 | 0.8855 | 9.5773 |
| 53 | 0.6447 | 8.4201 | 1.8263 | 5.1299 | 105 | 0.0649 | 7.6123 | 0.8765 | 9.6633 |
| 54 | 0.6163 | 8.4002 | 1.7903 | 5.2206 | 106 | 0.0621 | 7.6030 | 0.8677 | 9.7494 |
| 55 | 0.5893 | 8.3802 | 1.7557 | 5.3109 | 107 | 0.0595 | 7.5938 | 0.8591 | 9.8354 |
| 56 | 0.5634 | 8.3601 | 1.7223 | 5.4010 | 108 | 0.0569 | 7.5849 | 0.8506 | 9.9215 |
| 57 | 0.5388 | 8.3399 | 1.6900 | 5.4908 | 109 | 0.0545 | 7.5761 | 0.8423 | 10.0076 |
| 58 | 0.5152 | 8.3198 | 1.6588 | 5.5804 | 110 | 0.0521 | 7.5675 | 0.8342 | 10.0937 |
| 59 | 0.4928 | 8.2996 | 1.6288 | 5.6697 | 111 | 0.0499 | 7.5592 | 0.8262 | 10.1798 |
| 60 | 0.4713 | 8.2796 | 1.5997 | 5.7588 | 112 | 0.0477 | 7.5509 | 0.8184 | 10.2659 |
| 61 | 0.4508 | 8.2596 | 1.5716 | 5.8477 | 113 | 0.0457 | 7.5429 | 0.8107 | 10.3521 |
| 62 | 0.4312 | 8.2397 | 1.5443 | 5.9365 | 114 | 0.0437 | 7.5350 | 0.8032 | 10.4382 |
| 63 | 0.4125 | 8.2200 | 1.5180 | 6.0250 | 115 | 0.0418 | 7.5273 | 0.7958 | 10.5244 |
| 64 | 0.3946 | 8.2005 | 1.4925 | 6.1133 | 116 | 0.0400 | 7.5198 | 0.7885 | 10.6106 |
| 65 | 0.3775 | 8.1811 | 1.4678 | 6.2015 | 117 | 0.0383 | 7.5124 | 0.7814 | 10.6968 |
| 66 | 0.3611 | 8.1619 | 1.4439 | 6.2895 | 118 | 0.0367 | 7.5052 | 0.7744 | 10.7830 |
| 67 | 0.3455 | 8.1429 | 1.4207 | 6.3774 | 119 | 0.0351 | 7.4981 | 0.7676 | 10.8693 |
| 68 | 0.3306 | 8.1242 | 1.3982 | 6.4652 | 120 | 0.0336 | 7.4912 | 0.7608 | 10.9556 |
| 69 | 0.3163 | 8.1057 | 1.3763 | 6.5528 | 121 | 0.0321 | 7.4844 | 0.7542 | 11.0419 |
| 70 | 0.3026 | 8.0874 | 1.3551 | 6.6402 | 122 | 0.0308 | 7.4778 | 0.7477 | 11.1282 |
| 71 | 0.2895 | 8.0694 | 1.3346 | 6.7276 | 123 | 0.0294 | 7.4713 | 0.7413 | 11.2146 |
| 72 | 0.2770 | 8.0517 | 1.3146 | 6.8148 | 124 | 0.0282 | 7.4649 | 0.7350 | 11.3009 |
| 73 | 0.2651 | 8.0342 | 1.2952 | 6.9020 | 125 | 0.0270 | 7.4587 | 0.7288 | 11.3873 |
| 74 | 0.2536 | 8.0169 | 1.2763 | 6.9890 | 126 | 0.0258 | 7.4526 | 0.7227 | 11.4737 |
| 75 | 0.2427 | 8.0000 | 1.2579 | 7.0759 | 127 | 0.0247 | 7.4467 | 0.7167 | 11.5602 |
| 76 | 0.2323 | 7.9833 | 1.2401 | 7.1628 | 128 | 0.0236 | 7.4409 | 0.7109 | 11.6466 |
| 77 | 0.2222 | 7.9669 | 1.2227 | 7.2496 | 129 | 0.0226 | 7.4352 | 0.7051 | 11.7331 |
| 78 | 0.2127 | 7.9507 | 1.2058 | 7.3363 | 130 | 0.0217 | 7.4296 | 0.6994 | 11.8197 |
| 79 | 0.2035 | 7.9348 | 1.1894 | 7.4229 | 131 | 0.0207 | 7.4241 | 0.6938 | 11.9062 |

TABLE 12h (continued)    Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL
Capacitance and Inductance for Er =12.88

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 80 | 0.1947 | 7.9192 | 1.1734 | 7.5095 | 132 | 0.0198 | 7.4188 | 0.6883 | 11.9928 |
| 81 | 0.1864 | 7.9039 | 1.1578 | 7.5960 | 133 | 0.0190 | 7.4136 | 0.6829 | 12.0794 |
| 82 | 0.1783 | 7.8889 | 1.1425 | 7.6825 | 134 | 0.0182 | 7.4085 | 0.6775 | 12.1660 |
| 83 | 0.1707 | 7.8741 | 1.1277 | 7.7689 | 135 | 0.0174 | 7.4035 | 0.6723 | 12.2527 |
| 84 | 0.1633 | 7.8596 | 1.1133 | 7.8552 | 136 | 0.0166 | 7.3986 | 0.6671 | 12.3393 |
| 85 | 0.1563 | 7.8453 | 1.0992 | 7.9415 | 137 | 0.0159 | 7.3938 | 0.6621 | 12.4261 |
| 86 | 0.1496 | 7.8314 | 1.0854 | 8.0278 | 138 | 0.0152 | 7.3891 | 0.6570 | 12.5128 |
| 87 | 0.1431 | 7.8176 | 1.0720 | 8.1140 | 139 | 0.0146 | 7.3845 | 0.6521 | 12.5996 |
| 88 | 0.1370 | 7.8042 | 1.0589 | 8.2002 | 140 | 0.0140 | 7.3800 | 0.6473 | 12.6863 |
| 89 | 0.1311 | 7.7910 | 1.0461 | 8.2864 | 141 | 0.0134 | 7.3756 | 0.6425 | 12.7732 |
| 90 | 0.1255 | 7.7781 | 1.0336 | 8.3725 | 142 | 0.0128 | 7.3713 | 0.6378 | 12.8600 |
| 91 | 0.1201 | 7.7654 | 1.0215 | 8.4587 | 143 | 0.0122 | 7.3671 | 0.6331 | 12.9469 |
| 92 | 0.1149 | 7.7529 | 1.0095 | 8.5448 | 144 | 0.0117 | 7.3630 | 0.6286 | 13.0338 |
| 93 | 0.1100 | 7.7407 | 0.9979 | 8.6309 | 145 | 0.0112 | 7.3590 | 0.6241 | 13.1207 |
| 94 | 0.1052 | 7.7288 | 0.9865 | 8.7169 | 146 | 0.0107 | 7.3551 | 0.6196 | 13.2077 |
| 95 | 0.1007 | 7.7171 | 0.9754 | 8.8030 | 147 | 0.0103 | 7.3512 | 0.6152 | 13.2946 |
| 96 | 0.0964 | 7.7056 | 0.9645 | 8.8890 | 148 | 0.0098 | 7.3475 | 0.6109 | 13.3817 |
| 97 | 0.0922 | 7.6944 | 0.9539 | 8.9751 | 149 | 0.0094 | 7.3438 | 0.6067 | 13.4687 |
| 98 | 0.0883 | 7.6833 | 0.9435 | 9.0611 | 150 | 0.0090 | 7.3402 | 0.6025 | 13.5558 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

TABLE 12i    Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance
and Inductance for Er =35

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 61.2525 | 33.5453 | 193.1947 | 0.1932 | 57 | 0.1141 | 20.3209 | 2.6380 | 8.5709 |
| 2 | 29.6179 | 32.3412 | 94.8478 | 0.3794 | 58 | 0.1063 | 20.2652 | 2.5890 | 8.7093 |
| 3 | 19.1302 | 31.3265 | 62.2321 | 0.5601 | 59 | 0.0990 | 20.2113 | 2.5417 | 8.8477 |
| 4 | 13.9141 | 30.4569 | 46.0216 | 0.7363 | 60 | 0.0923 | 20.1591 | 2.4961 | 8.9860 |
| 5 | 10.8011 | 29.7005 | 36.3573 | 0.9089 | 61 | 0.0860 | 20.1087 | 2.4521 | 9.1243 |
| 6 | 8.7367 | 29.0345 | 29.9561 | 1.0784 | 62 | 0.0801 | 20.0598 | 2.4096 | 9.2626 |
| 7 | 7.2699 | 28.4417 | 25.4132 | 1.2452 | 63 | 0.0746 | 20.0126 | 2.3686 | 9.4010 |
| 8 | 6.1757 | 27.9094 | 22.0275 | 1.4098 | 64 | 0.0695 | 19.9670 | 2.3289 | 9.5393 |
| 9 | 5.3291 | 27.4273 | 19.4101 | 1.5722 | 65 | 0.0648 | 19.9228 | 2.2906 | 9.6776 |
| 10 | 4.6555 | 26.9878 | 17.3286 | 1.7329 | 66 | 0.0604 | 19.8801 | 2.2534 | 9.8160 |
| 11 | 4.1073 | 26.5845 | 15.6351 | 1.8918 | 67 | 0.0562 | 19.8389 | 2.2175 | 9.9543 |
| 12 | 3.6529 | 26.2124 | 14.2315 | 2.0493 | 68 | 0.0524 | 19.7990 | 2.1827 | 10.0928 |
| 13 | 3.2705 | 25.8674 | 13.0501 | 2.2055 | 69 | 0.0488 | 19.7604 | 2.1490 | 10.2312 |
| 14 | 2.9445 | 25.5460 | 12.0424 | 2.3603 | 70 | 0.0455 | 19.7232 | 2.1163 | 10.3697 |
| 15 | 2.6635 | 25.2453 | 11.1732 | 2.5140 | 71 | 0.0424 | 19.6872 | 2.0846 | 10.5082 |
| 16 | 2.4189 | 24.9629 | 10.4161 | 2.6665 | 72 | 0.0395 | 19.6525 | 2.0538 | 10.6468 |
| 17 | 2.2042 | 24.6968 | 9.7510 | 2.8180 | 73 | 0.0368 | 19.6189 | 2.0239 | 10.7855 |
| 18 | 2.0144 | 24.4452 | 9.1623 | 2.9686 | 74 | 0.0343 | 19.5865 | 1.9949 | 10.9242 |
| 19 | 1.8358 | 24.1924 | 8.6351 | 3.1173 | 75 | 0.0319 | 19.5551 | 1.9667 | 11.0630 |
| 20 | 1.6891 | 23.9716 | 8.1658 | 3.2663 | 76 | 0.0298 | 19.5249 | 1.9394 | 11.2018 |
| 21 | 1.5569 | 23.7610 | 7.7427 | 3.4145 | 77 | 0.0277 | 19.4957 | 1.9127 | 11.3407 |
| 22 | 1.4372 | 23.5597 | 7.3594 | 3.5619 | 78 | 0.0258 | 19.4674 | 1.8869 | 11.4796 |
| 23 | 1.3284 | 23.3669 | 7.0106 | 3.7086 | 79 | 0.0241 | 19.4402 | 1.8617 | 11.6187 |
| 24 | 1.2292 | 23.1820 | 6.6918 | 3.8545 | 80 | 0.0224 | 19.4139 | 1.8372 | 11.7578 |
| 25 | 1.1385 | 23.0043 | 6.3995 | 3.9997 | 81 | 0.0209 | 19.3884 | 1.8133 | 11.8970 |

TABLE 12i (continued)    Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =35

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 26 | 1.0554 | 22.8334 | 6.1304 | 4.1442 | 82 | 0.0195 | 19.3639 | 1.7900 | 12.0362 |
| 27 | 0.9790 | 22.6972 | 5.8857 | 4.2907 | 83 | 0.0181 | 19.3402 | 1.7674 | 12.1755 |
| 28 | 0.9087 | 22.6289 | 5.6670 | 4.4429 | 84 | 0.0169 | 19.3173 | 1.7453 | 12.3149 |
| 29 | 0.8438 | 22.5532 | 5.4624 | 4.5939 | 85 | 0.0157 | 19.2952 | 1.7238 | 12.4544 |
| 30 | 0.7840 | 22.4719 | 5.2708 | 4.7437 | 86 | 0.0147 | 19.2739 | 1.7028 | 12.5940 |
| 31 | 0.7286 | 22.3863 | 5.0911 | 4.8925 | 87 | 0.0137 | 19.2533 | 1.6823 | 12.7336 |
| 32 | 0.6774 | 22.2977 | 4.9222 | 5.0403 | 88 | 0.0127 | 19.2334 | 1.6624 | 12.8733 |
| 33 | 0.6300 | 22.2069 | 4.7633 | 5.1873 | 89 | 0.0119 | 19.2142 | 1.6429 | 13.0131 |
| 34 | 0.5861 | 22.1148 | 4.6136 | 5.3333 | 90 | 0.0111 | 19.1957 | 1.6238 | 13.1530 |
| 35 | 0.5453 | 22.0220 | 4.4724 | 5.4787 | 91 | 0.0103 | 19.1778 | 1.6052 | 13.2929 |
| 36 | 0.5074 | 21.9291 | 4.3390 | 5.6233 | 92 | 0.0096 | 19.1605 | 1.5871 | 13.4329 |
| 37 | 0.4723 | 21.8365 | 4.2128 | 5.7673 | 93 | 0.0089 | 19.1439 | 1.5693 | 13.5730 |
| 38 | 0.4397 | 21.7445 | 4.0933 | 5.9107 | 94 | 0.0083 | 19.1278 | 1.5520 | 13.7132 |
| 39 | 0.4093 | 21.6536 | 3.9800 | 6.0535 | 95 | 0.0078 | 19.1122 | 1.5350 | 13.8535 |
| 40 | 0.3811 | 21.5638 | 3.8724 | 6.1959 | 96 | 0.0072 | 19.0972 | 1.5184 | 13.9938 |
| 41 | 0.3549 | 21.4755 | 3.7702 | 6.3378 | 97 | 0.0067 | 19.0828 | 1.5022 | 14.1342 |
| 42 | 0.3305 | 21.3889 | 3.6730 | 6.4792 | 98 | 0.0063 | 19.0688 | 1.4863 | 14.2747 |
| 43 | 0.3078 | 21.3039 | 3.5805 | 6.6203 | 99 | 0.0059 | 19.0553 | 1.4708 | 14.4152 |
| 44 | 0.2867 | 21.2208 | 3.4923 | 6.7610 | 100 | 0.0055 | 19.0422 | 1.4556 | 14.5559 |
| 45 | 0.2670 | 21.1396 | 3.4081 | 6.9014 | 101 | 0.0051 | 19.0297 | 1.4407 | 14.6966 |
| 46 | 0.2487 | 21.0603 | 3.3278 | 7.0416 | 102 | 0.0047 | 19.0175 | 1.4261 | 14.8374 |
| 47 | 0.2317 | 20.9831 | 3.2510 | 7.1814 | 103 | 0.0044 | 19.0058 | 1.4118 | 14.9782 |
| 48 | 0.2158 | 20.9078 | 3.1776 | 7.3211 | 104 | 0.0041 | 18.9945 | 1.3978 | 15.1191 |
| 49 | 0.2010 | 20.8346 | 3.1073 | 7.4605 | 105 | 0.0038 | 18.9836 | 1.3841 | 15.2601 |
| 50 | 0.1873 | 20.7635 | 3.0399 | 7.5998 | 106 | 0.0036 | 18.9730 | 1.3707 | 15.4012 |
| 51 | 0.1745 | 20.6944 | 2.9753 | 7.7388 | 107 | 0.0033 | 18.9629 | 1.3575 | 15.5423 |
| 52 | 0.1625 | 20.6272 | 2.9134 | 7.8778 | 108 | 0.0031 | 18.9530 | 1.3446 | 15.6835 |
| 53 | 0.1514 | 20.5621 | 2.8539 | 8.0166 | 109 | 0.0029 | 18.9436 | 1.3319 | 15.8247 |
| 54 | 0.1411 | 20.4989 | 2.7967 | 8.1553 | 110 | 0.0027 | 18.9344 | 1.3195 | 15.9661 |
| 55 | 0.1314 | 20.4377 | 2.7418 | 8.2939 | 111 | 0.0025 | 18.9256 | 1.3073 | 16.1074 |
| 56 | 0.1224 | 20.3784 | 2.6889 | 8.4324 | 112 | 0.0023 | 18.9170 | 1.2954 | 16.2489 |
| 113 | 0.0022 | 18.9088 | 1.2836 | 16.3904 | 132 | 0.0006 | 18.7969 | 1.0956 | 19.0896 |
| 114 | 0.0020 | 18.9009 | 1.2721 | 16.5320 | 133 | 0.0005 | 18.7928 | 1.0872 | 19.2321 |
| 115 | 0.0019 | 18.8932 | 1.2608 | 16.6736 | 134 | 0.0005 | 18.7889 | 1.0790 | 19.3747 |
| 116 | 0.0018 | 18.8858 | 1.2497 | 16.8153 | 135 | 0.0005 | 18.7851 | 1.0709 | 19.5173 |
| 117 | 0.0016 | 18.8786 | 1.2387 | 16.9571 | 136 | 0.0004 | 18.7815 | 1.0629 | 19.6600 |
| 118 | 0.0015 | 18.8717 | 1.2280 | 17.0989 | 137 | 0.0004 | 18.7779 | 1.0551 | 19.8027 |
| 119 | 0.0014 | 18.8651 | 1.2175 | 17.2407 | 138 | 0.0004 | 18.7745 | 1.0473 | 19.9454 |
| 120 | 0.0013 | 18.8587 | 1.2071 | 17.3826 | 139 | 0.0003 | 18.7713 | 1.0397 | 20.0882 |
| 121 | 0.0012 | 18.8524 | 1.1970 | 17.5246 | 140 | 0.0003 | 18.7681 | 1.0322 | 20.2310 |
| 122 | 0.0012 | 18.8465 | 1.1870 | 17.6666 | 141 | 0.0003 | 18.7650 | 1.0248 | 20.3738 |
| 123 | 0.0011 | 18.8407 | 1.1771 | 17.8087 | 142 | 0.0003 | 18.7621 | 1.0175 | 20.5167 |
| 124 | 0.0010 | 18.8351 | 1.1675 | 17.9508 | 143 | 0.0003 | 18.7592 | 1.0103 | 20.6596 |
| 125 | 0.0009 | 18.8297 | 1.1580 | 18.0930 | 144 | 0.0002 | 18.7565 | 1.0032 | 20.8026 |
| 126 | 0.0009 | 18.8245 | 1.1486 | 18.2352 | 145 | 0.0002 | 18.7538 | 0.9962 | 20.9456 |
| 127 | 0.0008 | 18.8195 | 1.1394 | 18.3775 | 146 | 0.0002 | 18.7513 | 0.9893 | 21.0886 |
| 128 | 0.0008 | 18.8146 | 1.1304 | 18.5198 | 147 | 0.0002 | 18.7488 | 0.9825 | 21.2316 |
| 129 | 0.0007 | 18.8100 | 1.1215 | 18.6622 | 148 | 0.0002 | 18.7464 | 0.9758 | 21.3747 |
| 130 | 0.0007 | 18.8055 | 1.1127 | 18.8046 | 149 | 0.0002 | 18.7441 | 0.9692 | 21.5178 |
| 131 | 0.0006 | 18.8011 | 1.1041 | 18.9471 | 150 | 0.0002 | 18.7419 | 0.9627 | 21.6609 |

Notes: Calculation of W/H has an error of less than 1%.
Source: Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.

**TABLE 12j**  Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =85

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 38.5925 | 79.6824 | 297.7560 | 0.2978 | 26 | 0.3739 | 51.7462 | 9.2288 | 6.2387 |
| 2 | 18.3705 | 75.6651 | 145.0765 | 0.5803 | 27 | 0.3349 | 51.4124 | 8.8583 | 6.4577 |
| 3 | 11.6859 | 72.5009 | 94.6738 | 0.8521 | 28 | 0.3000 | 51.0886 | 8.5150 | 6.6757 |
| 4 | 8.3710 | 69.9235 | 69.7318 | 1.1157 | 29 | 0.2688 | 50.7757 | 8.1961 | 6.8930 |
| 5 | 6.3982 | 67.7680 | 54.9189 | 1.3730 | 30 | 0.2409 | 50.4745 | 7.8994 | 7.1095 |
| 6 | 5.0937 | 65.9270 | 45.1398 | 1.6250 | 31 | 0.2159 | 50.1850 | 7.6226 | 7.3253 |
| 7 | 4.1695 | 64.3277 | 38.2191 | 1.8727 | 32 | 0.1935 | 49.9076 | 7.3640 | 7.5407 |
| 8 | 3.4821 | 62.9184 | 33.0733 | 2.1167 | 33 | 0.1734 | 49.6422 | 7.1218 | 7.7557 |
| 9 | 2.9517 | 61.6613 | 29.1034 | 2.3574 | 34 | 0.1554 | 49.3886 | 6.8947 | 7.9702 |
| 10 | 2.5309 | 60.5285 | 25.9513 | 2.5951 | 35 | 0.1393 | 49.1467 | 6.6813 | 8.1845 |
| 11 | 2.1895 | 59.4981 | 23.3904 | 2.8302 | 36 | 0.1249 | 48.9161 | 6.4804 | 8.3986 |
| 12 | 1.8946 | 58.5089 | 21.2622 | 3.0618 | 37 | 0.1119 | 48.6966 | 6.2911 | 8.6125 |
| 13 | 1.6651 | 57.6611 | 19.4840 | 3.2928 | 38 | 0.1003 | 48.4877 | 6.1124 | 8.8263 |
| 14 | 1.4696 | 56.8730 | 17.9682 | 3.5218 | 39 | 0.0899 | 48.2891 | 5.9435 | 9.0400 |
| 15 | 1.3012 | 56.1365 | 16.6614 | 3.7488 | 40 | 0.0806 | 48.1003 | 5.7835 | 9.2537 |
| 16 | 1.1551 | 55.4455 | 15.5236 | 3.9740 | 41 | 0.0723 | 47.9210 | 5.6319 | 9.4673 |
| 17 | 1.0274 | 54.7949 | 14.5245 | 4.1976 | 42 | 0.0648 | 47.7509 | 5.4881 | 9.6810 |
| 18 | 0.9153 | 54.4535 | 13.6748 | 4.4306 | 43 | 0.0581 | 47.5893 | 5.3514 | 9.8947 |
| 19 | 0.8165 | 54.1607 | 12.9202 | 4.6642 | 44 | 0.0521 | 47.4361 | 5.2213 | 10.1085 |
| 20 | 0.7290 | 53.8383 | 12.2376 | 4.8950 | 45 | 0.0467 | 47.2907 | 5.0975 | 10.3224 |
| 21 | 0.6514 | 53.4976 | 11.6179 | 5.1235 | 46 | 0.0418 | 47.1529 | 4.9794 | 10.5364 |
| 22 | 0.5825 | 53.1467 | 11.0534 | 5.3498 | 47 | 0.0375 | 47.0222 | 4.8667 | 10.7505 |
| 23 | 0.5211 | 52.7921 | 10.5375 | 5.5743 | 48 | 0.0336 | 46.8984 | 4.7590 | 10.9648 |
| 24 | 0.4664 | 52.4383 | 10.0645 | 5.7972 | 49 | 0.0301 | 46.7810 | 4.6561 | 11.1792 |
| 25 | 0.4176 | 52.0888 | 9.6297 | 6.0185 | 50 | 0.0270 | 46.6697 | 4.5575 | 11.3938 |
| 51 | 0.0242 | 46.5643 | 4.4631 | 11.6085 | 101 | 0.0001 | 44.8028 | 2.2106 | 22.5503 |
| 52 | 0.0217 | 46.4644 | 4.3726 | 11.8234 | 102 | 0.0001 | 44.7963 | 2.1888 | 22.7720 |
| 53 | 0.0195 | 46.3698 | 4.2857 | 12.0385 | 103 | 0.0001 | 44.7901 | 2.1674 | 22.9936 |
| 54 | 0.0175 | 46.2801 | 4.2023 | 12.2538 | 104 | 0.0001 | 44.7842 | 2.1464 | 23.2153 |
| 55 | 0.0156 | 46.1952 | 4.1221 | 12.4693 | 105 | 0.0001 | 44.7787 | 2.1258 | 23.4371 |
| 56 | 0.0140 | 46.1148 | 4.0449 | 12.6849 | 106 | 0.0001 | 44.7734 | 2.1056 | 23.6589 |
| 57 | 0.0126 | 46.0386 | 3.9707 | 12.9008 | 107 | 0.0001 | 44.7685 | 2.0858 | 23.8808 |
| 58 | 0.0113 | 45.9665 | 3.8992 | 13.1168 | 108 | 0.0000 | 44.7638 | 2.0664 | 24.1027 |
| 59 | 0.0101 | 45.8982 | 3.8302 | 13.3330 | 109 | 0.0000 | 44.7593 | 2.0474 | 24.3247 |
| 60 | 0.0091 | 45.8335 | 3.7637 | 13.5495 | 110 | 0.0000 | 44.7551 | 2.0287 | 24.5467 |
| 61 | 0.0081 | 45.7722 | 3.6996 | 13.7661 | 111 | 0.0000 | 44.7511 | 2.0103 | 24.7688 |
| 62 | 0.0073 | 45.7142 | 3.6376 | 13.9829 | 112 | 0.0000 | 44.7473 | 1.9923 | 24.9908 |
| 63 | 0.0065 | 45.6592 | 3.5777 | 14.1999 | 113 | 0.0000 | 44.7437 | 1.9745 | 25.2130 |
| 64 | 0.0059 | 45.6072 | 3.5198 | 14.4170 | 114 | 0.0000 | 44.7404 | 1.9572 | 25.4351 |
| 65 | 0.0052 | 45.5579 | 3.4638 | 14.6344 | 115 | 0.0000 | 44.7371 | 1.9401 | 25.6573 |
| 66 | 0.0047 | 45.5112 | 3.4095 | 14.8519 | 116 | 0.0000 | 44.7341 | 1.9233 | 25.8795 |
| 67 | 0.0042 | 45.4670 | 3.3570 | 15.0696 | 117 | 0.0000 | 44.7312 | 1.9068 | 26.1018 |
| 68 | 0.0038 | 45.4252 | 3.3061 | 15.2875 | 118 | 0.0000 | 44.7285 | 1.8906 | 26.3241 |
| 69 | 0.0034 | 45.3856 | 3.2568 | 15.5056 | 119 | 0.0000 | 44.7259 | 1.8746 | 26.5464 |
| 70 | 0.0030 | 45.3481 | 3.2089 | 15.7238 | 120 | 0.0000 | 44.7235 | 1.8589 | 26.7688 |
| 71 | 0.0027 | 45.3126 | 3.1625 | 15.9422 | 121 | 0.0000 | 44.7212 | 1.8435 | 26.9911 |
| 72 | 0.0024 | 45.2789 | 3.1174 | 16.1607 | 122 | 0.0000 | 44.7190 | 1.8284 | 27.2135 |
| 73 | 0.0022 | 45.2471 | 3.0736 | 16.3794 | 123 | 0.0000 | 44.7169 | 1.8135 | 27.4360 |
| 74 | 0.0020 | 45.2169 | 3.0311 | 16.5982 | 124 | 0.0000 | 44.7149 | 1.7988 | 27.6584 |
| 75 | 0.0018 | 45.1884 | 2.9897 | 16.8172 | 125 | 0.0000 | 44.7131 | 1.7844 | 27.8809 |
| 76 | 0.0016 | 45.1614 | 2.9495 | 17.0363 | 126 | 0.0000 | 44.7113 | 1.7702 | 28.1034 |
| 77 | 0.0014 | 45.1358 | 2.9104 | 17.2556 | 127 | 0.0000 | 44.7097 | 1.7562 | 28.3259 |
| 78 | 0.0013 | 45.1115 | 2.8723 | 17.4750 | 128 | 0.0000 | 44.7081 | 1.7425 | 28.5484 |
| 79 | 0.0011 | 45.0886 | 2.8352 | 17.6946 | 129 | 0.0000 | 44.7066 | 1.7289 | 28.7710 |
| 80 | 0.0010 | 45.0669 | 2.7991 | 17.9142 | 130 | 0.0000 | 44.7052 | 1.7156 | 28.9936 |

**TABLE 12j (continued)**   Zero Thickness Microstrip Dimensions, Effective Dielectric Constant, and PUL Capacitance and Inductance for Er =85

| Zo [Ohms] | W/h | Keff | pF/cm | nH/mm | Zo [Ohms] | W/h | Keff | pF/cm | nH/mm |
|---|---|---|---|---|---|---|---|---|---|
| 81 | 0.0009 | 45.0463 | 2.7639 | 18.1340 | 131 | 0.0000 | 44.7038 | 1.7025 | 29.2162 |
| 82 | 0.0008 | 45.0268 | 2.7296 | 18.3539 | 132 | 0.0000 | 44.7026 | 1.6896 | 29.4388 |
| 83 | 0.0007 | 45.0084 | 2.6962 | 18.5739 | 133 | 0.0000 | 44.7014 | 1.6768 | 29.6614 |
| 84 | 0.0007 | 44.9909 | 2.6636 | 18.7941 | 134 | 0.0000 | 44.7002 | 1.6643 | 29.8840 |
| 85 | 0.0006 | 44.9744 | 2.6317 | 19.0143 | 135 | 0.0000 | 44.6992 | 1.6519 | 30.1067 |
| 86 | 0.0005 | 44.9587 | 2.6007 | 19.2347 | 136 | 0.0000 | 44.6981 | 1.6398 | 30.3293 |
| 87 | 0.0005 | 44.9439 | 2.5704 | 19.4551 | 137 | 0.0000 | 44.6972 | 1.6278 | 30.5520 |
| 88 | 0.0004 | 44.9299 | 2.5408 | 19.6757 | 138 | 0.0000 | 44.6963 | 1.6160 | 30.7747 |
| 89 | 0.0004 | 44.9166 | 2.5118 | 19.8963 | 139 | 0.0000 | 44.6954 | 1.6043 | 30.9974 |
| 90 | 0.0003 | 44.9040 | 2.4836 | 20.1171 | 140 | 0.0000 | 44.6946 | 1.5929 | 31.2201 |
| 91 | 0.0003 | 44.8921 | 2.4560 | 20.3379 | 141 | 0.0000 | 44.6938 | 1.5816 | 31.4429 |
| 92 | 0.0003 | 44.8808 | 2.4290 | 20.5588 | 142 | 0.0000 | 44.6931 | 1.5704 | 31.6656 |
| 93 | 0.0002 | 44.8701 | 2.4026 | 20.7798 | 143 | 0.0000 | 44.6924 | 1.5594 | 31.8883 |
| 94 | 0.0002 | 44.8600 | 2.3767 | 21.0009 | 144 | 0.0000 | 44.6917 | 1.5486 | 32.1111 |
| 95 | 0.0002 | 44.8504 | 2.3515 | 21.2220 | 145 | 0.0000 | 44.6911 | 1.5379 | 32.3339 |
| 96 | 0.0002 | 44.8414 | 2.3267 | 21.4432 | 146 | 0.0000 | 44.6905 | 1.5273 | 32.5567 |
| 97 | 0.0002 | 44.8328 | 2.3025 | 21.6645 | 147 | 0.0000 | 44.6899 | 1.5169 | 32.7794 |
| 98 | 0.0001 | 44.8247 | 2.2788 | 21.8859 | 148 | 0.0000 | 44.6894 | 1.5067 | 33.0022 |
| 99 | 0.0001 | 44.8170 | 2.2556 | 22.1073 | 149 | 0.0000 | 44.6889 | 1.4966 | 33.2250 |
| 100 | 0.0001 | 44.8097 | 2.2329 | 22.3288 | 150 | 0.0000 | 44.6884 | 1.4866 | 33.4478 |

*Notes:* Calculation of W/H has an error of less than 1%.

*Source:* Gupta, K.C., Garg, R., Bahl, I., Bhartia, P., *Microstrip Lines and Slotlines,* 2nd Ed., Artech House, Norwood, MA, 1996, 103.
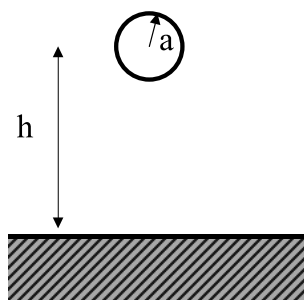
$$L_{WIR\,EoverGND} = \frac{\mu_0 \mu_r}{2\pi} \cosh^{-1}\frac{h}{a} \quad \text{(nH/m)} \qquad \text{for } h \gg a$$

**FIGURE 5**   Inductance of a wire over a ground plane. When consistent units are used for the wire radius, a, and the height over the ground plane, h, the formula provides an estimate of the inductance per unit length in (nH/m).

## Bondwires, Ribbons, Mesh

The assembly of semiconductor and hybrid integrated circuits for microwave and millimeter-wave frequencies generally requires the use of gold bondwires, ribbons, or mesh. The impedance of the interconnection must be accounted for in a good design. Unfortunately, there is no single accepted electrical model. The complexity required of the model will depend on the frequency of operation and the general impedance levels of the circuits being connected. At low frequencies and moderate to high impedances, the connection is frequently modeled as an inductor (sometimes in series with a resistor); at high frequencies, a full 3-D electromagnetic simulation may be required for accurate results. At intermediate points it may be modeled as a high impedance transmission line or as a lumped LC circuit. Note that

the resistances of the RF interconnects should be included in the design of extremely low-noise circuits as they will affect the noise figure. In connecting a semiconductor die to package leads, it may also be necessary to model the mutual inductances and interlead capacitances in addition to the usual self-inductances and shunt capacitance. Figure 5 illustrates one method of modeling bond wire inductance that has been shown adequate for many microwave applications. More sophisticated methods of modeling bond wires, ribbon or mesh are described in the references.

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