ΚΕΦΑΛΑΙΟ 2

Μικροκυματικά Στοιχεία – Τυπωμένες Γραμμές

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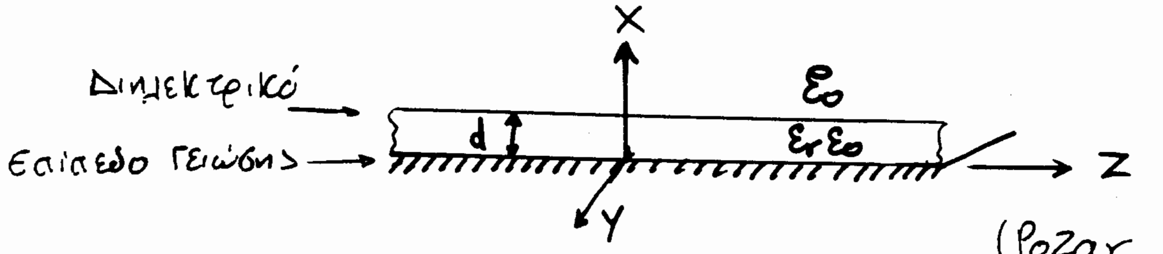
ΕΠΙΦΑΝΕΙΑΚΑ ΚΥΜΑΤΑ ΣΕ ΓΕΙΩΜΕΝΟ ΔΙΗΛΕΚΤΡΙΚΟ



(Pozar σελ. 170)

- Επιφανειακοί ρυθμοί διεγείρονται σε : μη-γειωμένη (και γειωμένη) διηλεκτρική πλάκα, διηλεκτρική ράβδο, αγώγιμη ράβδο με διηλεκτρική επικάλυψη και  "corrugated" αγωγούς

→ Τα Επιφανειακά κύματα χαρακτηρίζονται από την μεγάλη εξασθένιση στην κάθετη διεύθυνση προς το διηλεκτρικό (άξονας-x; e^{-ax}) και διάδοση παράλληλα με το αγώγιμο επίπεδο.

- Όσο αυξάνεται η συχνότητα τόσο περισσότερο το Η/Μ πεδίο περιορίζεται μέσα και κοντά στο διηλεκτρικό ⟹

⟹ Επιφανειακός Κυματοδηγός

(Τυπωμένες μικροκυματικές γραμμές - Μικροταινιακές, ταινιογραμμές κ.

ΡΥΘΜΟΙ ΤΜ → TM_z → $H_z = 0$

Υποθέτουμε: { Διάδοση στην διεύθυνση $-z$ $\Longrightarrow \bar{E}, \bar{H} \propto e^{-j\beta}$
Αμετάβλητο πεδίο στην διεύθυνση $-y \Longrightarrow \partial/\partial y = 0$
(Η διάταξη εκτείνεται απεριόριστα στην διεύθυνση $-y$)

Η συνιστώσα E_z πληρεί την εξίσωση κύματος:

Περιοχή αέρα $x \geq d$: $\bar{\nabla}_t^2 E_{z1} + k_0^2 E_{z1} = 0$ ①

Περιοχή Διηλεκτρικού $0 \leq x \leq d$: $\bar{\nabla}_t^2 E_{z2} + k^2 E_{z2} = 0$ ②

όπου $\bar{\nabla}_t^2 = \partial/\partial x^2 + \frac{\partial}{\partial z^2}$

$k_0^2 = \omega^2 \mu_0 \varepsilon_0 \quad k_e^2 = \omega^2 \mu \varepsilon = \varepsilon_r k_0^2$ }

Θέτουμε: $E_z(x,y,z) = e_z(x,y) e^{-j\beta}$

άρα: $\bar{\nabla}_t^2 E_z = \frac{\partial^2 e_z}{\partial x^2} + (-j\beta)^2 e_z$

① → $$\frac{\partial^2 e_{z1}(x,y)}{\partial x^2} + \overbrace{(k_0^2 - \beta^2)}^{\to -h^2} e_{z1}(x,y) = 0$$ για $x \geq d$

② → $$\frac{\partial^2 e_{z2}(x,y)}{\partial x^2} + \overbrace{(\varepsilon_r k_0^2 - \beta^2)}^{\to +k_e^2} e_{z2}(x,y) = 0$$ για $0 \leq x \leq d$

ΡΥΘΜΟΙ TM ⟷ Επιφανειακά Κύματα $H_z=0$

Λύση Εξισώσεων Κύματος:

Περιοχή αέρα $e_{z1}(x,y) = C e^{hx} + D e^{-hx}$ $x \geq d$ ③

-״- Διηλεκτρικού $e_{z2}(x,y) = A\sin(k_e x) + B\cos(k_e x)$ $0 \le x \le$

Οριακές Συνθήκες: όπου $h^2 = -(k_0^2-\beta^2)$ και $k_e^2 = +(\varepsilon_r k_0^2 - \beta^2)$

α) Μηδενισμός του εφαπτομενικού Ηλεκτρικού πεδίου στο γειωμένο αγώγιμο επίπεδο: $E_{z2}|_{x=0} = 0$: ④ $\longrightarrow B=0$

β) Οριακή συνθήκη ακτινοβολίας

$E_{z1}|_{x\to\infty}$ → πεπερασμένο πεδίο και πεπερασμένη ενέργεια μακριά από την πηγή → $C=0$

γ) Συνέχεια του εφαπτομενικού ηλεκτρικού πεδίου στην οριακή επιφάνεια αέρα - διηλεκτρικού $E_{z1}|_{x=d^+} = E_{z2}|_{x=d^-}$ και $E_{y1}|_{x=d^+} = E_{y2}|_{x=}$

$$\left.\begin{array}{l} e_{z1}(x,y) = D e^{-hx} \\ e_{z2}(x,y) = A\sin(k_e x) \end{array}\right\} \Downarrow\; A\sin(k_e d) = D e^{-hd} \quad ⑤$$

$$\partial/\partial y = 0 \rightarrow E_y = 0$$

δ) Συνέχεια του εφαπτομενικού μαγνητικού πεδίου ($\bar{H}_t$) στην οριακή επιφάνεια αέρα - διηλεκτρικού:

$$\bar{H}_t = H_y\hat{y} + \underset{0}{\cancel{H_z}}\hat{z} \Longrightarrow H_{y1}|_{x=d^+} = H_{y2}|_{x=d^-}$$

$$\Updownarrow$$

$$H_y = \frac{-j\omega\varepsilon}{k_c^2}\frac{\partial E_z}{\partial x}$$

$$\frac{\cancel{(-j\omega\varepsilon_0)}}{\underset{\to(-h^2)}{k_{c1}^2}}(-h)\cdot D e^{-hd} = \frac{\cancel{(-j\omega\varepsilon_0)}\varepsilon_r}{\underset{\to(k_e^2)}{k_{c2}^2}}(A k_e)\cos(k_e d) \quad ⑥$$

Κυματαριθμοί αποκοπής:

$$\left.\begin{array}{l} h = jk_{x1},\ \beta = k_z,\ k_e = k_{x2} \\ k_c^2 = k_x^2 + k_y^2 \\ k_c^2 + k_z^2 = k^2 \end{array}\right\} \begin{array}{l} k_{c1}^2 = k_0^2 - \beta^2 = -h^2 \Longleftrightarrow h^2 = \beta^2 - k_0^2 \\ k_{c2}^2 = k^2 - \beta^2 = +k_e^2 \longleftrightarrow k_e^2 = -(\beta^2 - \varepsilon_r k_0^2) \end{array}$$

$$\left.\begin{array}{l} ⑤ \longrightarrow A\sin(k_e d) = D e^{-hd} \\ ⑥ \longrightarrow \dfrac{\varepsilon_r A}{k_e}\cos(k_e d) = +\dfrac{D}{h} e^{-hd} \end{array}\right\} k_e\tan(k_e d) = +\varepsilon_r h$$

(Shaums σελ 164) $\dfrac{d^2y}{dx^2} + by = 0 \rightarrow \begin{cases} y = C_1 e^{m_1 x} + C_2 e^{m_2 x} & \text{όπου } m_{1,2}^2 = -b \\ y = C_1\cos(qx) + C_2\sin(qx) & \text{όπου } q^2 = +b \end{cases}$

ΡΥΘΜΟΙ ΤΕ $\longleftrightarrow$ Επιφανειακού Κύματος $E_z=0$, $H_z\neq 0$

Εξίσωση Κύματος με $\partial/\partial z=-j\beta$ και $\partial/\partial y=0$, $H_z=h_z(x,y)e^{-j}$

Περιοχή αέρα: $\bar{\nabla}_t^2 H_{z1}+k_0^2 H_{z1}=0 \Leftrightarrow \dfrac{\partial^2 h_z(x,y)}{\partial x^2}+(k_0^2-\beta^2)h_{z1}(x,y)=0$

Περιοχή διηλεκτρικού: $\bar{\nabla}_t^2 H_{z2}+k^2 H_{z2}=0 \Leftrightarrow \dfrac{\partial^2 h_{z2}(x,y)}{\partial x^2}+(\varepsilon_r k_0^2-\beta^2)h_{z2}(x,y)=$

Λύσεις:

Περιοχή αέρα: $h_{z1}(x,y)=Ce^{hx}+De^{-hx}$ για $x\geq d$

—||— διηλεκτρικού: $h_{z2}(x,y)=A\sin(k_m x)+B\cos(k_m x)$ $0\leq x\leq d$

όπου $-h^2=k_0^2-\beta^2=k_{c1}$, $k_m^2=\varepsilon_r k_0^2-\beta^2=k_{c2}$

Οριακές Συνθήκες:

α) Μηδενισμός Εφαπτομενικών Ηλεκτρ. Πεδίου στο γειωμένο αγ. επ

$E_{y2}=\dfrac{-j\omega\mu}{k_{c2}^2}\dfrac{\partial H_{z2}}{\partial x}\Big|_{x=0}=0 \longrightarrow \dfrac{\partial h_{z2}}{\partial x}=k_m[A\cos(k_m x)-B\sin(k_m x)]\Big|_{x=0}=0$

$\rightarrow \boxed{A=0}$ και $h_{z2}(x,y)=B\cos(k_m x)$

β) Οριακή συνθήκη ακτινοβολίας

$H_{z1}\big|_{x\to\infty} \rightsquigarrow$ πεπερασμένο $\longrightarrow C=0$ και $h_{z1}(x,y)=De^{-hx}$

γ) Συνέχεια των Εφαπτομενικών Ηλεκτρ. Πεδίο στο όριο αέρα - διηλεκτρικού

$E_{y1}\big|_{x=d^+}=E_{y2}\big|_{x=d^-} \longrightarrow \dfrac{\cancel{-j\omega}\mu_0}{k_{c1}^2}\cancel{e^{-j\beta z}}\dfrac{\partial h_{z1}}{\partial x}\Big|_{x=d^+}=\dfrac{\cancel{-j\omega}\mu}{k_{c2}^2}\cancel{e^{-j\beta z}}\dfrac{\partial h_{z2}}{\partial x}\Big|_{x=}$

$\rightarrow \dfrac{\mu_0}{(-h^2)}(-\cancel{h})\cdot De^{-hd}=\dfrac{\mu}{k_m^{\cancel{2}}}(-\cancel{k_m})B\sin(k_m d)$ ①

δ) Συνέχεια των Εφαπτομενικών Μαγν. Πεδίου στο όριο αέρα - διηλεκτρικού

$\bar{H}_t=H_y\hat{y}+H_z\hat{z}$ αλλά $H_y=\dfrac{-j\beta}{k_c^2}\dfrac{\partial H_z}{\partial y}$ για $\partial/\partial y=0 \rightarrow H_y=0$

$H_{z1}\big|_{x=d^-}=H_{z2}\big|_{x=d^+} \longrightarrow h_{z1}\big|_{x=d^-}=h_{z2}\big|_{x=d^+} \rightarrow De^{-hd}=B\cos(k_m d)$ ②

$$\left.\begin{aligned} &① \quad \frac{\cancel{\mu_0}}{h}De^{-hd}=-\frac{\mu_r\cancel{\mu_0}}{k_m}B\sin(k_m d) \\ &② \quad De^{-hd}=B\cos(k_m d) \end{aligned}\right\} h=\frac{-k_m}{\mu_r}\cot(k_m d) \Rightarrow k_m\cot(k_m d)=-h$$

ΣΥΣΧΕΤΙΣΗ ΕΓΚΑΡΣΙΩΝ ΚΑΙ ΑΞΟΝΙΚΩΝ ΣΥΝΙΣΤΟΥΣΩΝ

- Διάδοση κατά την διεύθυνση -z : $\bar{E}, \bar{H} \propto e^{-j\beta z} \rightarrow \frac{\partial}{\partial z} = -j\beta$
- Συνδιάζοντας τις δύο εξισώσεις στροφής για χώρο χωρίς πηγές $\bar{J}=0$, $\rho=0$:

$$\bar{\nabla} \times \bar{E} = -j\omega\mu\bar{H} \qquad \bar{\nabla} \times \bar{H} = j\omega\varepsilon\bar{E}$$

Ρυθμοί TE → TE_z :

$E_z = 0$, $H_z \neq 0$

$$E_x = \frac{-j\omega\mu}{k_c^2}\frac{\partial H_z}{\partial y}$$

$$E_y = \frac{j\omega\mu}{k_c^2}\frac{\partial H_z}{\partial x}$$

$$H_x = \frac{-j\beta}{k_c^2}\frac{\partial H_z}{\partial x}$$

$$H_y = \frac{-j\beta}{k_c^2}\frac{\partial H_z}{\partial y}$$

Ρυθμοί TM → TM_z

$H_z = 0$, $E_z \neq 0$

$$E_x = \frac{-j\beta}{k_c^2}\frac{\partial E_z}{\partial x}$$

$$E_y = \frac{-j\beta}{k_c^2}\frac{\partial E_z}{\partial y}$$

$$H_x = \frac{j\omega\varepsilon}{k_c^2}\frac{\partial E_z}{\partial y}$$

$$H_y = \frac{-j\omega\varepsilon}{k_c^2}\frac{\partial E_z}{\partial x}$$

όπου $\beta = \sqrt{k^2 - k_c^2} \longrightarrow k_c^2 = k^2 - \beta^2$ και $\gamma \rightarrow j\beta$ $(\alpha \neq 0)$

$k_c^2 = k_x^2 + k_y^2$, $k_c^2 + k_z^2 = k^2$, $\beta = k_z$

$$H_z = \begin{cases} D\, e^{-hx} e^{-j\beta z} & \text{αέρας} \\ B\cos(k_m x)\, e^{-j\beta z} & \text{διηλεκτρ.} \end{cases}$$

$$E_z = \begin{cases} D\, e^{-hx}\; e^{-j\beta z} & \text{αέρας} \\ A\sin(k_e x)\; e^{-j\beta z} & \text{διηλεκτρ.} \end{cases}$$

$$k_m \cot(k_m d) = -\mu_r h$$

$$D = B\, e^{hd}\cos(k_m d)$$

$$h^2 = \beta^2 - k_0^2 = -k_{c1}^2$$

$$k_m^2 = k^2 - \beta^2 = \varepsilon_r\mu_r k_0^2 - \beta^2 = k_{c2}^2$$

$$\beta^2 = h^2 + k_c^2 = \varepsilon_r\mu_r k_0^2 - k_m^2$$

$$h^2 + k_m^2 = k_0^2(\varepsilon_r\mu_r - 1)$$

$$k_e \tan(k_e d) = \varepsilon_r h$$

$$D = A\, e^{hd}\sin(k_e d)$$

$$h^2 = \beta^2 - k_0^2 = -k_{c1}^2$$

$$k_e^2 = k^2 - \beta^2 = \varepsilon_r\mu_r k_0^2 - \beta^2 = k_{c2}^2$$

$$\beta^2 = h^2 + k_0^2 = \varepsilon_r\mu_r k_0^2 - k_e^2$$

$$h^2 + k_e^2 = k_0^2(\varepsilon_r\mu_r - 1)$$

Η/Μ ΠΕΔΙΟ ΕΠΙΦΑΝΕΙΑΚΩΝ ΡΥΘΜΩΝ

Περιοχή αέρα $x \geq d$

ΡΥΘΜΟΙ ΤΜ

$$E_z = A\sin(k_e d)\, e^{-h(x-d)} e^{-j\beta z}$$

$$E_x = \frac{-j\beta}{h} A\sin(k_e d)\, e^{-h(x-d)} e^{-j\beta z}$$

$$E_y = 0 \;,\quad H_x = 0$$

$$H_y = -j\frac{\omega\varepsilon_0}{h} A\sin(k_e d)\, e^{-h(x-d)} e^{-j\beta z}$$

$$H_z = 0$$

ΡΥΘΜΟΙ ΤΕ

$$H_z = B\cos(k_m d)\, e^{-h(x-d)} e^{-j\beta z}$$

$$E_x = 0$$

$$E_y = j\frac{\omega\mu_0}{h} B\cos(k_m d)\, e^{-h(x-d)} e^{-j\beta z}$$

$$E_z = 0 \;,\quad H_y = 0$$

$$H_x = \frac{-j\beta}{h} B\cos(k_m d)\, e^{-h(x-d)} e^{-j\beta z}$$

Περιοχή διηλεκτρικού $0 \leq x \leq d$

$$E_z = A\sin(k_e x)\, e^{-j\beta z}$$

$$E_x = \frac{-j\beta}{k_e} A\cos(k_e x)\, e^{-j\beta z}$$

$$E_y = 0 \;,\quad H_x = 0$$

$$H_y = -j\frac{\omega\varepsilon_0\varepsilon_r}{k_e} \cdot A\cos(k_e x)\, e^{-j\beta z}$$

$$H_z = 0$$

$$H_z = B\cos(k_m x)\, e^{-j\beta z}$$

$$E_x = 0$$

$$E_y = -j\frac{\omega\mu_0\mu_r}{k_m} B\sin(k_m x)\, e^{-j\beta z}$$

$$E_z = 0 \;,\quad H_y = 0$$

$$H_x = \frac{j\beta}{k_m} B\sin(k_m x)\, e^{-j\beta z}$$

Χαρακτηριστικές Εξισώσεις

Ρυθμοί ΤΜ

$$\left.\begin{aligned} k_e\tan(k_e d) &= \varepsilon_r h \\ h^2 + k_e^2 &= k_0^2(\varepsilon_r\mu_r - 1) \end{aligned}\right\}$$

Ρυθμοί ΤΕ

$$\left\{\begin{aligned} k_m\cot(k_m d) &= -\mu_r h \\ h^2 + k_m^2 &= k_0^2(\varepsilon_r\mu_r - 1) \end{aligned}\right.$$

Σταμάτημα της διάδοσης $\beta = 0$

$$\left.\begin{aligned} \beta^2 &= h^2 + k_0^2 = 0 \\ \beta^2 &= \varepsilon_r\mu_r k_0^2 - k_m^2 = 0 \end{aligned}\right\} \begin{aligned} h^2 &= -k_0^2 \\ k_m^2 &= \varepsilon_r\mu_r k_0^2 \end{aligned}$$

$$\left.\begin{aligned} \beta^2 &= h^2 + k_0^2 = 0 \\ \beta^2 &= \varepsilon_r\mu_r k_0^2 - k_m^2 = 0 \end{aligned}\right\} \begin{aligned} h^2 &= -k_0^2 \\ k^2 & \end{aligned}$$

Συχνότητες Αποκοπής Επιφανειακών Ρυθμών: $(h=0)$

Ρυθμοί TM_n^z

- Χαρακτηριστική Εξίσωση:

$$\begin{cases} K_c d \cdot \tan(K_c d) = \varepsilon_r h \cdot d & (1) \\ K_c^2 d^2 + h^2 d^2 = k_0^2 (\varepsilon_r \mu_r - 1) d^2 & (2) \end{cases}$$

- Αποκοπή Επιφανειακών Ρυθμών = Σταμάτημα της διάδοσης (εκθετικής εξασθένησης) στον αέρα: $h=0$

- Διάγραμμα 4.19: Αποκοπή TM_n-ρυθμών: $\leftrightarrow K_c d = n \cdot \pi = 0, \pi, 2\pi$

(2) για $h=0 \rightarrow K_c = k_0 \sqrt{\varepsilon_r \mu_r - 1}$ όπου $k_0 = \frac{\omega}{c} = \frac{2\pi f}{c}$

$\hookrightarrow K_c d = k_0 d \sqrt{\varepsilon_r \mu_r - 1} = n \cdot \pi$ και $n = 0, 1, 2, \ldots$

$\hookrightarrow$ Συχνότητες Αποκοπής: $\frac{2\pi f_c}{c} \cdot d \cdot \sqrt{\varepsilon_r \mu_r - 1} = n\pi$; $n = 0, 1, 2 \ldots$

$$\boxed{f_{cn}^{TM} = \frac{n \cdot c}{2d\sqrt{\varepsilon_r \mu_r - 1}}}$$

$n = 0 \rightarrow f_{c0}^{TM} = 0$

$n = 1 \rightarrow f_{c1}^{TM} = \frac{c}{2d\sqrt{\varepsilon_r \mu_r - 1}}$

Ρυθμοί TE_n^z

- Χαρακτηριστική Εξίσωση

$$\begin{cases} K_c d \cdot \cot(K_c d) = -\mu_r \cdot h \\ K_c^2 d + h^2 d = k_0^2 (\varepsilon_r - 1) d^2 \end{cases}$$

- Αποκοπή $\leftrightarrow h = 0 \rightarrow K_c^2 = k_0^2 (\varepsilon_r - 1)$

$\hookrightarrow$ Διάγραμμα 4.20 $\rightarrow K_c d = (2n-1)\frac{\pi}{2}$ για $n = 1, 2, 3, \ldots$

$\hookrightarrow$ Συχνότητα αποκοπής: $f_{cn}^{TE} = \frac{(2n-1)c}{4d\sqrt{\varepsilon_r - 1}}$ για $n = 1, 2, 3, \ldots$ 2.26 mm

$\hookrightarrow$ Αποφυγή της διέγερσης στον 1ου TE ρυθμού: 1.15 mm

$f < f_{c1}^{TE} = \frac{c}{4d\sqrt{\varepsilon_r - 1}}$ $\varepsilon_r = 12$, $f = 10GHz$ $d \leq \frac{1}{\sqrt{n}}$ $d < \frac{c}{4f\sqrt{\varepsilon_r - 1}} = \frac{\lambda_0}{4\sqrt{\varepsilon_r - 1}}$ 1.15 mm $d \leq$

$$\boxed{\text{Επιλογή Πάχους Υποστρώματος: } d < \frac{\lambda_0}{4\sqrt{\varepsilon_r - 1}} = \frac{c}{4f\sqrt{\varepsilon_r - 1}}}$$

20 GHz

Παράδειγμα: RO-4003 $\varepsilon_r = 3.38$, $f = 10GHz$ $\Big\}$ $\lambda_0 = 30mm$, $d \leq 4.86mm$

$\hookrightarrow \varepsilon_r = 9.6$ (Αλουμίνα) $\rightarrow d \leq 2.56mm$

TM

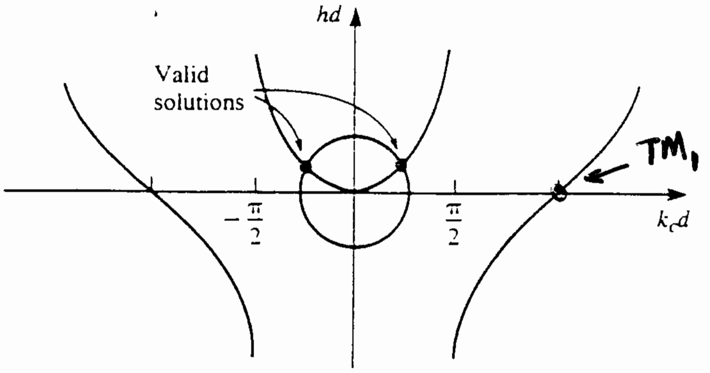


FIGURE 4.19 Graphical solution of the transcendental equation for the cutoff frequency of a TM surface wave mode of the grounded dielectric slab.

TE

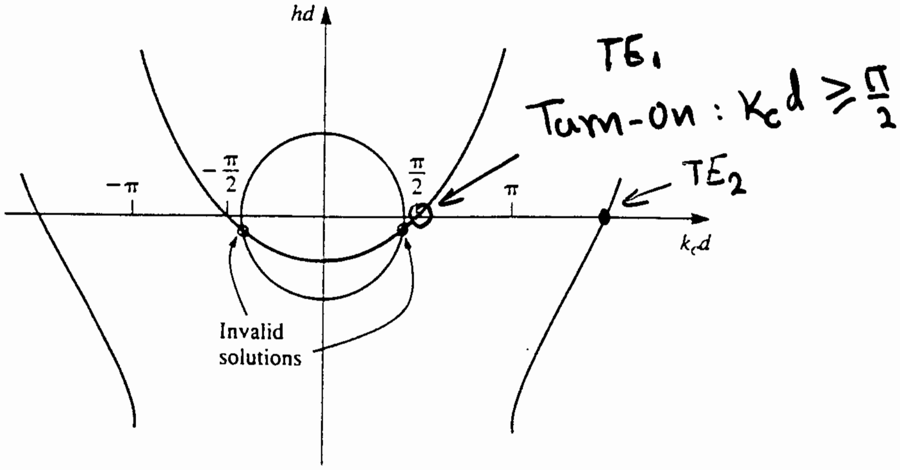


FIGURE 4.20 Graphical solution of the transcendental equation for the cutoff frequency of a TE surface wave mode. Figure depicts a mode below cutoff.

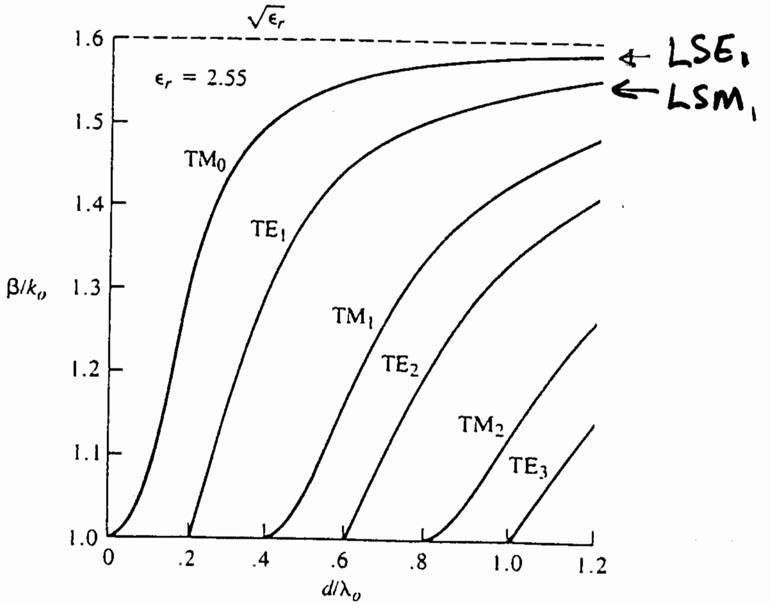
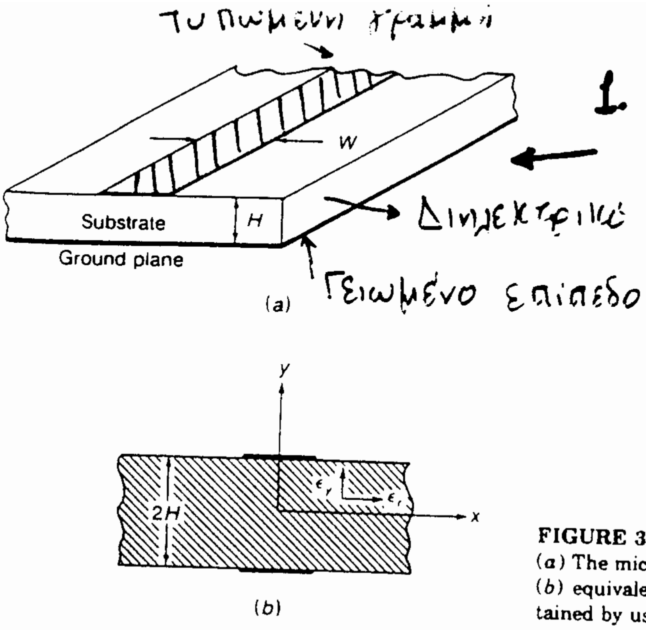


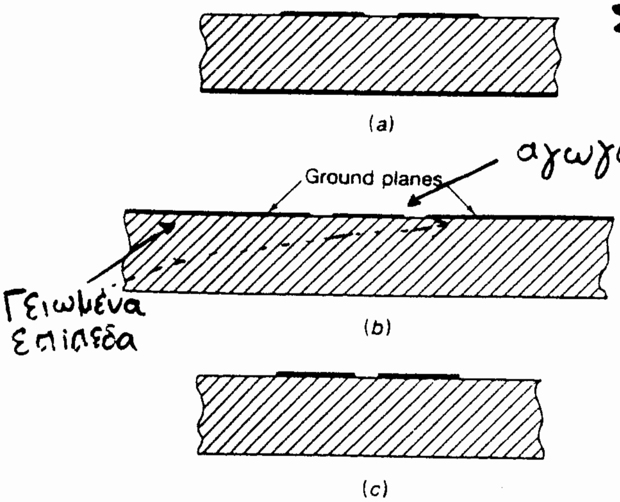
FIGURE 4.21 Surface wave propagation constants for a grounded dielectric slab with $\epsilon_r = 2.55$.



1. Μικροταινιακή γραμμή (Microstrip Line)

ΟΛΟΚΛΗΡΩΜΕΝΕΣ - ΤΥΠΩΜΕΝΕΣ ΜΙΚΡΟΚΥΜ. ΓΡΑΜΜΕΣ ΜΕΤΑΦΟΡΑΣ

FIGURE 3.17
(*a*) The microstrip transmission li
(*b*) equivalent parallel strip line
tained by using image theory.



Συζευγμένες μικροταινιακές γραμμές

2. Ομοεπίπεδες Γραμμές (ή κυματοδηγοί) (Coplanar waveguides)

FIGURE 3.18
(*a*) Coupled microstrip lines; (*b*) coplanar transmission line; (*c*) coplanar strip transmission line.

3. Υπερυψωμένη μικροταινιακή γραμμή (Suspended microstrip)

4. Ανεστραμμένη μικροτ. γραμμή (inverted microstri

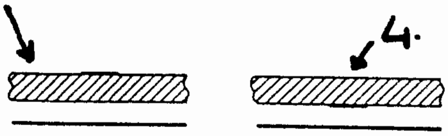
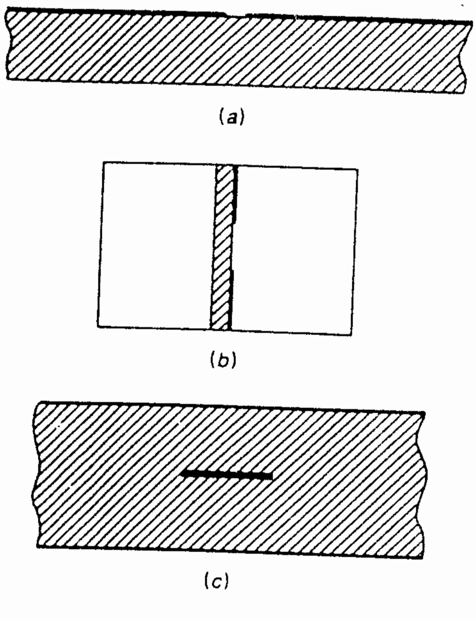


FIGURE 3.19
Suspended and inverted suspended microstrip line.



5. Σχισμοειδής Γραμμή (Slot line)

6. Θωρακισμένη σχισμοειδής γραμμή (Shielded slot line or Fin line)

7. Ταινιογραμμή (Stripline)

FIGURE 3.20
(*a*) Slot line; (*b*) shielded slot line or fin line; (*c*) strip line.

RF - MICROWAVE TRANSMISSION LINES

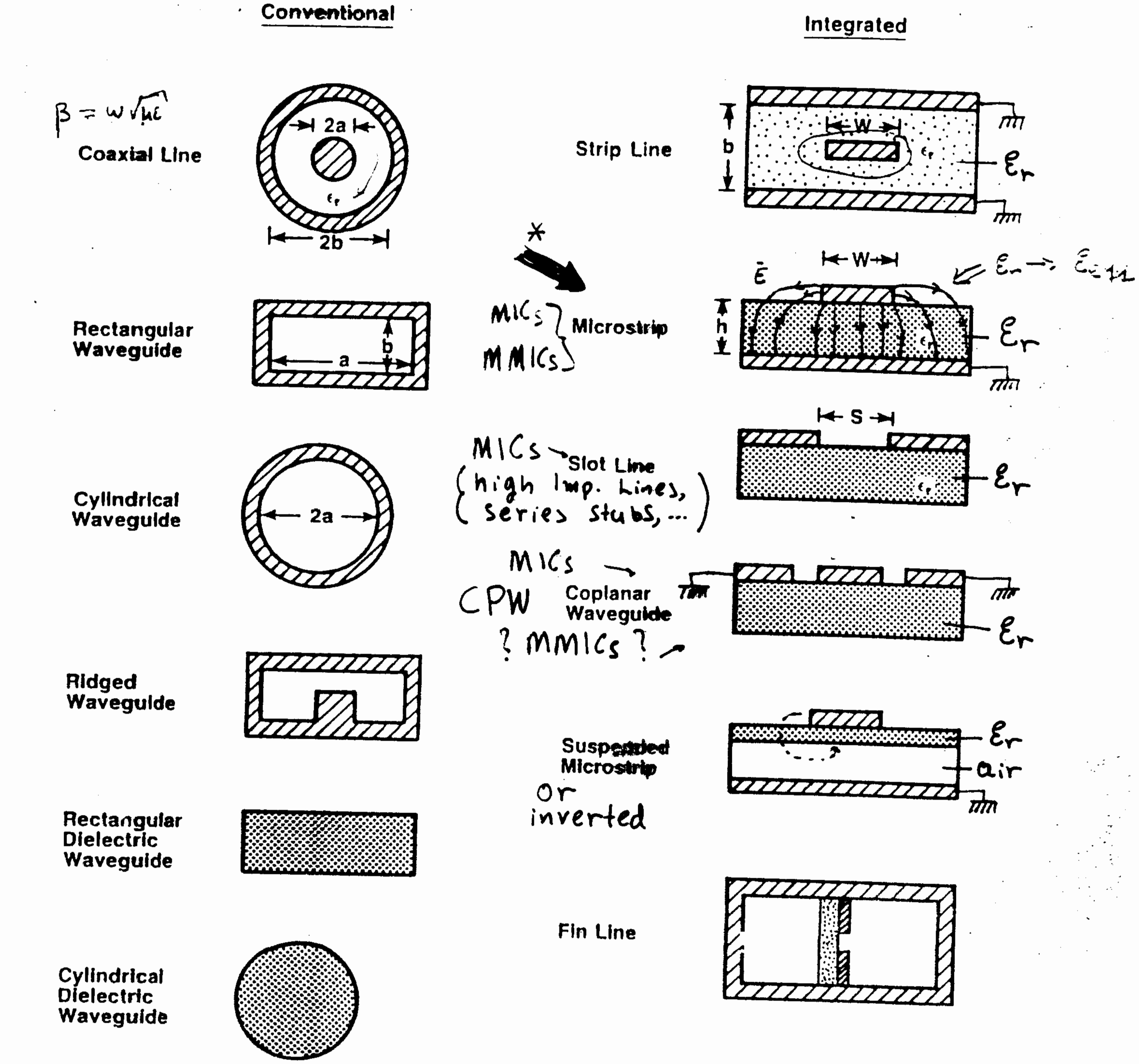


Figure 2.2 Transmission structures for microwave circuits.

⇒ Half Wavelength $\lambda_g/2$, Quarter Wavelength $\lambda_g/4$ or smaller Sections of these lines form the basic building blocks in most Microwave Circuits.

$$\lambda_g = \frac{2\pi}{\beta} = \frac{2\pi}{k_0\sqrt{\varepsilon_{eff}}} = \frac{2\pi}{2\pi/\lambda_0 \cdot \sqrt{\varepsilon_{eff}}} = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \Rightarrow \boxed{\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} = \frac{c}{f\sqrt{\varepsilon_{eff}}}}$$

Size Reduction Using High Dielectric Const. ε_r

Alumina Al_2O_3	GaAs → MMICs	Si	$\varepsilon_{eff} \propto \varepsilon_r$
$\varepsilon_r = 9.9$, $\tan\delta = 10^{-4}$	$\varepsilon_r = 12.9$, $\tan\delta = 6 \cdot 10^{-4}$	$\varepsilon_r = 12$, $\tan\delta = 10^{-3} \to 10^{-2}$	$\varepsilon_{eff} < \varepsilon_r$

INTEGRATED MICROWAVE TRANSMISSION LINES

Strip line : TEM dominant Mode.

- Simple analytical expressions ⟺ Electrostatic analysis
- difficult fabrication

Microstrip quasi - TEM dom. mode MICs and MMICs

→ Appoximate Quasi - Static models → $\begin{cases}\text{Closed form expr.} \\ Z_0, \varepsilon_{eff}\end{cases}$

⇒ → Almost exlusively used in MMICs

⇒ → Convenient only in series mounting

Suspended and Inverted MicroStrip Lines

- Higher Q than MicroStrips
- Wide range of Impedance values ⇒ Particularly suitable for filters

Slot Line dominant mode → Almost TE ⇒ MIC

- Useful in circuits requiring high Impedance Lines, Series Stubs, Short circuits

Z_0, λ_g approximate expressions by curve fitting the numerical resu

⇒ • Convenient only in Shunt mounting

Coplanar Lines C.P.W. , dominant mode is Quasi TEM MICs

\+ • Extensive applications in MICs

\+ • Flexibility in Circuit design

\+ • Avoiding vias for grounding (drilling holes)

(−) • Difficulties in the analysis ⟺ Available Approx. expr. for Z_0, ε_g

- Combine Microstrip and Slot line advantages

only series mounted comp. ↙ ↘ Only Shunt mounted component

- Interest for use in MMICs

Coupled Lines

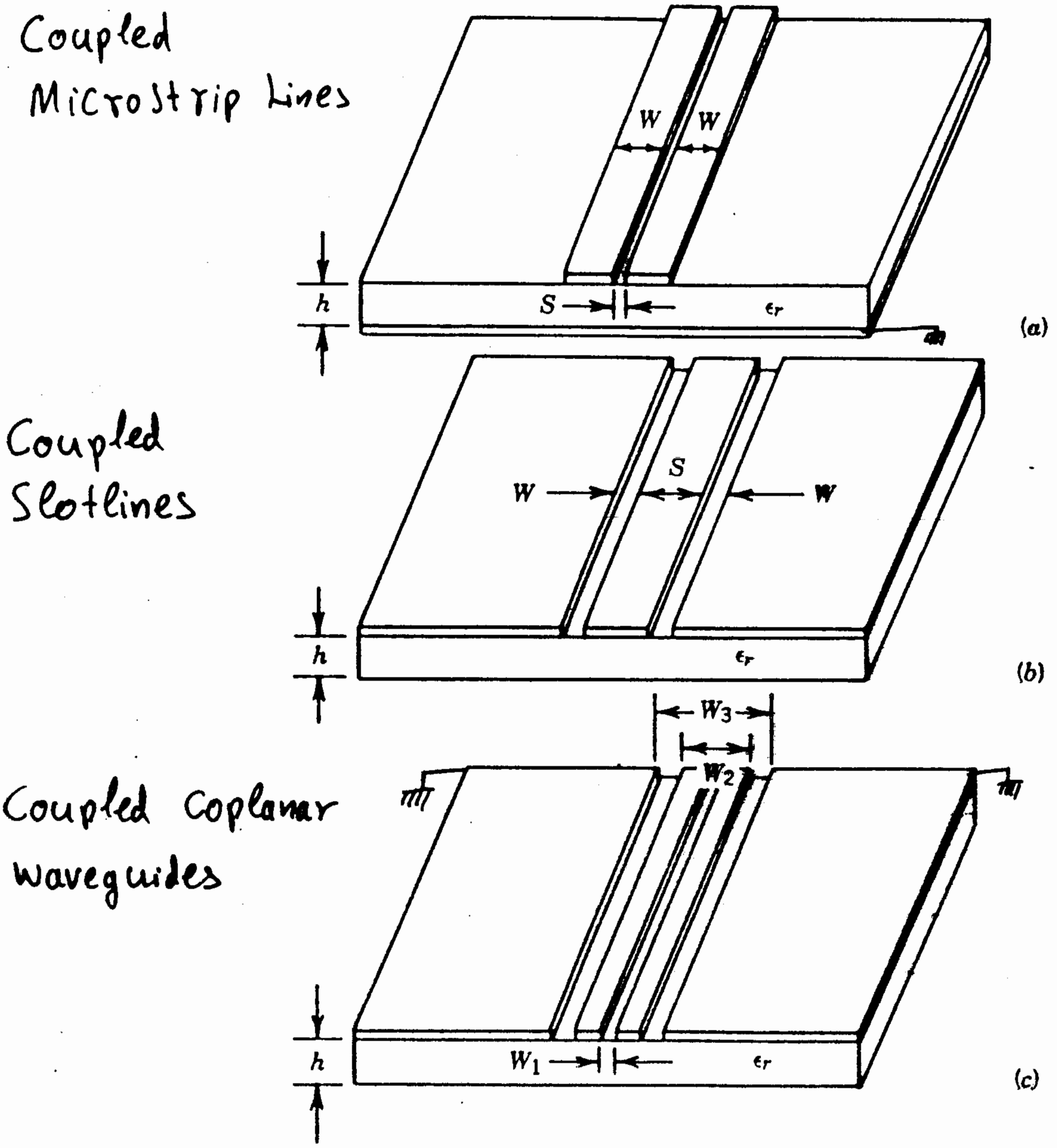


Figure D.9 Configurations of (*a*) coupled microstrip lines; (*b*) coupled slotlines; and (*c*) coupled coplanar waveguides.

Coupled Lines → Basic Elements for :

- directional Couplers
- Filters
- Phase Shifters
- Baluns

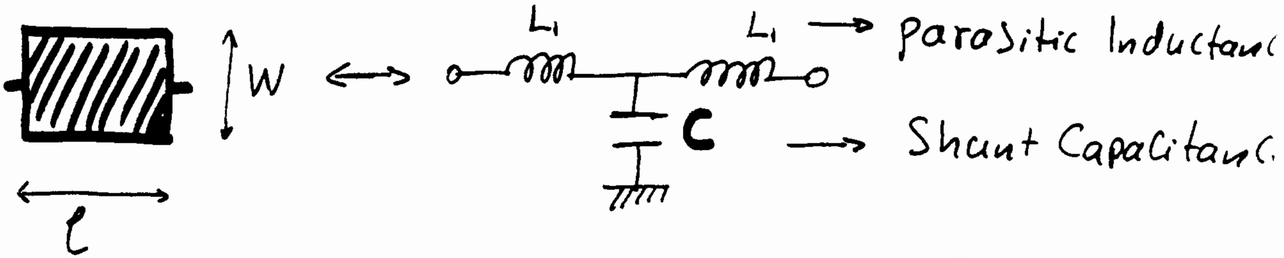
- Due to Coupling they support two different Modes of prop

$$\left.\begin{array}{llll} \text{Even Modes} & Z_{0e}, & v_{pe}, & \varepsilon_{eff,e} \\ & \# & \# & \# \\ \text{Odd Modes} & Z_{0o}, & v_{po}, & \varepsilon_{eff,o} \end{array}\right\} \Rightarrow$$

Desirable property for the design of Directional Couplers

Microstrip Capacitors MICs and MMICs

Wide Microstrip Lines (or Stubs) = Shunt Capacito

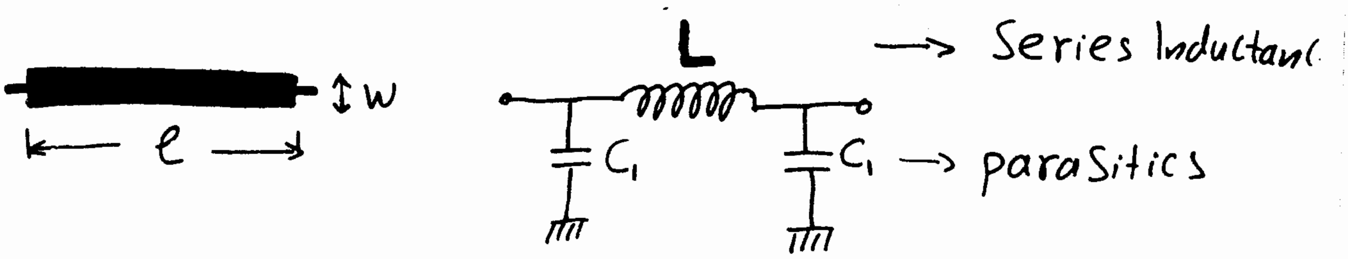


$0 \le C \le 0.1\,pF$ design: $\ell \simeq \frac{\lambda_g}{2\pi} \cdot \sin^{-1}(\omega . C . Z_o)$

$$\frac{L}{2} = L_1 = \frac{Z_o}{2\omega} \sin\left(\frac{2\pi \ell}{\lambda_g}\right)$$

Microstrip Inductors MICs and MMICs

Narrow Microstrip Lines

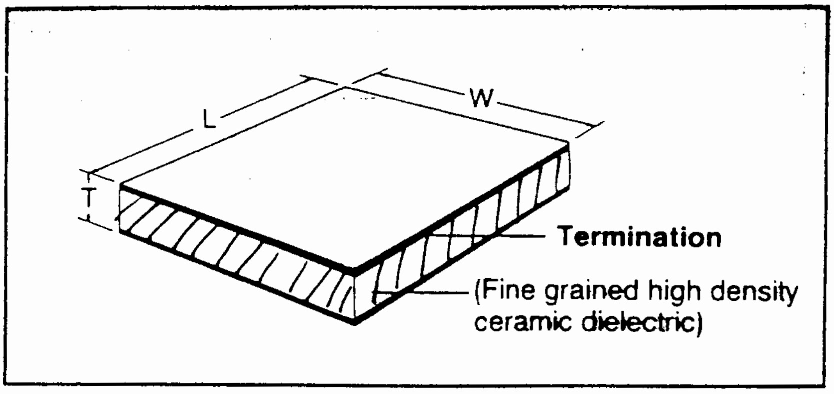


$L < 2$ to $3\,nH$ design: $\ell \approx \frac{\lambda_g}{2\pi} \sin^{-1}\left(\frac{\omega L}{2\pi}\right)$ $\leftarrow Z_o$

$$C_1 = \frac{C}{2} = \frac{1}{2\omega Z_o} \tan\left(\frac{\pi \ell}{\lambda_g}\right)$$

CHIP CAPACITORS → Used in Hybrid MICs

Single-layer



Metal-Insulator-Metal

⇓

MIM

$0.1pF \le C \le 25pF$

Multi-layer

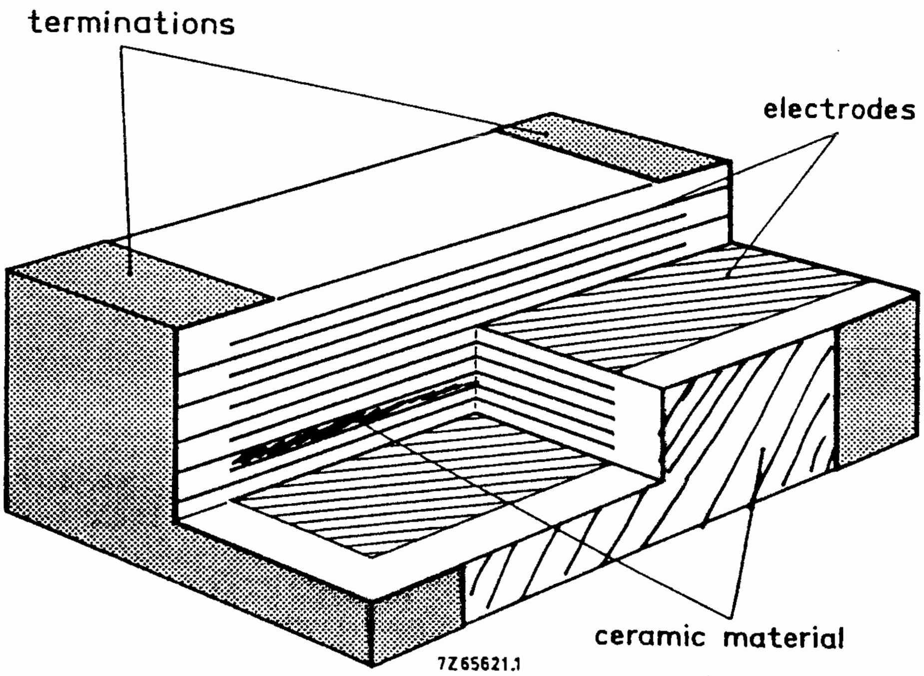


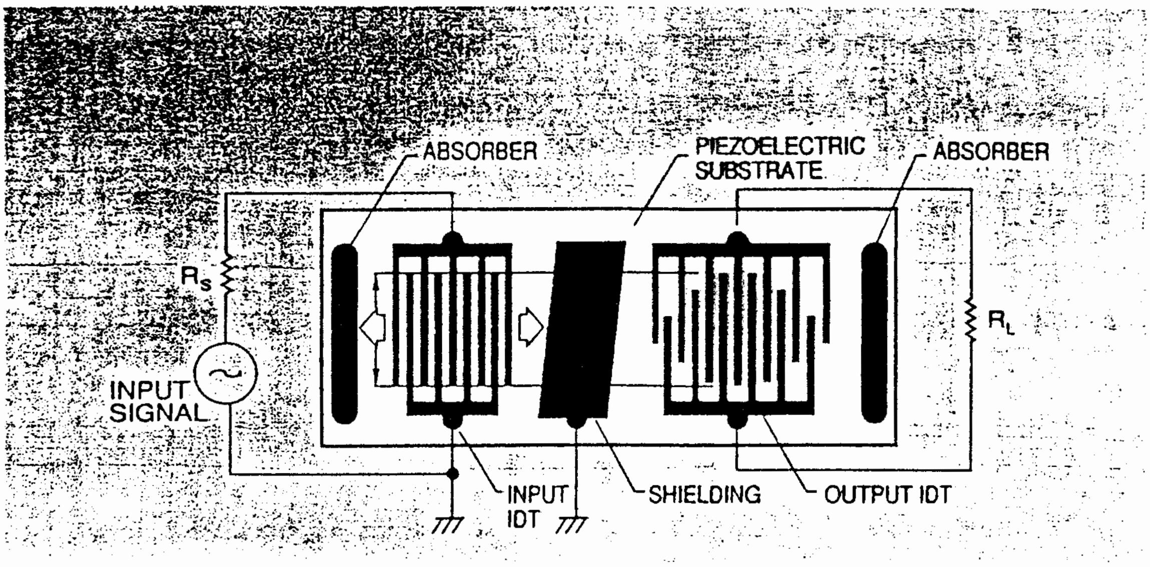
Fig.1 Construction of a ceramic multilayer capacitor.

Smaller distance

↓

Larger C

SAW FILTERS (Band-Pass)



D.4 MONOLITHIC ELEMENTS for MMICs

Interdigital Capacitor

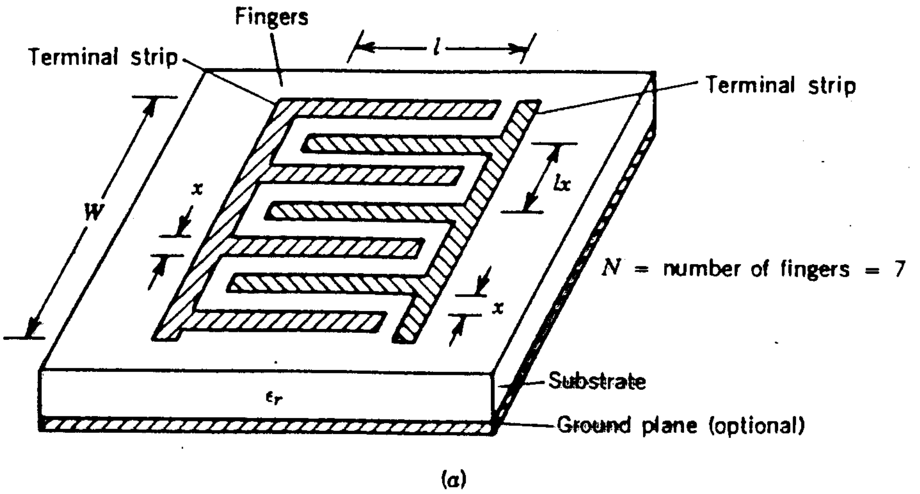


Figure D.22 (*a*) Configuration of an interdigital capacitor.

$0.05\ pF \le C \le 0.5\ pF$

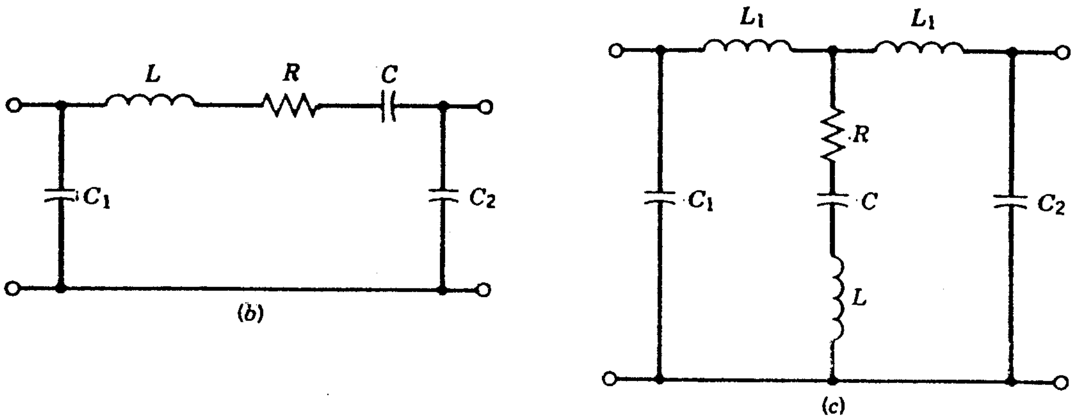


Figure D.22 (*b*) Equivalent circuit for series mounting; (*c*) Equivalent circuit for shunt mounting.

Methods: The capacitance between two sets of digits in interdigital structure is found by using the capacitance formula for the odd mode in coupled microstrip lines, with the ground plane spacing tending to an infinitely large value.

- Schottky Junction Capacitors

$0.5pF \le C \le 100pF$ Voltage dependent

- Metal - Insulator - Metal M.I.M Capacitors

$0.1pF \le C \le 25pF$

Interdigital Rectangular and Spiral Inductor

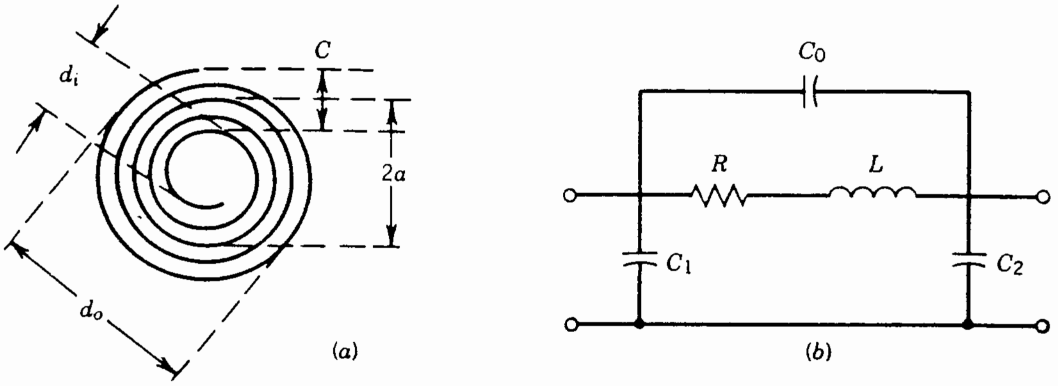


Figure D.23 (*a*) Configuration of a spiral inductor; (*b*) Equivalent circuit for a spiral inductor.

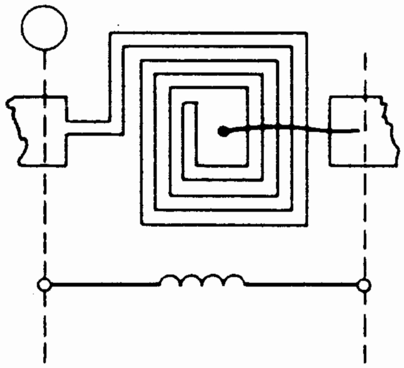


Figure D.24 Interdigital rectangular inductor layout and the equivalent circuit.

Interdigital transformer

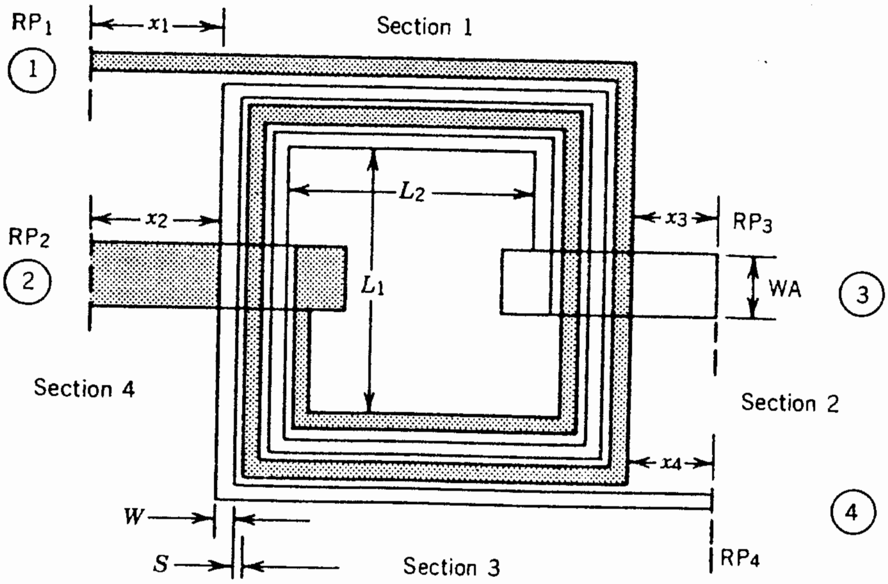


Figure D.25 Geometry parameters for the module PLTRAN describing the general transformer geometry.

GaAs— MMIC Spiral Inductor

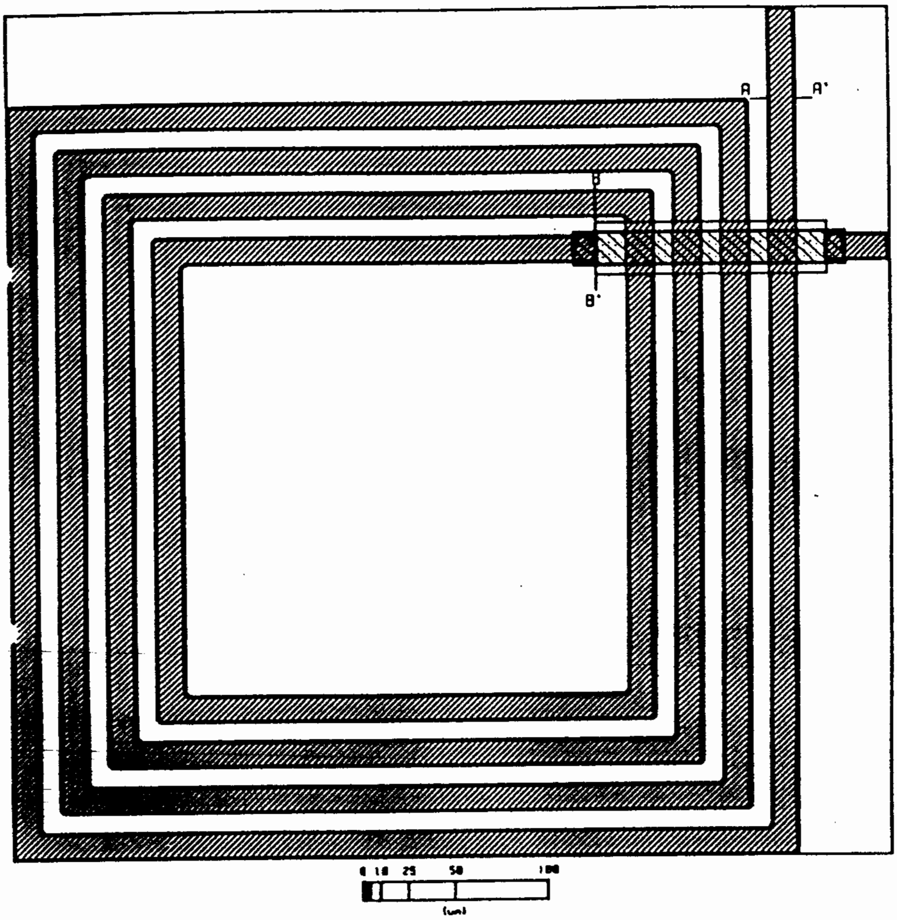


Figure 8.5 Standard four-turn spiral inductor layout.

layout

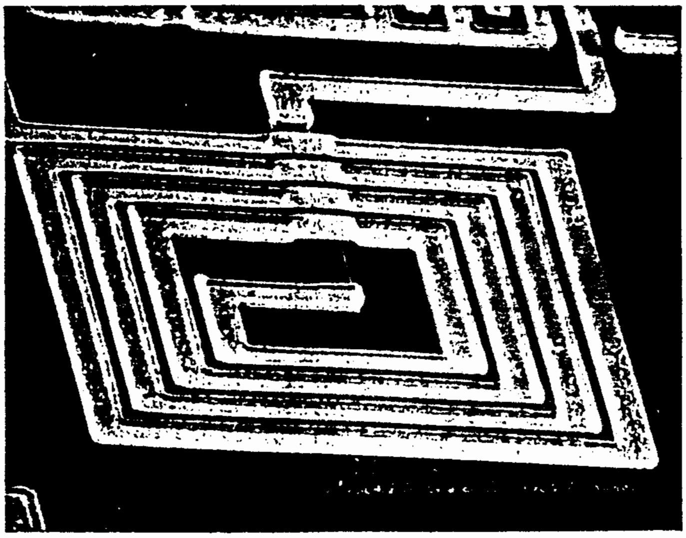


Figure 8.6 Scanning electron micrograph of a four-turn inductor.

photograph

MICs or MMICs Resistors

Thin film

Dielectric
or Semiconductor

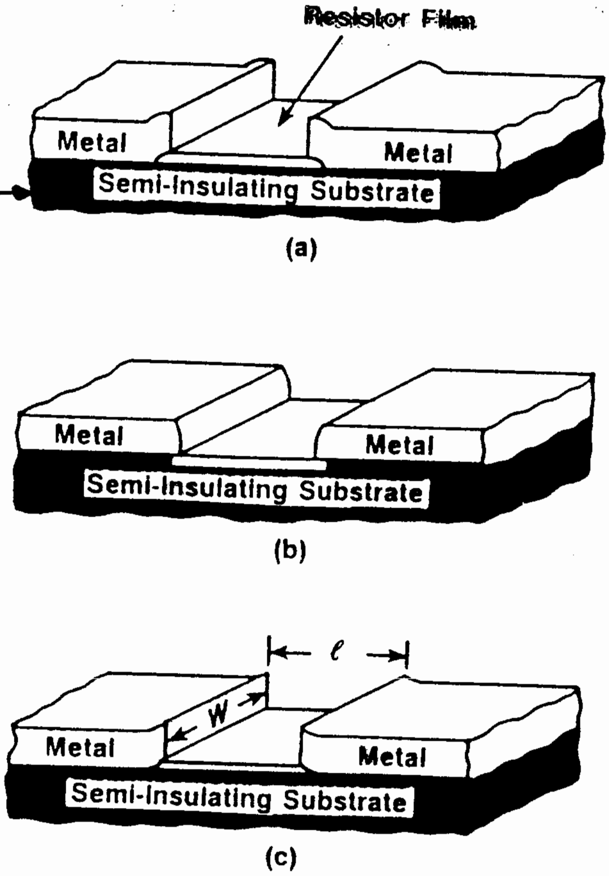
Chip Resistors
are usualy used
in MICs
(Hybrid MICs).

mesa-type

MICs → dielectri
- Nichrome
- Tantalum Nitrid

MMICs
GaAs, Si

Implanted



(a)

(b)

(c)

Figure 2.23 Planar resistors. (*a*) Thin-film. (*b*) Mesa. (*c*) Implanted.

$$R \approx R_s \frac{l}{W}$$

or

or

$$R = \rho_s \frac{l}{dW} \tag{2.37b}$$

Here R_s is the surface resistance (Ω/square) and ρ_s is the specific resistivity (Ω-m) of the resistor film. The thickness d, width W, and length l of the film are measured in meters. The capacitance can be determined from the microstrip-line considerations. When film thickness $d \geq 1\ \mu\text{m}$, the formula containing R_s should be used. However, for very thin films, $d \leq 1\ \mu\text{m}$, the formula with ρ_s should be used. Desirable characteristics of film resistors are

- good stable-resistance value, which should not change with time,
- low temperature coefficient of resistance (TCR),
- adequate dissipation capability,
- ρ_s sheet resistivities in the range of 10 to 1000 Ω/square, so that parasitics can be minimized,
- l maximum resistor length less than 0.1λ if transmission line effects are to be ignored.

MICs and MMICs Couplers

Coupler (Lange, Rat-Race, Branch-Line)

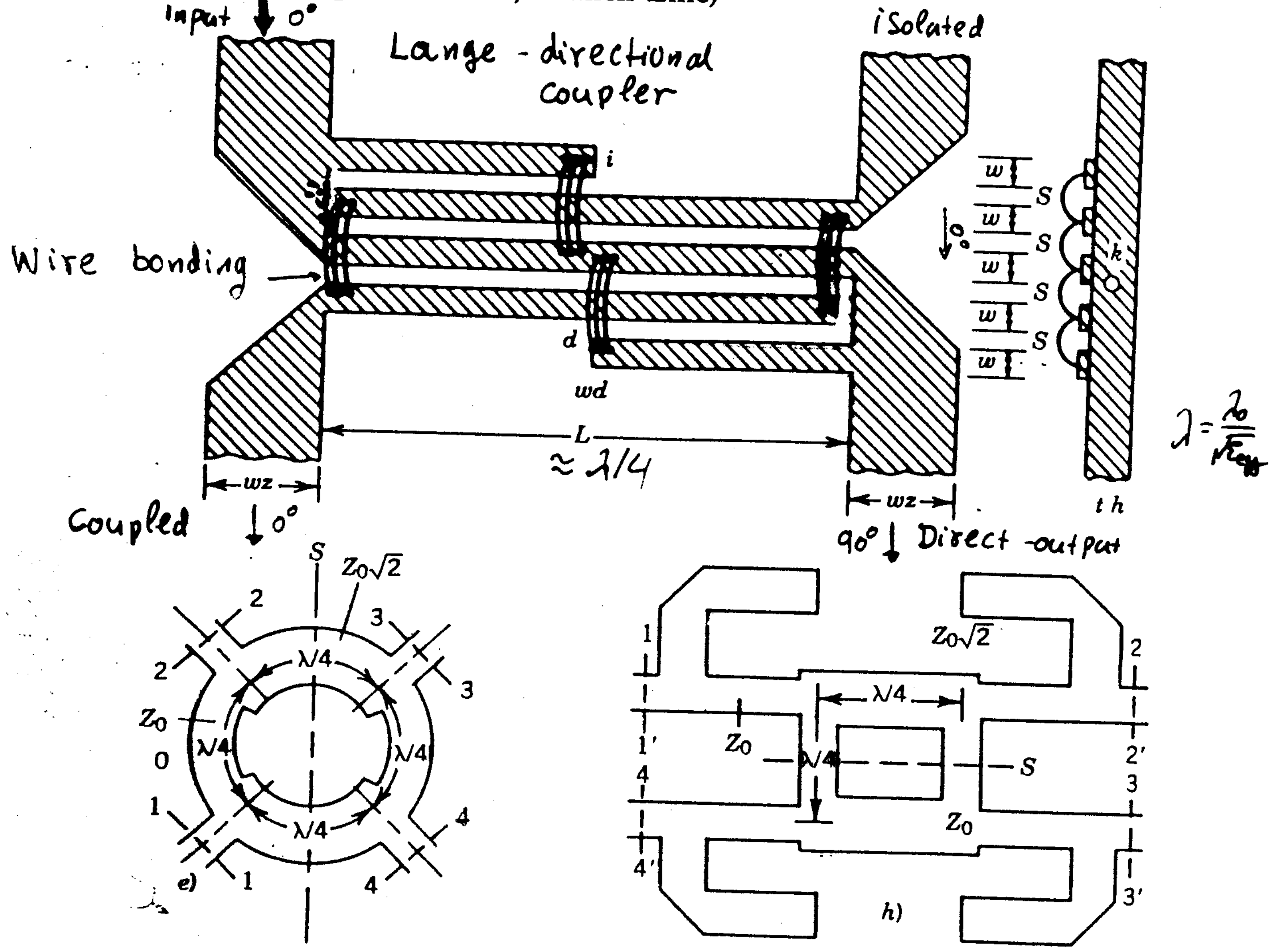


Figure D.14 Couplers.

Description: There are two kinds of couplers. Directional couplers and hybrid couplers (such as rat-race and branch-line)

ACTIVE DEVICES → MICs

3.2.3 MODFET/HEMT

Modulation Doped FET / High Electron Mobility Transistor

By using heterojunction semiconductor material, AlGaAs interfacing with GaAs, a new field-effect microwave semiconductor device can be manufactured with superior microwave performance. This device is the MODFET (modulation-doped field-effect transistor), which is also called a HEMT (high electron mobility transistor), a SDHT (selectively doped heterostructure transistor), or a TEGFET (two-dimensional electron gas FET); the cross section of this transistor is given in Fig. 3.23 [3.58, 3.1].

HEMT

Operation frequency up to 60GHz

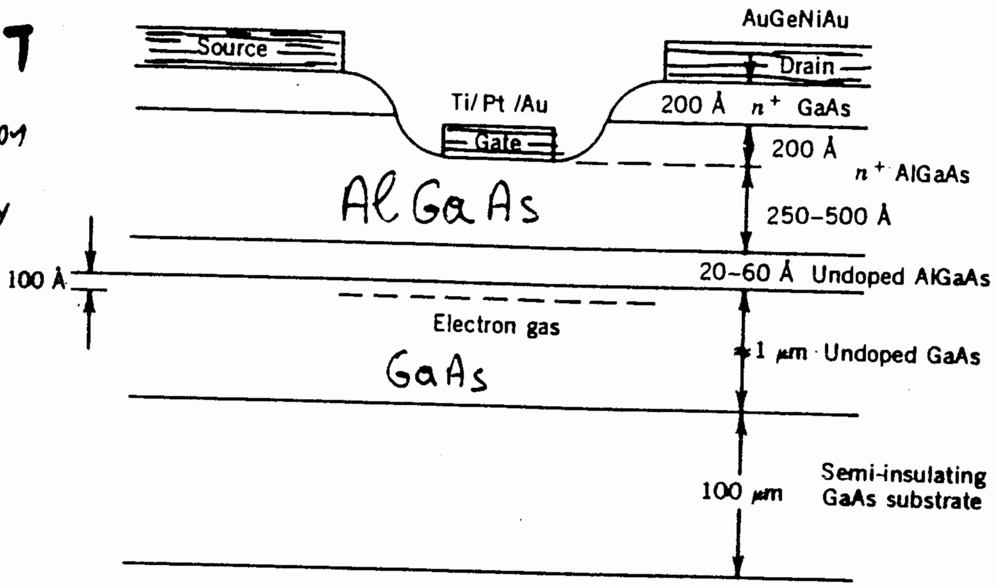


Figure 3.23 MODFET/HEMT structure. (From Refs. 3.1 and 3.58.)

AlGaAs interface GaAs

⇓

Very high mobility electrons

12 GHz

$F_{min} = 0.5$ dB

1/f Cor. Freq. = 30MHz

MESFET → Metal - Semiconductor Field Effect Transistor

Operating up to ~18GHz

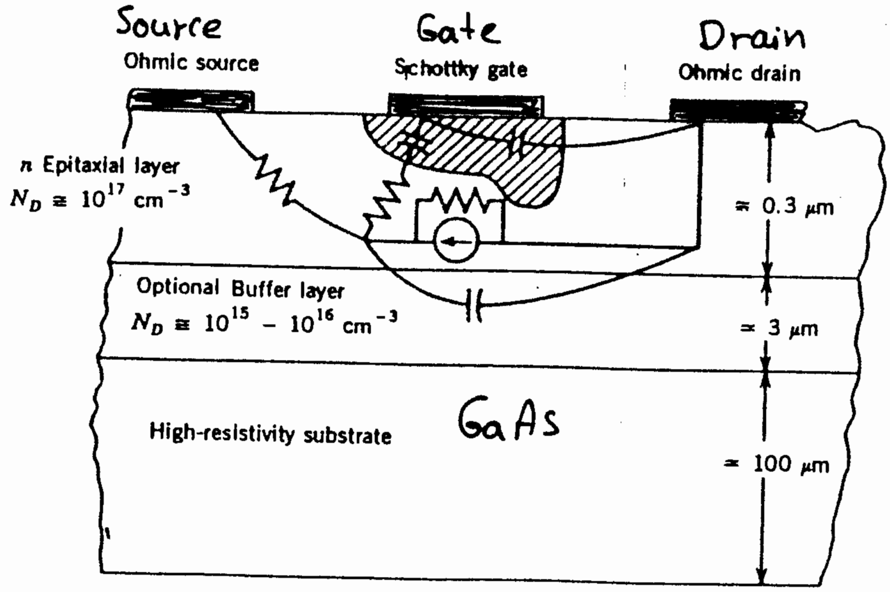


Figure 3.11 GaAs MESFET cross section.

GaAs has higher electron mobility than Si

⇓

Higher gain

+ Very low noise Figure $F_{min} = 0.5$dB at 4GHz ↔ $P_{out} = 15$W

(Silicon Bipolar $F_{min} = 2.5$ dB at 4GHz) ↔ $P_{out} = 6$W

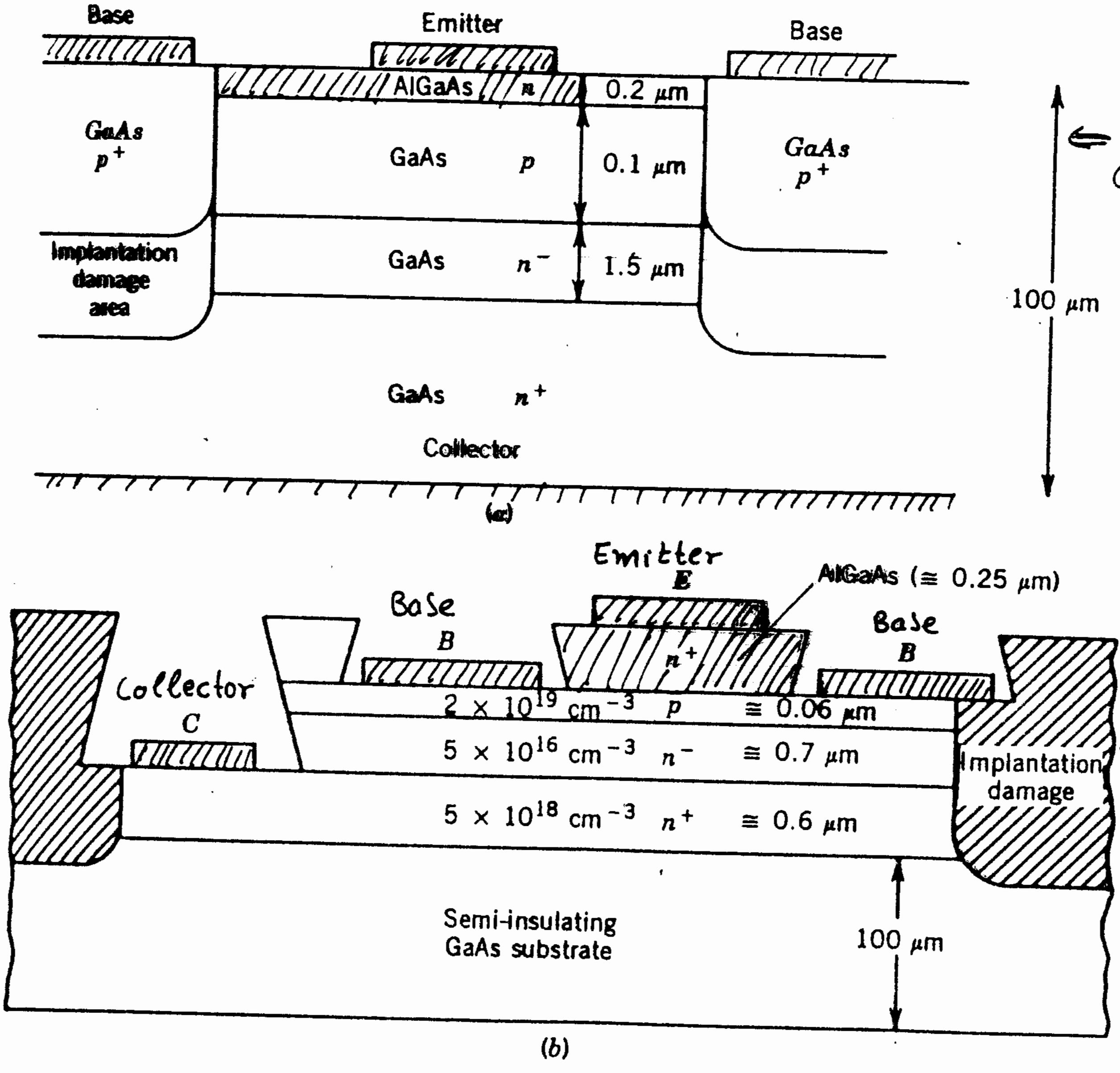
(−) 1/f Corner frequency 30 MHz ; (Si-HBT → 10KHz)

3.1.4 Heterojunction Bipolar Transistor HBT

Because of the superior material properties of group III–V compounds such as GaAs, a bipolar transistor using this material has been a goal since 1957 [3.22]. The use of the heterojunction emitter–base has made the heterojunction bipolar transistor (HBT) a reality. Three primary advantages result from this structure (Fig. 3.8) [3.23]:

1. The forward-bias emitter injection efficiency is very high since the wider-bandgap A1 GaAs emitter injects electrons into the GaAs base at a lower

Opertating upto 60 GHz



⇐ Single Chip Stru
⇓
Hybrid MICs HBT

HBT for ⇐ MMI

Figure 3.8 Heterojunction bipolar transistor structure (HBT): (*a*) single-chip structure; (*b*) HBT structure for GaAs monolithic circuits. [(*b*) from Ref. 3.23.] © 1987 IEEE.

+ 1/f corner frequency 1 MHz !! (very low)

+ Power density 1.5 mW/mm at 36 GHz

− High Noise Figure Fmin = 4 dB at 20 GHz

A very promising Microwave transistor.

MESFET versus Si - BJT

NOISE PERFORMANCE

Noise Power

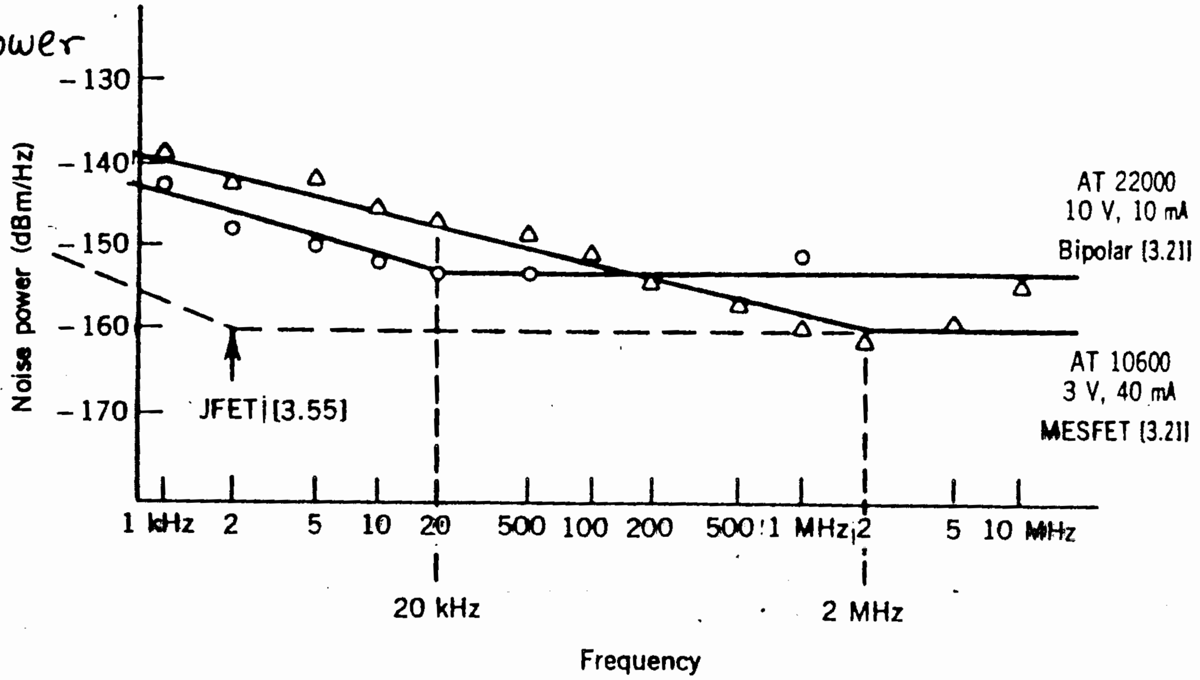


Figure 3.21 1/*f* noise for microwave transistors. (From Refs. 3.21 and 3.55.)

transistors has been plotted in Fig. 3.22 for room temperature. The GaAs MESFETs will dominate the microwave region, but silicon bipolars will continue to find applications, especially for low-noise oscillators.

Minimum Noise Figure

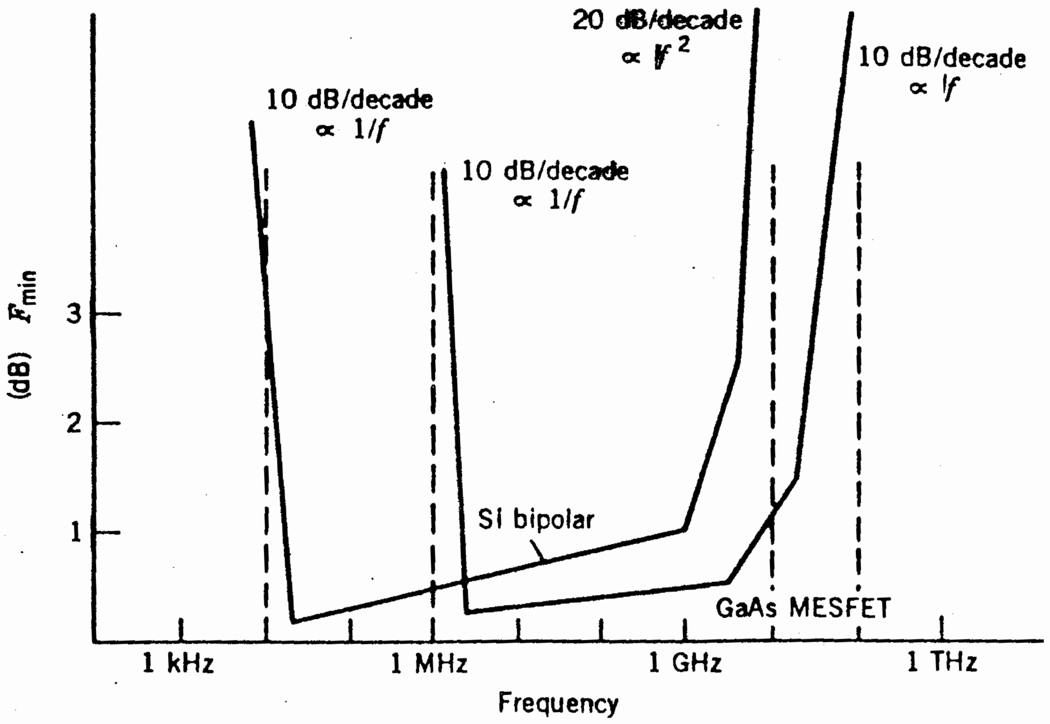


Figure 3.22 F_{min} versus frequency for low-noise silicon bipolar transistor and for noise gallium arsenide FET.

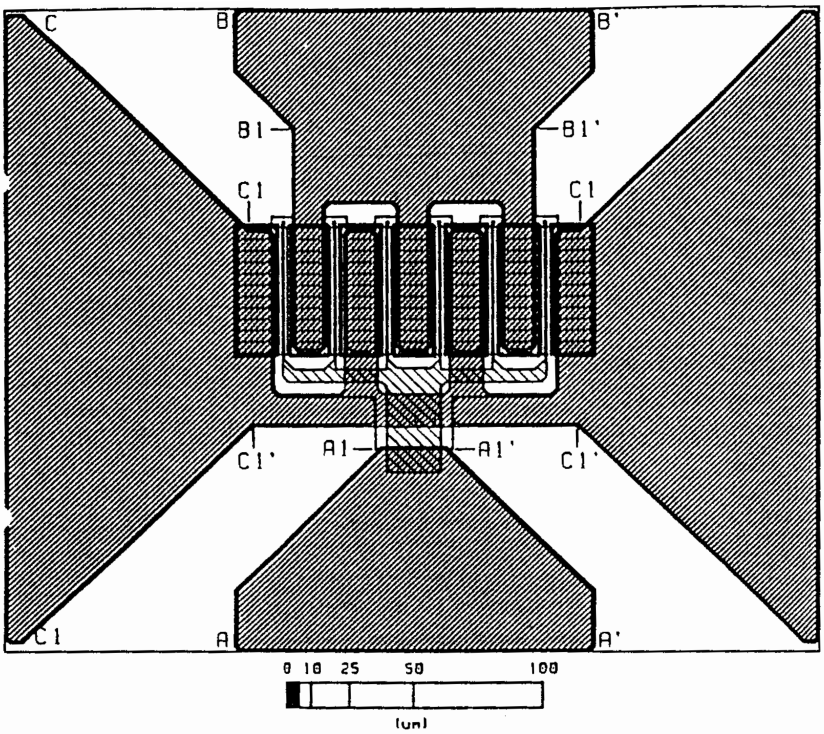
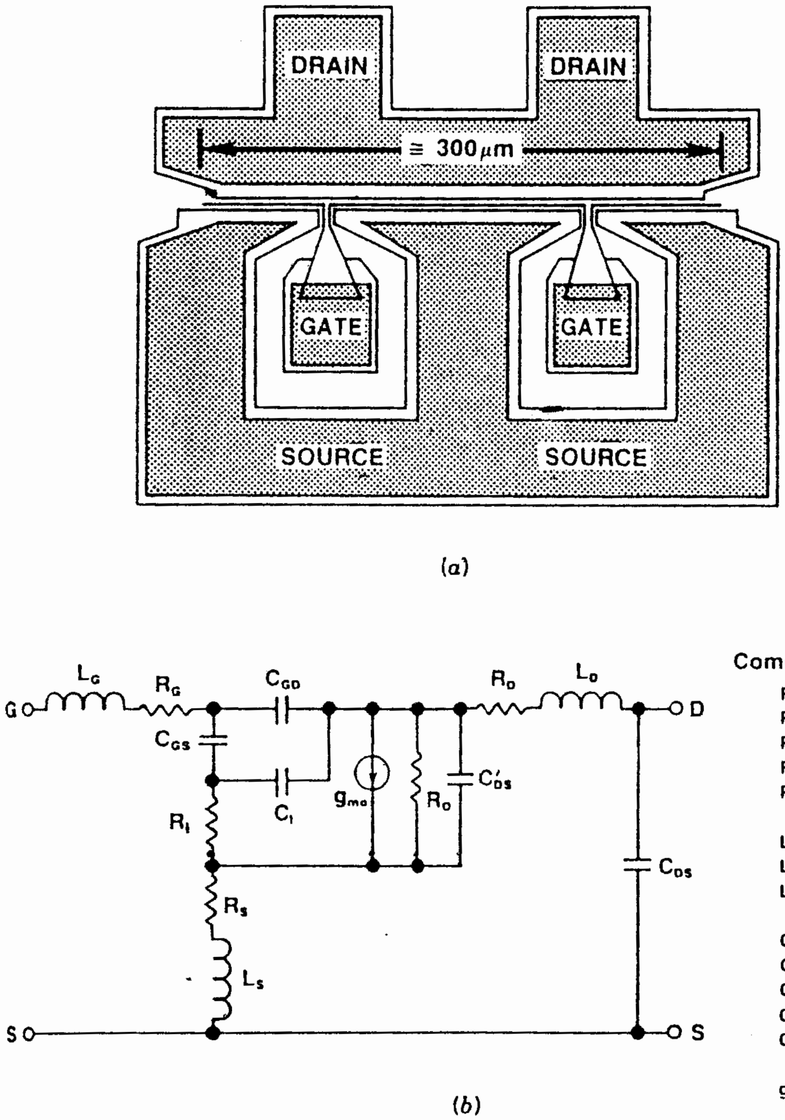


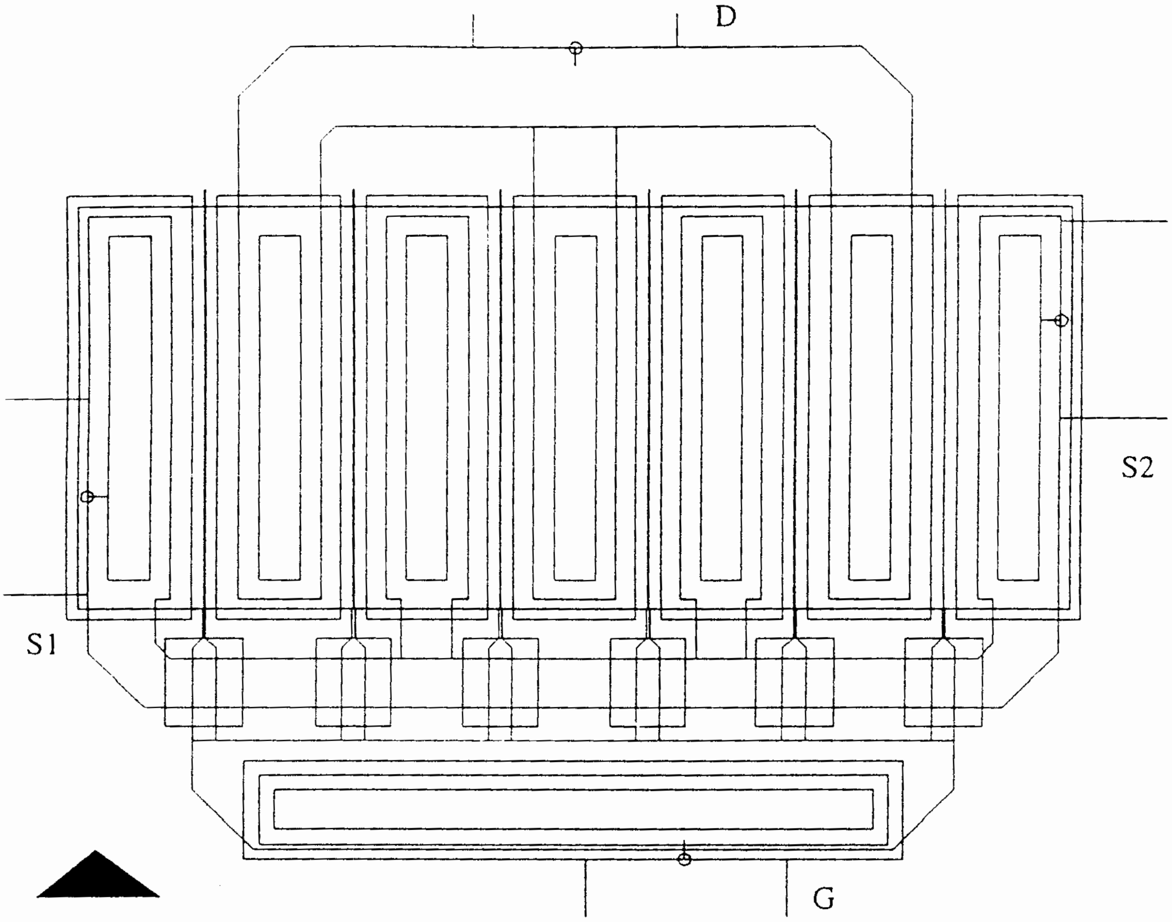
Figure 8.4 Standard 0.5-μm gate length FET layout.



Component	Value
R_G	2.0 Ω
R_i	1.0 Ω
R_S	2.5 Ω
R_O	300 Ω
R_D	4.0 Ω
L_G	0.02 nH
L_S	0.05 nH
L_D	0.02 nH
C_{GS}	0.4 pF
C_{GD}	0.02 [illegible]F
C_i	0.001 pF
C'_{DS}	0.02 pF
C_{DS}	0.03 pF
g_{mo}	35 mS

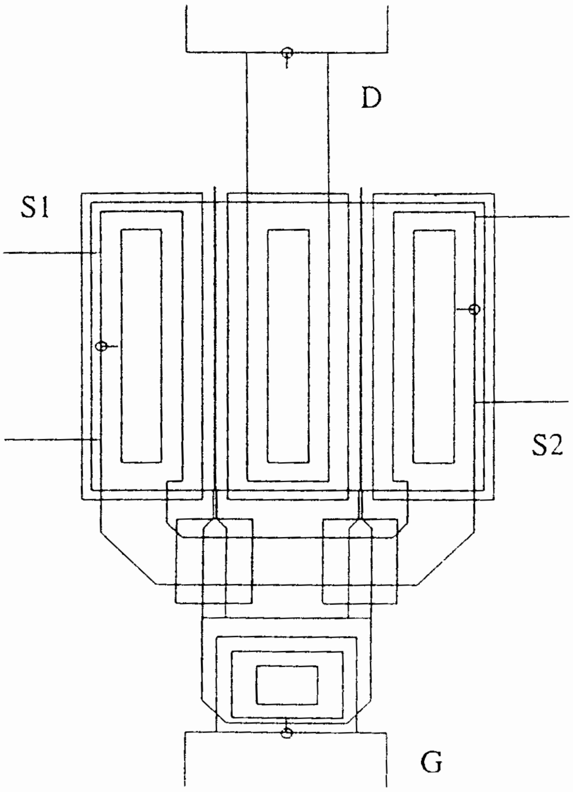
Figure 10.11 (*a*) Four-finger MESFET configuration. (*b*) Equivalent circuit.

Layout Examples :

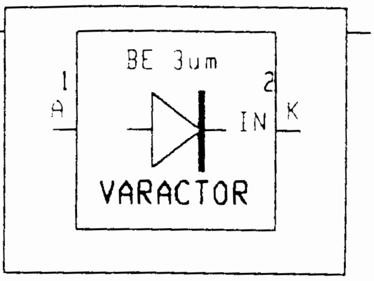


Nbd = 6
Wu = 40 um
Wg = 20 um
Pg = 0.5
Wd = 20 um
Pd = 0
Ws1 = 20 um
Ps1 = -1
Ws2 = 20 um
Ps2 = 1

Nbd = 2
Wu = 30 um
Wg = 20 um
Pg = 1
Wd = 20 um
Pd = 0
Ws1 = 20 um
Ps1 = 0
Ws2 = 20 um
Ps2 = 1



EDDIBE

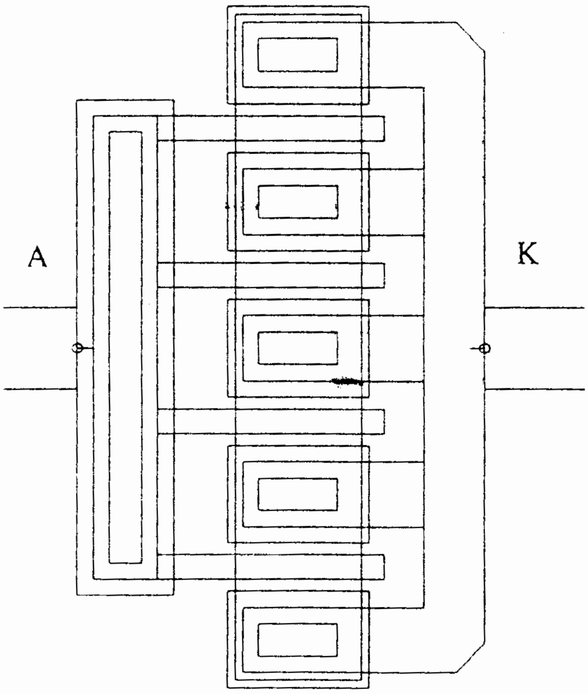


Description : Large signal model of BE diode.

Arguments :

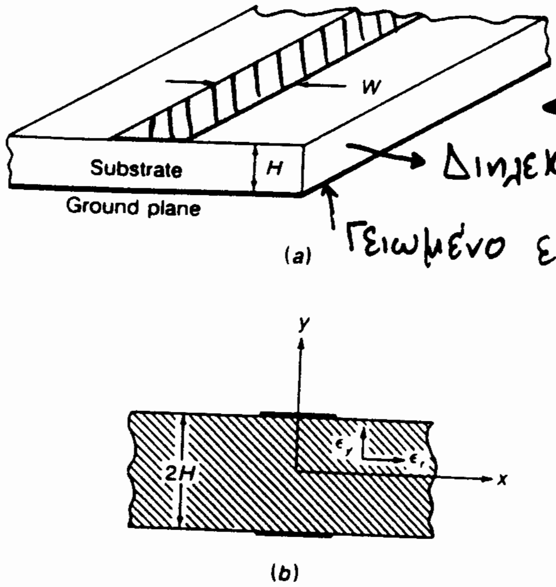
Name	*Default*	*Description*
Nbd	4	Number of gate fingers.
Wu	15 µm	Width of an individual gate finger.
Wa	10 µm	Anode access line width.
Pa	0	Lateral position of the anode access line (-1 < Pa < 1).
Wk	10 µm	Cathode access line width.
Pk	0	Lateral position of the cathode access line (-1 < Pk < 1).

Layout Example : Nbd = 4, Wu = 15 µm :



ΟΛΟΚΛΗΡΩΜΕΝΕΣ - ΤΥΠΩΜΕΝΕΣ ΜΙΚΡΟΚΥΜ ΓΡΑΜΜΕΣ ΜΕΤΑΦΟΡΑΣ

Τυπωμένη γραμμή

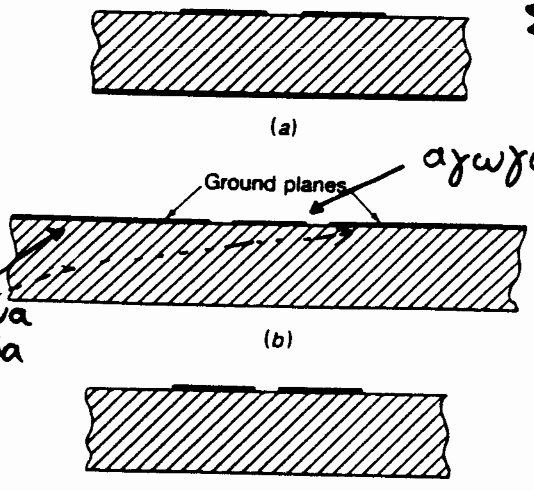


1. Μικροταινιακή γραμμή (Microstrip Line)

Διηλεκτρικό υπόστρωμα

Γειωμένο επίπεδο

FIGURE 3.17
(*a*) The microstrip transmission li
(*b*) equivalent parallel strip line
tained by using image theory.



Συζευγμένες μικροταινιακές γραμμές

αγωγός σήματος

2. Ομοεπίπεδες γραμμές (κυματοδηγο
(Coplanar waveguides)

Γειωμένα επίπεδα

FIGURE 3.18
(*a*) Coupled microstrip lines; (*b*) coplanar transmission line; (*c*) coplanar strip transmission line.

3. Υπερυψωμένη μικροταινιακή γραμμή (Suspended microstrip)

4. Ανεστραμμένη μικροτ. γραμμή (inverted microst.

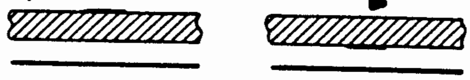
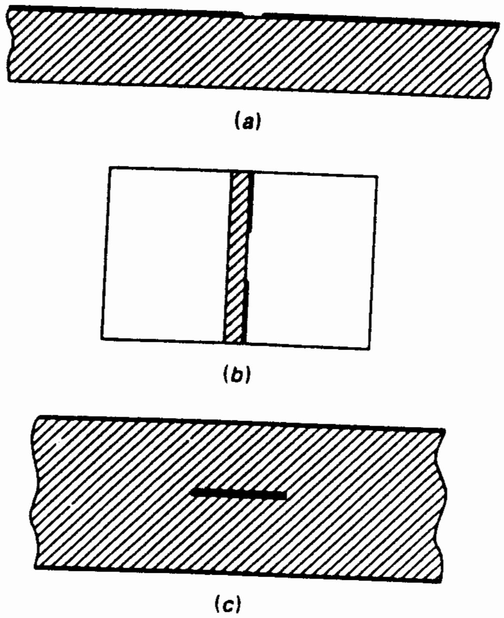


FIGURE 3.19
Suspended and inverted suspended microstrip line.



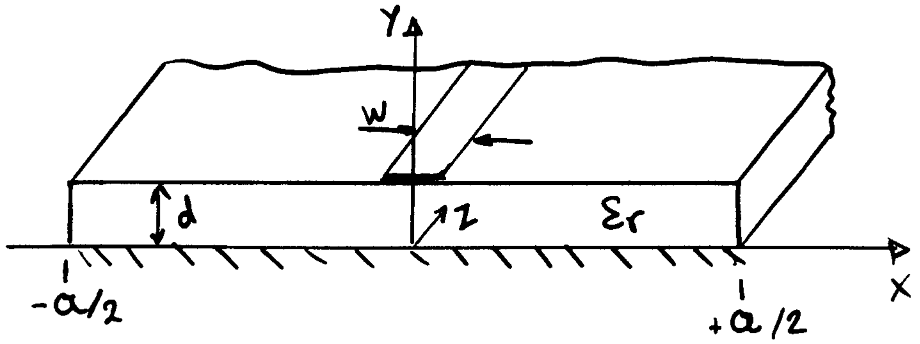
5. Σχισμοειδής Γραμμή (Slot line

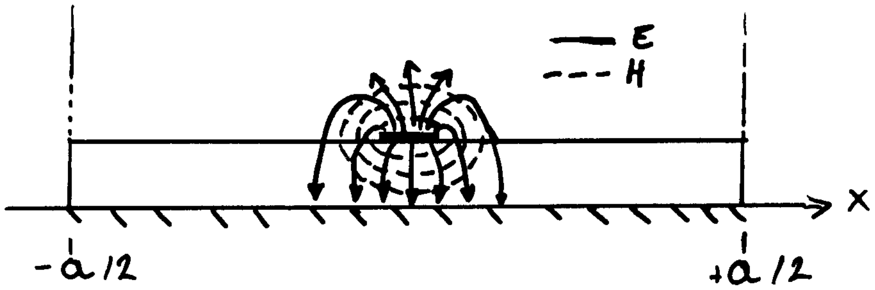
6. Θωρακισμένη σχισμοειδής γραμμή (Shielded slot line or Fin line)

7. Ταινιογραμμή (Stripline)

FIGURE 3.20
(*a*) Slot line; (*b*) shielded slot line or fin line; (*c*) strip line.

Μικροταινιακή Γραμμή - Λειτουργία σε ημι-TEM ρυθμό
(Pozar, σελ. 184)





Ρυθμός ημι-TEM: Υπάρχουν μη-μηδενικές συνιστώσες του ηλεκτρομαγνητικού πεδίου στη διεύθυνση διάδοσης, αλλά είναι πολύ ασθενείς: E_z, H_z <<

Προσεγγιστική: Ηλεκτροστατική Λύση

- Υποθέτουμε ρυθμό TEM: $E_z, H_z \rightsquigarrow 0$
- Υποθέτουμε ιδανικά ηλεκτρικά τοιχώματα στη θέση $x=-\frac{a}{2}, +\frac{a}{2}$ σε απόσταση πολύ μεγαλύτερη από το πάχος του υποστρώματος $x=\pm a/2$, $a \gg d$ για να μην διαταράσσουν το Η/Μ πεδίο που περιορίζεται γύρω από την μικροταινιακή γραμμή.

Ρυθμός TEM:
- Διάδοση στην διεύθυνση - z : $\hat{E}, \hat{H} \propto e^{-j\beta z}$
- Ηλεκτροστατική συμπεριφορά στην εγκάρσια διατομή:

Εξίσωση Laplace $\swarrow$ $\bar{\nabla}_t^2 \Phi(x,y) = 0$ για $|x| \le a/2$, $0 \le y \le \infty$

$$\nabla_t^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

Οριακές Συνθήκες:

$\Phi(x,y)\Big|_{x=\pm a/2} = 0$: $x=\pm a/2$ Ιδανικά ηλεκτρικά τοιχώματα

$\Phi(x,y)\Big|_{y=0,\infty} = 0$

y=0 επίπεδο γείωσης

y=∞ Συνθήκη ακτινοβολίας.

- Επίλυση με "χωρισμό μεταβλητών" και Εφαρμογή Οριακών Συνθηκών

Περιοχή Διηλεκτρικού $0 \leq y \leq d$ $\Big\}$ $\phi(x,y) = \sum_{n=1,3,\ldots}^{\infty} A_n \cos\left(\frac{n\pi x}{a}\right) \sinh\left(\frac{n\pi y}{a}\right)$

Περιοχή Αέρα $y \geq d$ $\Big\}$ $\phi(x,y) = \sum_{n=1,3,\ldots}^{\infty} B_n \cos\left(\frac{n\pi x}{a}\right) e^{-n\pi y/a}$

- Συνθήκη Συνέχειας στη διεπιφάνεια διηλεκτρικού - αέρα:

$$\phi(x,y)\Big|_{y=d^-} = \phi(x,y)\Big|_{y=d^+} \longrightarrow A_n \sinh\left(\frac{n\pi d}{a}\right) = B_n e^{-n\pi d/a}$$

- Ηλεκτρικό Πεδίο

$$E_y = -\frac{\partial \phi}{\partial y} = \begin{cases} -\sum_{n=1,3,\ldots}^{\infty} A_n \cdot \left(\frac{n\pi}{a}\right) \cdot \cos\left(\frac{n\pi x}{a}\right) \cdot \cosh\left(\frac{n\pi y}{a}\right) \\ +\sum_{n=1,3,\ldots}^{\infty} A_n \left(\frac{n\pi}{a}\right) \cdot \cos\left(\frac{n\pi x}{a}\right) \cdot \sinh\left(\frac{n\pi d}{a}\right) \cdot e^{-\frac{n\pi(y-d)}{a}} \end{cases}$$

- Επιφανειακή Πυκνότητα Φορτίου στην μικροταινία $\rho_s(x, y=d)$

$$\rho_s = D_y(x, y=d^+) - D_y(x, y=d^-) = \varepsilon_0 E_y(x,y=d^+) - \varepsilon_0 \varepsilon_r E_y(x,y=d^-) =$$

(1) $$= \varepsilon_0 \sum_{n=1,3,\ldots}^{\infty} A_n \left(\frac{n\pi}{a}\right) \cos\left(\frac{n\pi x}{a}\right) \cdot \left\{\sinh\left(\frac{n\pi d}{a}\right) + \varepsilon_r \cosh\left(\frac{n\pi d}{a}\right)\right\}$$

↑ ανάπτυγμα σε σειρά Fourier ως προς -x

- Προσέγγιση του ρ_s στην μικροταινία $-w/2 \leq x \leq w/2$

(2) $$\rho_s = \begin{cases} 1 & \text{για } |x| < w/2 \quad \text{Επιφάνεια μικροταινίας} \\ 0 & \text{για } |x| > w/2 \quad \text{Διεπιφάνεια διηλεκτρικού-αέρα.} \end{cases}$$

↳ Ομογενής (κατά προσέγγιση) κατανομή υποθέτοντας $a >> w$.

- Ορθογωνιότητα Τριγωνομετρικών Συναρτήσεων: m, n = ακέραιοι

(3) $$\int_0^{\pi} \cos(mx)\cos(nx)\,dx = \begin{cases} 0 & \text{για } m \neq n \\ \frac{\pi}{2} & \text{για } m = n \end{cases}$$ ισχύει η ίδια για ημίτονα

- Εξισώνοντας τις (1) και (2), πολλαπλασιάζοντας επί $\cos(n\pi x/a)$ και ολοκληρώνοντας από $-a/2$ έως $a/2$ παίρνουμε:

$$A_n = \frac{4a \sin(n\pi w/2a)}{(n\pi)^2 \cdot \varepsilon_0 \cdot \{\sinh(n\pi d/a) + \varepsilon_r \cosh(n\pi d/a)\}}$$

- Τάση ως προς το γειωμένο επίπεδο, στο μέσο της μικροταινίας:

$$V = -\int_0^d E_y(x=0,y)\,dy = \sum_{n=1,3,\dots}^{\infty} A_n \sinh\left(\frac{n\pi d}{a}\right)$$

- Ολικό φορτίο στην μικροταινία

$$Q = \int_{-W/2}^{W/2} \underbrace{\rho_s}_{=1}(x)\,dx = W \quad \text{cb/m}$$

- Στατική Χωρητικότητα - ανα μονάδα μήκους

$$C = \frac{Q}{V} = W \Big/ \sum_{n=1,3..}^{\infty} A_n \sinh(n\pi d/a)$$

- Δρώσα Διηλεκτρική Σταθερά $\varepsilon_{r,eff}$

$$\varepsilon_{r,eff} = \frac{C}{C_0} = \frac{\text{Χωρητικοτητα ανα μον. μήκος για } \varepsilon_r \neq 1}{\text{Χωρητικοτητα ανα μον. μήκος για } \varepsilon_r = 1}$$

Επειδή: γενικά $C = \varepsilon_0 \varepsilon_r \cdot \frac{\text{Επιφανεια πλακών}}{\text{Αποσταση πλακών}}$

Και η διαφορά της ε_{reff} απο την ε_r οφείλεται ακριβώς στο οτι το διηλεκτρικό δεν πληροί ομογενώς το χώρο γυρω απο την μικροταινία.

- Χαρακτηριστική Αντίσταση

$$Z_0 = \frac{1}{u_p \cdot C} = \frac{\sqrt{\varepsilon_{reff}}}{c_{φωτος} \cdot C}$$

Γραμμές Μεταφοράς. $Z = R + j\omega L \approx j\omega L$

$Y = G + j\omega C \approx j\omega C$

$$\gamma = j\beta = \sqrt{Z \cdot Y}$$

$$Z_0 = \sqrt{\frac{Z}{Y}}$$

Ταχύτητα Φάσης

$$u_p = \frac{\omega}{\beta} = \frac{c_{φωτος}}{\sqrt{\varepsilon_{reff}}}$$

$$\beta = \omega\sqrt{\mu\varepsilon_{eff}} = \frac{\omega}{c_{φωτος}} \cdot \sqrt{\varepsilon_{reff}} = k_0\sqrt{\varepsilon_{reff}}$$

- Σταθεραί Εξασθένισης a_c, a_d (Collin σελ. 155-156 & Pozar σελ. 186)

$$a_d = \frac{\pi}{\lambda_0} \frac{\varepsilon_r}{\sqrt{\varepsilon_{reff}}} \cdot \frac{\varepsilon_{reff} - 1}{\varepsilon_r - 1} \tan\delta \qquad a_c \approx \frac{R_s}{Z_0 W} \ \frac{\text{Neper}}{\text{m}} \qquad R_s = \sqrt{\frac{\omega\mu_0}{2\sigma}}$$

→ Δρώσα Διηλεκτρική Σταθερά

1. Ημιστατική Προσέγγιση (Pozar σελ. 185)

$$\varepsilon_{reff,1} \approx \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\cdot\frac{1}{\sqrt{1+12\cdot d/W}}$$

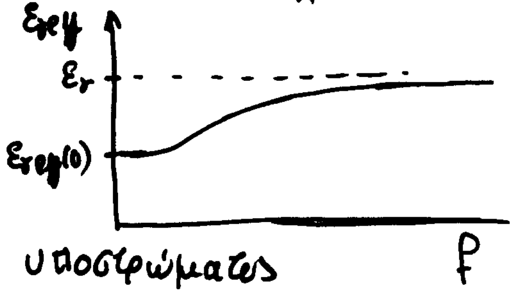
2. Βελτιωμένη ακρίβεια - Έκφραση Hammerstad: Collin σελ. 151.

$$\varepsilon_{reff}^{(0)} \approx \varepsilon_{reff,1} + F(\varepsilon_r, d) - 0.217\,(\varepsilon_r-1)\cdot\frac{T}{\sqrt{W\cdot d}}$$

$$F(\varepsilon_r, d) = \begin{cases} 0.02\,(\varepsilon_r-1)\,(1-W/d)^2 & \text{για } W/d<1 \\ 0 & \text{για } W/d>1 \end{cases}$$

3. Εξάρτηση της ε_{reff} από τη συχνότητα Collin σελ. 162

$$\varepsilon_{reff}(f) = \varepsilon_r - \frac{\varepsilon_r - \varepsilon_{reff}(0)}{1+(f/f_a)^m}$$



- Λεπτομέρειες Collin σελ. 162
- Πρόγραμμα: HP-AppCAD

T = πάχος χαλκού   d = H = πάχος υποστρώματος

→ Χαρακτηριστική Αντίσταση

$$Z_0 = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_{eff}}}\,\ln\left(\dfrac{8d}{W}+\dfrac{W}{4d}\right) & \text{για } \dfrac{W}{d}\le 1 \\[2ex] \dfrac{120\pi}{\sqrt{\varepsilon_{eff}}\cdot\left[W/d+1.393+0.667\ln(W/d+1.444)\right]} & \text{για } \dfrac{W}{d}\ge 1 \end{cases}$$

→ Υπολογισμός Πλάτους γραμμής W/d = ?
για δεδομένη Z_0 και ε_r

$$\frac{W}{d} = \begin{cases} 8e^A/(e^{2A}-2) & \text{για } W/d<2 \\ \dfrac{2}{\pi}\left\{B-1-\ln(2B-1)+\dfrac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln(B-1)+0.39-\dfrac{0.61}{\varepsilon_r}\right]\right\} & \text{για } \dfrac{W}{d}>2 \end{cases}$$

Όπου:

$$A = \frac{Z_0}{60}\sqrt{\frac{\varepsilon_r+1}{2}} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left(0.23+\frac{0.11}{\varepsilon_r}\right)$$

$$B = \frac{\eta_0\cdot\pi}{2Z_0\sqrt{\varepsilon_r}} = \frac{377\cdot\pi}{2Z_0\sqrt{\varepsilon_r}}$$

Ρευματική Κατανομή Μικροταινιακής Γραμμής

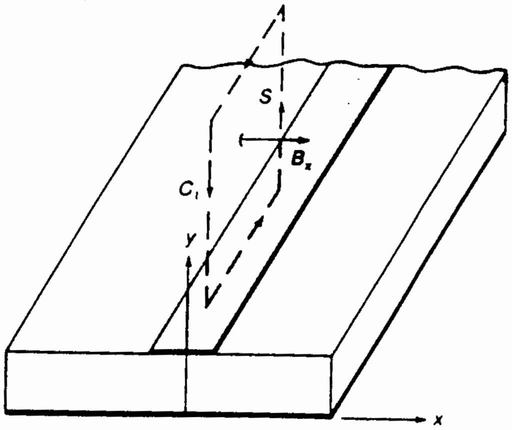
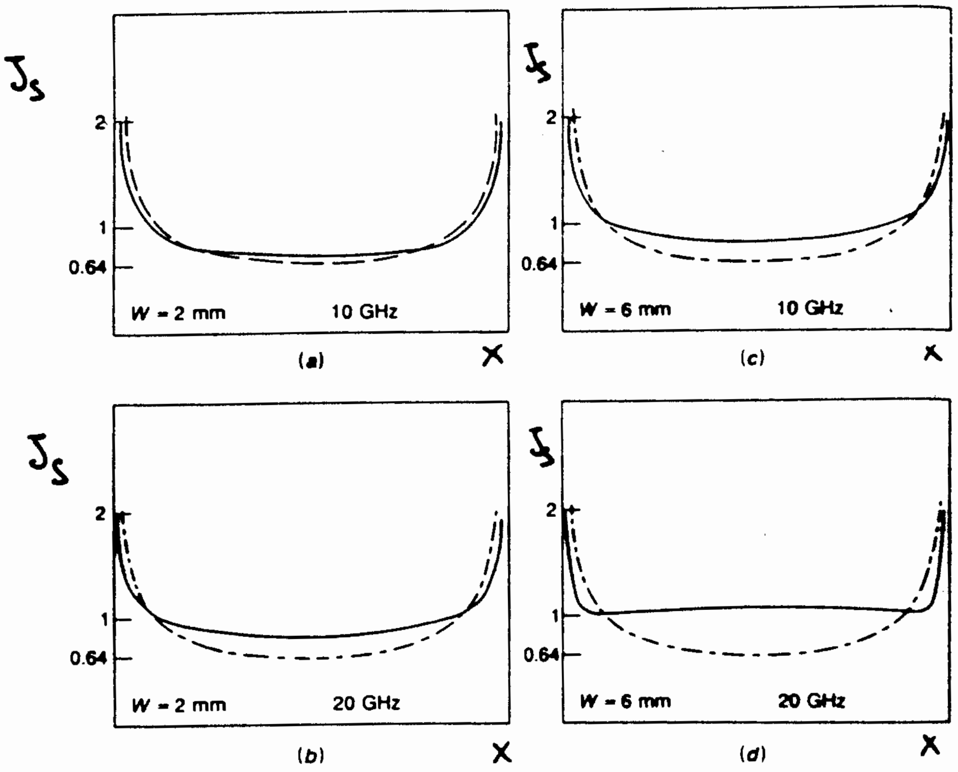


FIGURE 3.21
Surface used to find the magnetic flux linkage in a microstrip line.



—— Ακριβής
--- Προσεγγιστική

Κανονικοποιημένη J_s, ώστε
I = W σε A

Collin σελ. 164

FIGURE 3.29
Current distribution on the microstrip for an alumina substrate with $H = 1$ mm and two different widths. The broken curves give the quasistatic distribution. (a) $W = 2$ mm, $f = 10$ GHz; (b) $W = 2$ mm, $f = 20$ GHz; (c) $W = 6$ mm, $f = 10$ GHz; (d) $W = 6$ mm, $f = 20$ GHz.

- Προσεγγιστική ρευματική κατανομή από λύση "Σύμμορφης Απεικόνισης" (Collin σελ. 166)

$$\rho_s(x) \approx \frac{2Q}{\pi \cdot W \sqrt{1 - x^2/(W/2)^2}}$$

Ημι-στατική Προσέγγιση

- Ακριβής Ρευματική κατανομή

Χαρακτηριστική Αντίσταση και Δρώσα Διηλεκτρική Σταθερά – 1
Μικροταινιακών Γραμμών

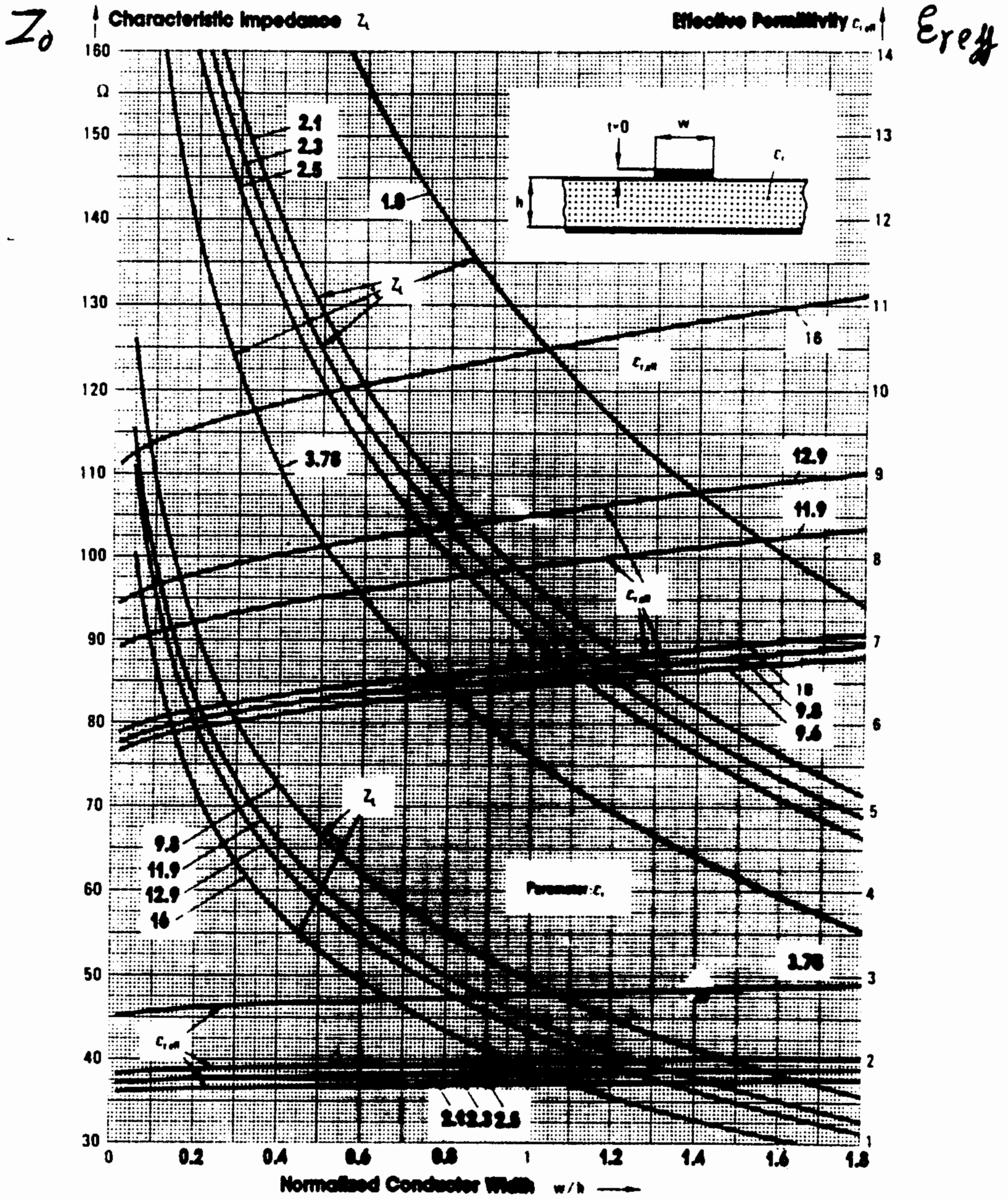


Fig. 3.4 Circuit parameters Z_L and $\epsilon_{r,\text{eff}}$ of microstrip on various technologically important substrates: PTFE ($\epsilon_r = 2.1$), polyolefin ($\epsilon_r = 2.3$), glass-reinforced PTFE ($\epsilon_r = 2.5$), fused quartz ($\epsilon_r = 3.78$), alumina ceramic ($\epsilon_r = 9.6$, 9.8, or 10), semi-insulating Si ($\epsilon_r = 11.9$), semi-insulating GaAs ($\epsilon_r = 12.9$), and nonmagnetic ferrite ($\epsilon_r = 16$), with $t = 0$ for $w/h \leq 1.8$ by the method of lines.

Χαρακτηριστική Αντίσταση και Δρώσα Διηλεκτρική Σταθερά - 2

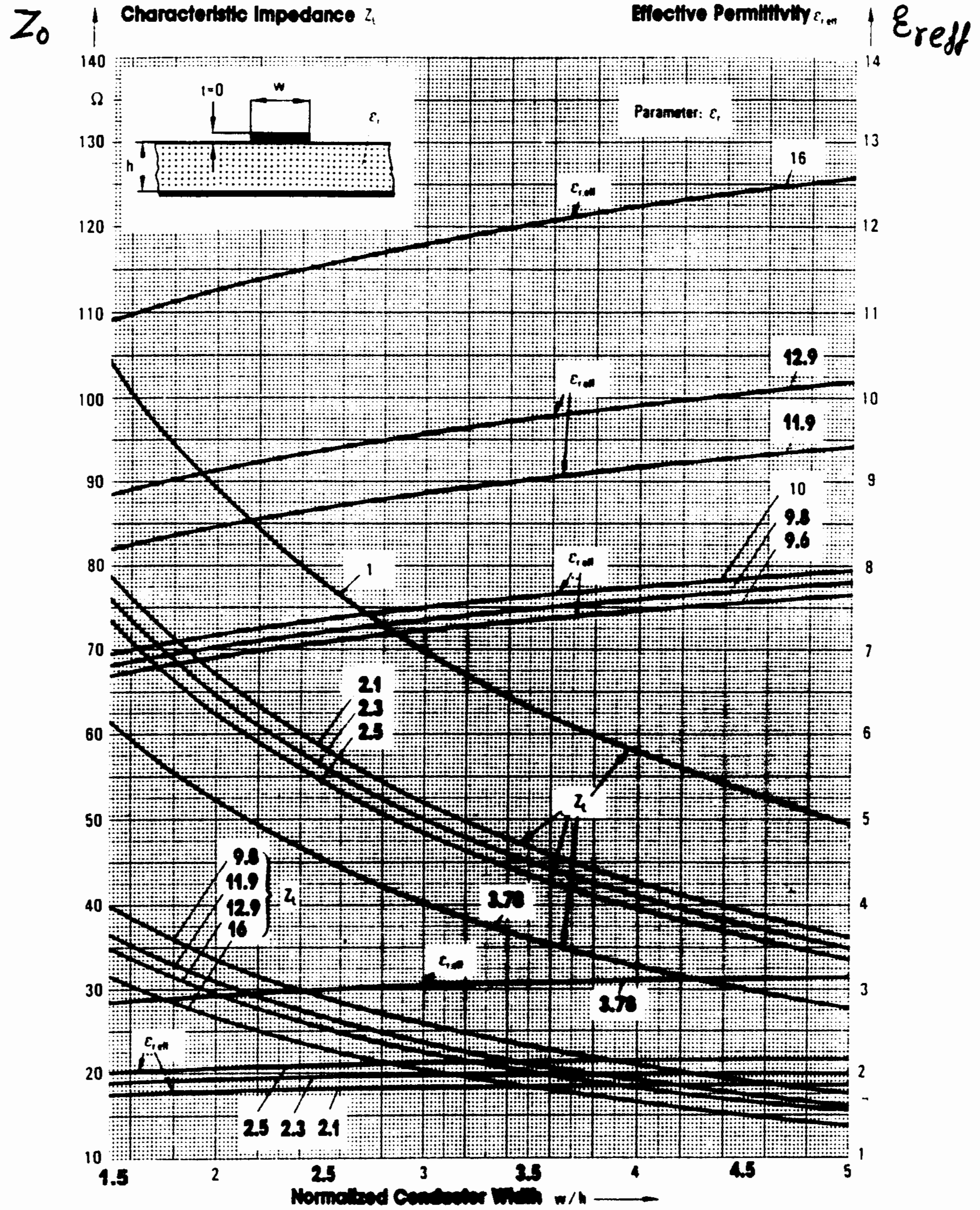


Fig. 3.5 Continuation of Figure 3.4 for larger conductor width $1.5 \leq w/h \leq 5$.

Χαρακτηριστική Αντίσταση και Δρώσα Διηλεκτρική Σταθερά - 3

Table 3.1 Calculated circuit parameters Z_{L0} and $\epsilon_{r,\mathrm{eff}}$ as shown in Figures 3.4 and 3.5, using static variation of the method of lines [2.86, 2.89, 3.99, 3.100].

		Effective Permittivity $\epsilon_{r,\mathrm{eff}}$ for ϵ_r =									
w/h	Z_{L0} in Ω	2.1	2.3	2.5	3.78	9.6	9.8	10.0	11.9	12.9	16
0.02	359.45	1.604	1.713	1.822	2.517	5.665	5.774	5.882	6.909	7.450	9.125
0.03	335.25	1.608	1.718	1.827	2.526	5.692	5.803	5.911	6.945	7.488	9.173
0.04	318.05	1.611	1.722	1.832	2.534	5.714	5.826	5.935	6.973	7.519	9.212
0.05	304.64	1.614	1.725	1.835	2.540	5.731	5.846	5.956	6.997	7.546	9.245
0.1	263.23	1.625	1.738	1.850	2.567	5.808	5.926	6.037	7.096	7.653	9.380
0.15	238.62	1.634	1.748	1.861	2.587	5.873	5.986	6.099	7.170	7.734	9.482
0.2	221.62	1.640	1.756	1.870	2.604	5.923	6.036	6.150	7.232	7.802	9.567
0.3	197.21	1.652	1.769	1.886	2.632	6.008	6.124	6.239	7.340	7.919	9.714
0.4	180.21	1.662	1.781	1.900	2.657	6.083	6.201	6.318	7.435	8.023	9.845
0.6	156.09	1.680	1.802	1.924	2.701	6.215	6.336	6.457	7.602	8.205	10.074
0.8	139.25	1.695	1.820	1.945	2.740	6.334	6.457	6.580	7.752	8.369	10.280
1.0	126.58	1.710	1.838	1.965	2.777	6.448	6.574	6.700	7.897	8.527	10.479
1.2	116.30	1.723	1.853	1.983	2.810	6.549	6.677	6.806	8.025	8.666	10.654
1.4	107.84	1.735	1.868	1.999	2.840	6.644	6.774	6.905	8.145	8.797	10.819
1.6	100.62	1.747	1.881	2.015	2.868	6.731	6.864	6.996	8.255	8.918	10.972
1.8	94.39	1.757	1.893	2.029	2.895	6.807	6.948	7.082	8.359	9.032	11.115
2.0	89.06	1.767	1.904	2.042	2.920	6.890	7.027	7.163	8.458	9.139	11.251
2.5	78.13	1.788	1.930	2.072	2.975	7.063	7.204	7.344	8.677	9.379	11.553
3.0	69.77	1.807	1.953	2.097	3.023	7.213	7.357	7.501	8.867	9.586	11.815
3.5	63.12	1.823	1.971	2.119	3.064	7.343	7.490	7.637	9.032	9.767	12.043
4.0	57.69	1.837	1.988	2.139	3.100	7.457	7.607	7.757	9.178	9.925	12.243
5.0	49.33	1.861	2.016	2.171	3.161	7.649	7.804	7.958	9.421	10.192	12.580
10.0	28.97	1.929	2.098	2.266	3.340	8.214	8.382	8.549	10.140	10.977	13.571

Συζευγμένες Μικροταινιακές Γραμμές

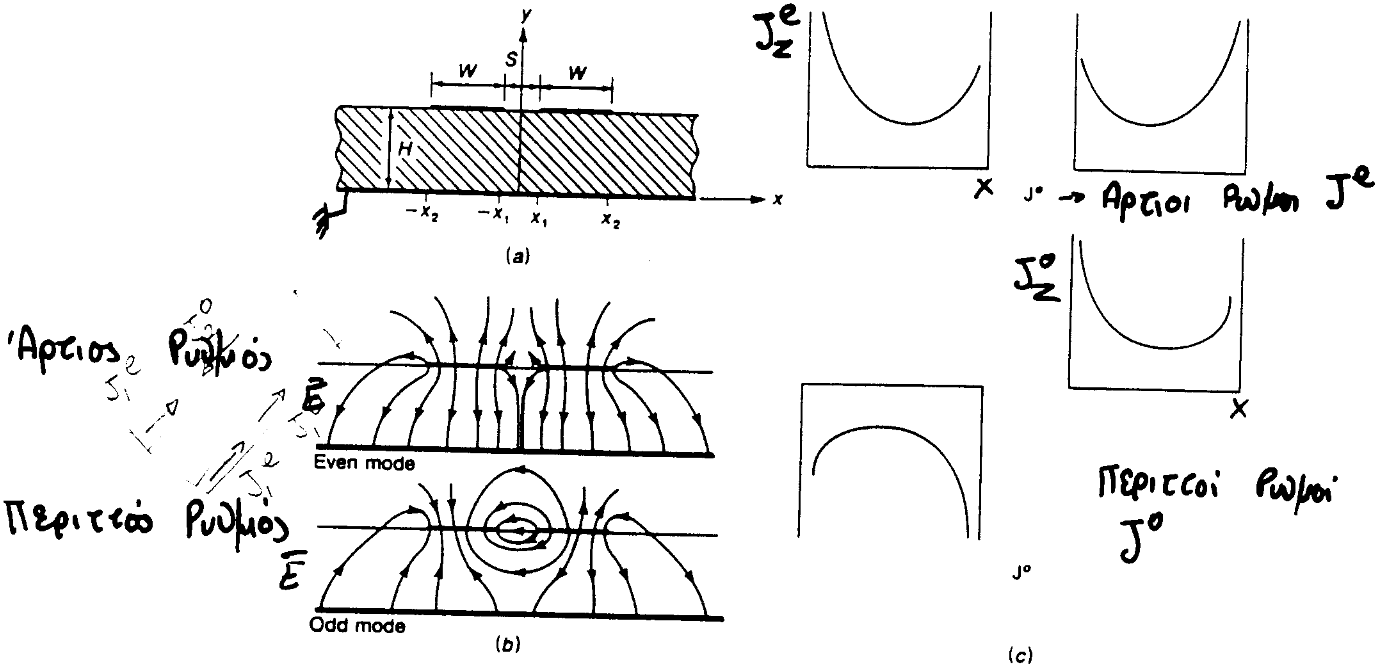
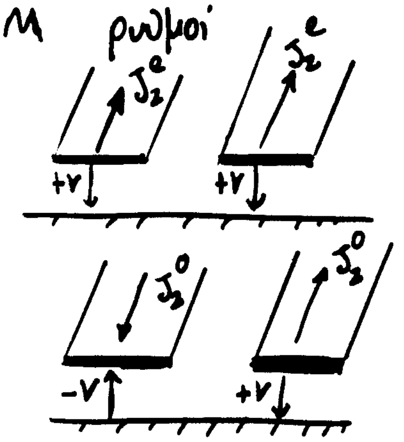


FIGURE 3.30
(a) Coupled microstrip line; (b) the electric field distribution for the even and odd odes; (c) the current distribution for the even and odd modes. Collin σελ. 165

Διεγειρόμενοι Ρυθμοί: Σε μια γραμμή 3-αγωγών διεγείρονται γενικά δύο τύποι ρυθμών TEM.

Συζευγμένες Μικροταινιακές γραμμές: Διεγείρονται δύο ημι-TEM ρυθμοί



Άρτιος ημι-TEM ρυθμός (even mode):

↳ Όταν οι δύο μικροταινιακές γραμμές βρίσκονται στο ίδιο δυναμικό +V, +V

Περιττός ημι-TEM ρυθμός (odd mode)

↳ Όταν οι δύο μικροταινιακές γραμμές βρίσκονται σε αντίθετα δυναμικά -V, +V

Ρευματική Κατανομή

- Όταν οι δύο μικροταινίες βρίσκονται στον αέρα - απουσία διηλεκτρικού υποστρώματος και απουσία επιπέδου γείωσης:

Άρτιοι ρυθμοί : $J_z^e(x) = \dfrac{x}{\sqrt{(x^2-x_1^2)(x_2^2-x^2)}}$

Περιττοί Ρυθμοί $J_z^o(x) = \dfrac{x_2}{\sqrt{(x^2-x_1^2)(x_2^2-x^2)}}$

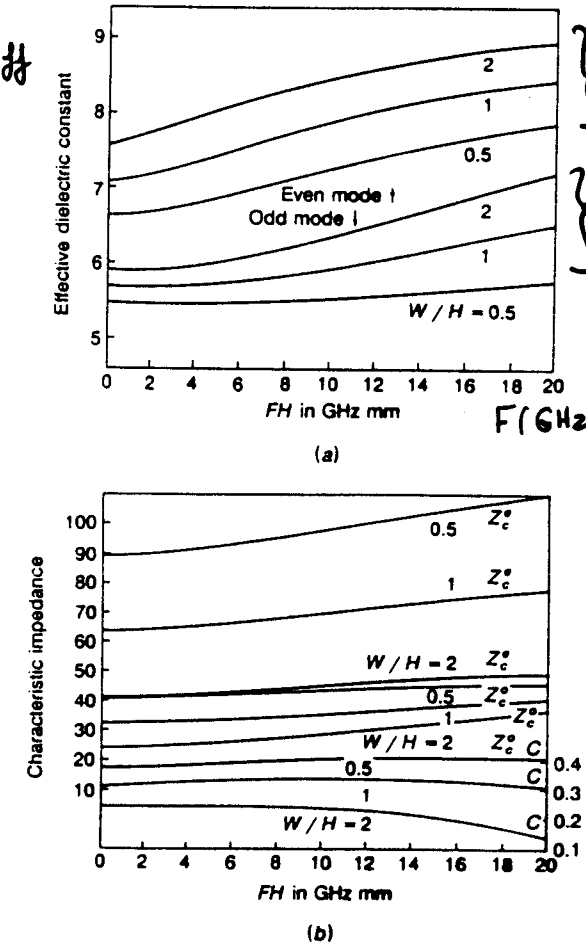
- Η ασυνέχεια στις ακμές είναι της μορφής $\propto 1/X$

Δρώσα Διηλεκτρική Σταθερά Άρτιου και Περιττού Ρυθμού

ε_{reff}

S/H = 0.25

$\varepsilon_r = 9.7$ (Al_2O_3)



} Άρτιος

} Ανακρίβεια ± 3%

↘ Περιττός

Ανακρίβεια ±8%

↑

Z_0^o, Z_0^e

↓

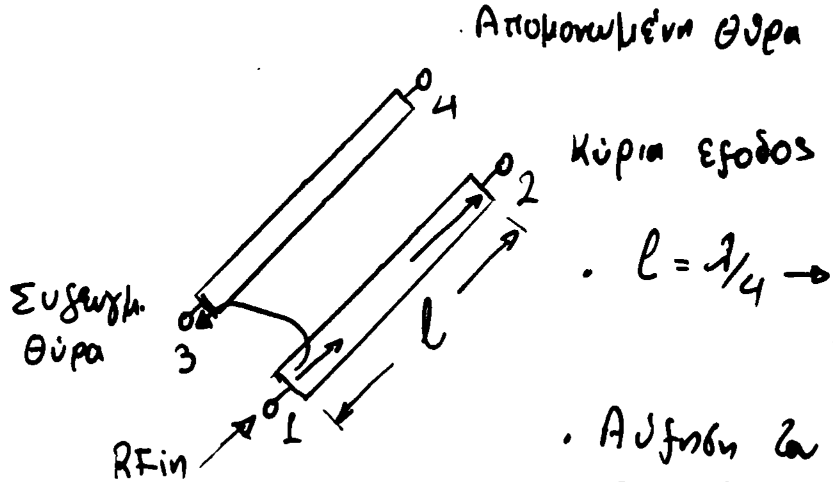
Ανακρίβεια ± 3%

FIGURE 3.31
Dispersion characteristics of a coupled microstrip line on an alumina substrate. $S/H = 0.25$, $\epsilon_r = 9.7$. (*a*) Even- and odd-mode effective dielectric constant; (*b*) even- and odd-mode characteristic impedance and coupling coefficient *C*.

Συντελεστής Σύζευξης $C = \dfrac{Z_0^e - Z_0^o}{Z_0^e + Z_0^o} = \dfrac{1-(Z_0^o/Z_0^e)}{1+(Z_0^o/Z_0^e)}$

↳ Επιτυγχάνονται τιμές μέχρι 2.5 : 1 ή 8 dB.

$C(dB) = 20 \log(C)$



· $l = \lambda/4$ → Μεγιστοποίηση του συν/στη σύζευξης C

· Αύξηση του C ↗ όσο μειώνεται η απόσταση των γραμμών S ↘

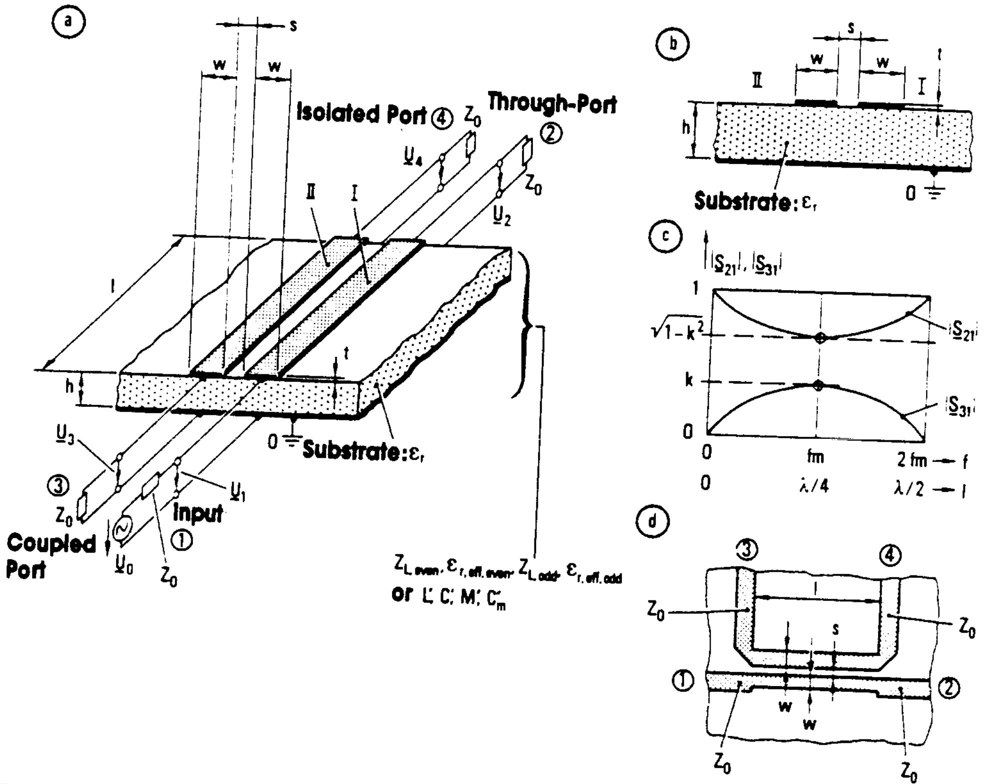


Fig. 9.1 Symmetric microstrip coupled section: (a) schematic diagram; (b) circuit cross section; (c) principal transmission characteristics (ideal TEM coupler); (d) actual circuit.

Συζευγμένες Ταινιογραμμές (coupled Striplines)

Collin σελ. 170-174

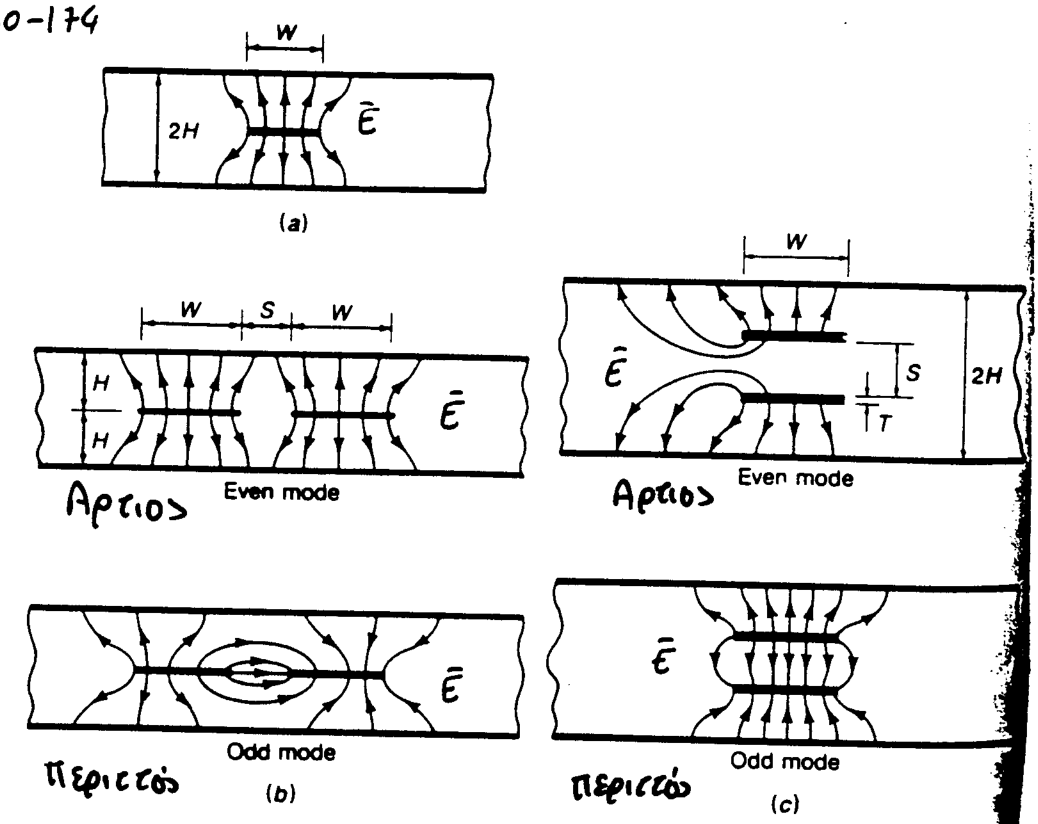


FIGURE 3.34
(a) The basic strip-line configuration; (b) coupled strip line using coplanar strips; (c) coupl strip line using broadside coupled strips. The electric field lines for the TEM modes are a shown.

- Οι διεγειρόμενοι ρυθμοί είναι καθαροί TEM
- Ο συντελεστής σύζευξης είναι μεγαλύτερος από αυτόν των μικροταινιακών γραμμών C (Υπολογισμοί : Collin σελ. 173)

Χαρακτηριστική Αντίσταση και Δρώσα διηλεκτρική σταθερά -1 μικροταινιακών γραμμών συζευγμένων σε Al_2O_3, $\varepsilon_r \approx 9.6$

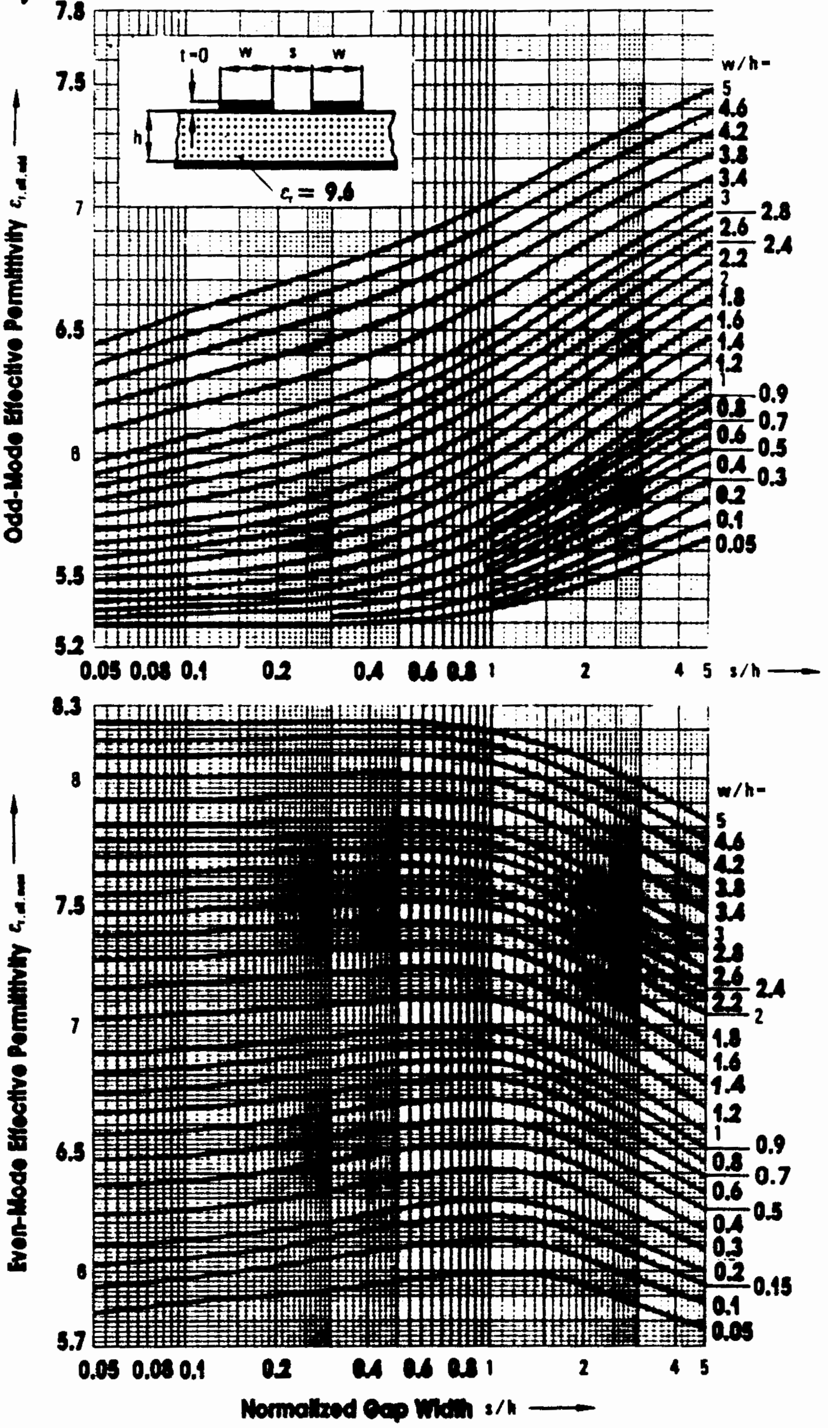


Fig. 9.4 Effective even and odd mode permittivities $\epsilon_{r,\mathrm{eff,even}}$ and $\epsilon_{r,\mathrm{eff,odd}}$ of coupled microstrip lines on Al_2O_3 substrate ($\epsilon_r = 9.6$) from static analysis with the Green's functions method [2.77, 2.80].

Χαρακτηριστική Αντίσταση και Δρώσα διηλεκτρική σταθερά -2
Συζευγμένων μικροταινιακών γραμμών τυπωμένων σε Al_2O_3, $\varepsilon_r = 9.6$

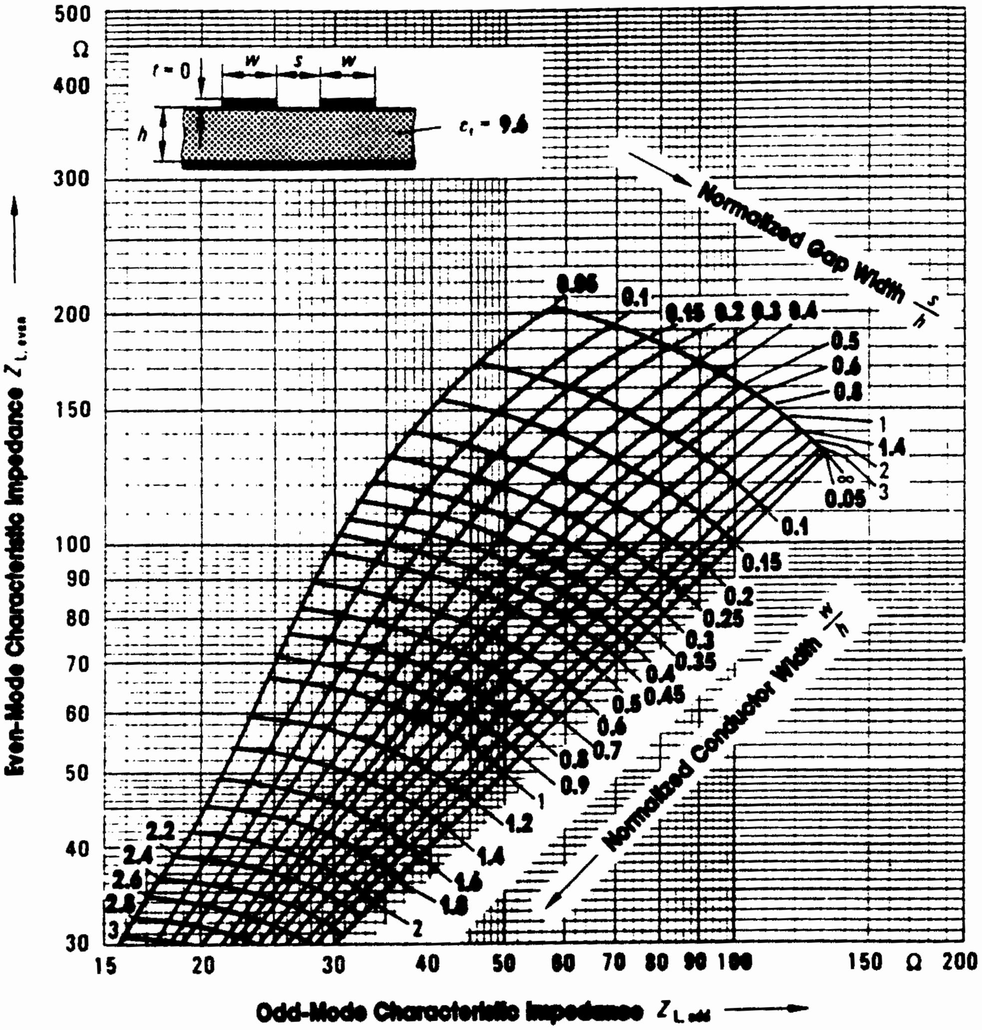


Fig. 9.3 Even and odd mode characteristic impedances $Z_{L,\text{even}}$ and $Z_{L,\text{odd}}$ of coupled microstrip lines on Al_2O_3 ceramic substrate ($\epsilon_r = 9.6$) from static analysis with the Green's functions method [2.77, 2.80].

Δρώσα Διηλεκτρική Σταθερά Συζευγμένων Μικροταινιακών Γραμμών τυπωμένων σε Al_2O_3, $\varepsilon_r = 9.8$

Table 9.2 Even and odd mode effective permittivities $\epsilon_{r,\mathrm{eff,even}}$, and $\epsilon_{r,\mathrm{eff,odd}}$ for coupled microstrip lines on Al_2O_3 ceramic substrates (ϵ_r = 9.8) for a conductor thickness t = 0 from the variational method [2.46, 3.32] for the quasistatic case $h/\lambda_0 = 10^{-5}$.

Άρτιος Ρυθμός

w/h	*Even-Mode Effective Permittivity* $\epsilon_{r,\mathrm{eff,even}}$ *for s/h* = 0.05	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.5	3	4
0.4	6.491	6.516	6.558	6.620	6.656	6.672	6.673	6.662	6.644	6.621	6.594	6.567	6.501	6.444	6.361
0.6	6.705	6.726	6.764	6.818	6.849	6.860	6.856	6.841	6.819	6.793	6.763	6.733	6.661	6.599	6.509
0.8	6.891	6.910	6.943	6.989	7.014	7.020	7.012	6.994	6.969	6.939	6.908	6.876	6.800	6.735	6.640
1	7.054	7.071	7.100	7.140	7.159	7.161	7.149	7.128	7.101	7.069	7.036	7.003	6.924	6.857	6.760
1.2	7.199	7.214	7.239	7.273	7.288	7.286	7.271	7.248	7.219	7.186	7.152	7.118	7.037	6.969	6.870
1.4	7.328	7.342	7.364	7.393	7.403	7.398	7.382	7.357	7.327	7.293	7.258	7.223	7.142	7.073	6.973
1.6	7.444	7.456	7.476	7.500	7.507	7.500	7.482	7.456	7.425	7.391	7.356	7.320	7.238	7.169	7.069
1.8	7.549	7.560	7.577	7.598	7.602	7.593	7.574	7.547	7.516	7.481	7.446	7.410	7.328	7.259	7.159
2	7.643	7.653	7.669	7.687	7.689	7.679	7.658	7.631	7.599	7.565	7.529	7.494	7.412	7.344	7.244
2.5	7.844	7.853	7.865	7.877	7.876	7.863	7.842	7.814	7.782	7.748	7.714	7.679	7.600	7.533	7.435
3	8.007	8.014	8.024	8.033	8.029	8.016	7.994	7.967	7.936	7.903	7.870	7.837	7.760	7.695	7.600
3.5	8.142	8.148	8.156	8.163	8.158	8.144	8.122	8.096	8.067	8.035	8.003	7.972	7.898	7.836	7.741

Περιττός Ρυθμός

Table 9.2 (cont'd)

w/h	*Odd-Mode Effective Permittivity* $\epsilon_{r,\mathrm{eff,odd}}$ *for s/h* = 0.05	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.5	3	4
0.4	5.428	5.439	5.457	5.495	5.535	5.577	5.620	5.661	5.702	5.740	5.777	5.810	5.883	5.941	6.022
0.6	5.458	5.474	5.501	5.552	5.603	5.653	5.702	5.750	5.795	5.838	5.877	5.914	5.992	6.054	6.139
0.8	5.496	5.519	5.554	5.617	5.676	5.733	5.788	5.840	5.889	5.934	5.976	6.014	6.095	6.159	6.247
1	5.542	5.571	5.615	5.687	5.754	5.817	5.875	5.931	5.982	6.029	6.072	6.111	6.194	6.259	6.348
1.2	5.594	5.630	5.681	5.762	5.834	5.901	5.963	6.020	6.073	6.121	6.165	6.205	6.289	6.354	6.444
1.4	5.650	5.693	5.750	5.839	5.916	5.986	6.050	6.109	6.163	6.212	6.256	6.296	6.380	6.445	6.535
1.6	5.708	5.758	5.822	5.916	5.997	6.069	6.135	6.195	6.249	6.299	6.344	6.384	6.468	6.532	6.622
1.8	5.768	5.825	5.894	5.994	6.077	6.151	6.218	6.279	6.334	6.383	6.428	6.468	6.552	6.616	6.704
2	5.829	5.893	5.967	6.071	6.156	6.231	6.299	6.360	6.415	6.464	6.509	6.549	6.632	6.695	6.783
2.5	5.980	6.060	6.146	6.257	6.345	6.421	6.489	6.550	6.604	6.653	6.697	6.736	6.816	6.878	6.964
3	6.125	6.219	6.314	6.430	6.519	6.594	6.662	6.722	6.775	6.823	6.866	6.904	6.982	7.041	7.125
3.5	6.260	6.368	6.471	6.589	6.677	6.752	6.818	6.877	6.929	6.976	7.017	7.054	7.130	7.187	7.269

Χαρακτηριστική Αντίσταση και Δρώσα Διηλεκτρική σταθερά Συζευγμένων μικροταινιακών γραμμών τυπωμένων σε Al_2O_3

Table 9.1 Even and odd mode characteristic impedances $Z_{L,\mathrm{even}}$ and $Z_{L,\mathrm{odd}}$ of coupled microstrip lines on Al_2O_3 ceramic substrate ($\epsilon_r = 9.8$) for conductor thickness $t = 0$ from the variational method [2.46, 3.32] for the quasistatic case $h/\lambda_0 = 10^{-5}$.

Άρτιος Ρυθμός

w/h	*Even-Mode Characteristic Impedance $Z_{L,\mathrm{even}}$ in Ω for s/h =* 0.05	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.5	3	4
0.4	106.75	104.22	99.89	93.41	88.81	85.44	82.92	81.02	79.58	78.48	77.63	76.98	75.92	75.33	74.75
0.6	88.09	86.40	83.43	78.77	75.32	72.74	70.78	69.28	68.14	67.27	66.60	66.08	65.24	64.78	64.32
0.8	75.44	74.22	72.03	68.50	65.83	63.79	62.22	61.02	60.10	59.39	58.84	58.43	57.75	57.38	57.02
1	66.17	65.23	63.54	60.77	58.64	56.99	55.71	54.73	53.97	53.39	52.94	52.60	53.05	51.75	51.47
1.2	59.03	58.29	56.94	54.71	52.96	51.60	50.54	49.72	49.09	48.60	48.23	47.95	47.50	47.26	47.03
1.4	53.34	52.74	51.64	49.80	48.34	47.20	46.31	45.61	45.08	44.67	44.35	44.12	43.75	43.55	43.37
1.6	48.69	48.19	47.27	45.73	44.50	43.53	42.76	42.17	41.71	41.36	41.09	40.90	40.59	40.43	40.28
1.8	44.81	44.39	43.62	42.30	41.24	40.40	39.73	39.23	38.83	38.53	38.31	38.14	37.88	37.75	37.63
2	41.52	41.16	40.50	39.36	38.44	37.71	37.14	36.69	36.35	36.09	35.89	35.75	35.53	35.43	35.33
2.5	35.13	34.88	34.40	33.58	32.91	32.37	31.95	31.62	31.37	31.18	31.04	30.94	30.81	30.75	30.69
3	30.48	30.29	29.93	29.31	28.80	28.38	28.06	27.81	27.62	27.48	27.38	27.31	27.22	27.19	27.14
3.5	26.93	26.79	26.51	26.02	25.61	25.29	25.03	24.83	24.68	24.58	24.50	24.45	24.39	24.37	24.55

Περιττός Ρυθμός

Table 9.1 (cont'd)

w/h	*Odd-Mode Characteristic Impedance $Z_{L,\mathrm{odd}}$ in Ω for s/h =* 0.05	0.1	0.2	0.4	0.6	0.8	1	1.2	1.4	1.6	1.8	2	2.5	3	4
0.4	29.93	35.12	41.72	49.87	55.12	58.85	61.61	63.72	65.37	66.67	67.72	68.57	70.10	71.09	72.21
0.6	26.88	31.22	36.66	43.34	47.63	50.69	52.96	54.71	56.07	57.16	58.05	58.77	60.11	60.98	62.00
0.8	24.86	28.66	33.32	38.98	42.59	45.15	47.06	48.53	49.69	50.62	51.38	52.01	53.18	53.96	54.89
1	23.35	26.74	30.83	35.71	38.80	40.99	42.63	43.88	44.88	45.68	46.35	46.90	47.94	48.65	49.50
1.2	22.14	25.19	28.82	33.10	35.79	37.69	39.10	40.19	41.06	41.77	42.35	42.84	43.77	44.42	45.20
1.4	21.11	23.89	27.15	30.94	33.30	34.96	36.20	37.16	37.93	38.55	39.07	39.51	40.36	40.95	41.67
1.6	20.22	22.76	25.71	29.10	31.19	32.66	33.76	34.61	35.29	35.85	36.15	36.71	37.48	38.02	38.70
1.8	19.42	21.75	24.44	27.49	29.37	30.68	31.66	32.42	33.04	33.53	33.96	34.32	35.02	35.52	36.15
2	18.70	20.86	23.32	26.08	27.77	28.95	29.85	30.51	31.07	31.52	31.91	32.24	32.89	33.36	33.94
2.5	17.15	18.96	20.97	23.18	24.51	25.44	26.13	26.67	27.11	27.48	27.79	28.06	28.60	29.00	29.49
3	15.87	17.41	19.10	20.92	21.99	22.74	23.30	23.74	24.10	24.41	24.67	24.90	25.35	25.69	26.09
3.5	14.79	16.12	17.56	19.08	19.97	20.59	21.05	21.42	21.72	21.98	22.20	22.40	22.78	23.07	23.39

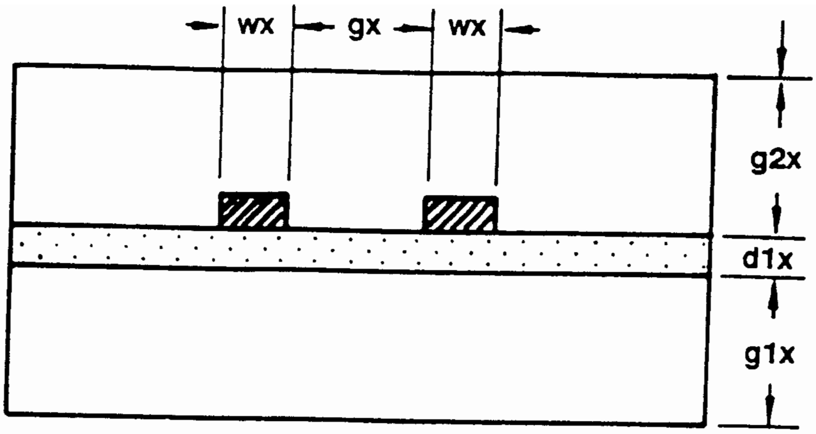


Figure 11. Suspended substrate coupled lines.

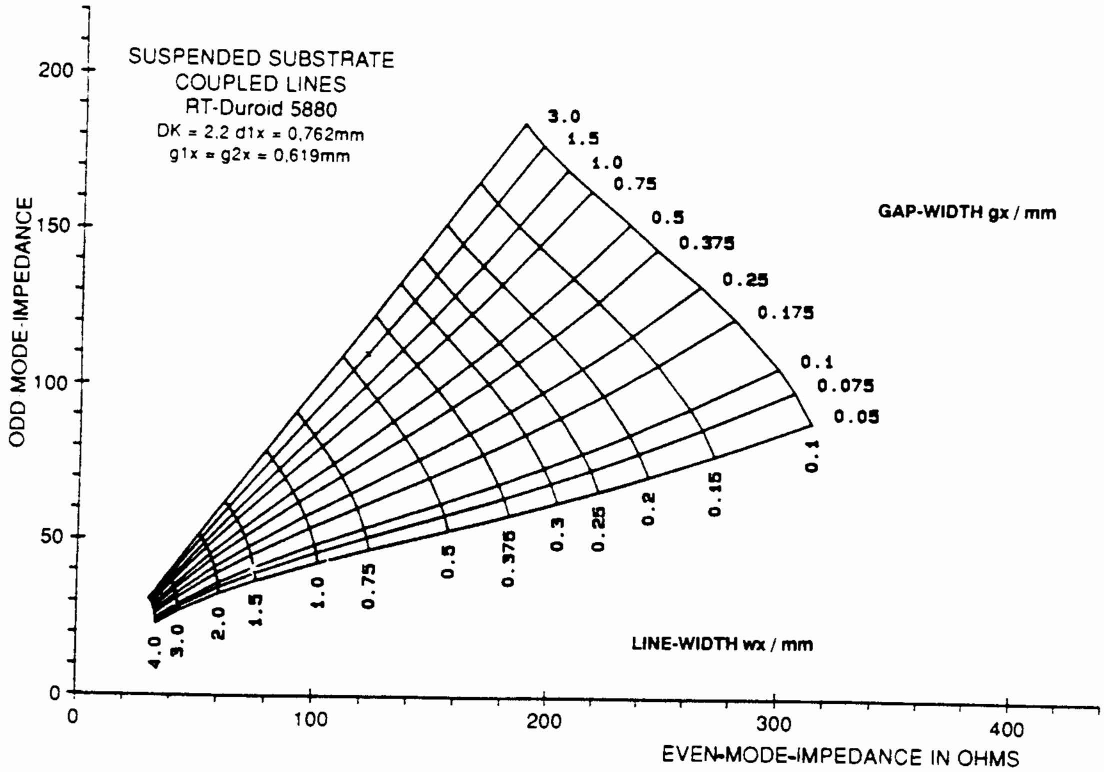


Figure 13. Even- and odd-mode impedances of suspended substrate coupled lines (substrate, RT 5880).

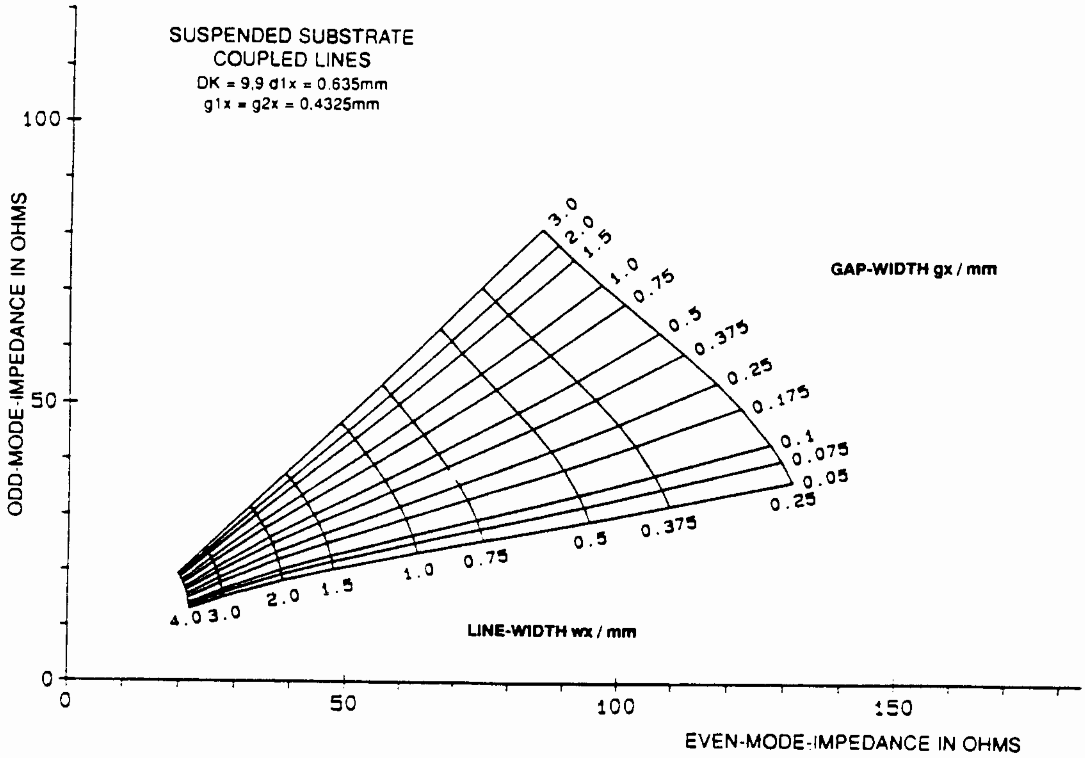


Figure 14. Even- and odd-mode, impedances of suspended substrate coupled lines (substrate, AL203).

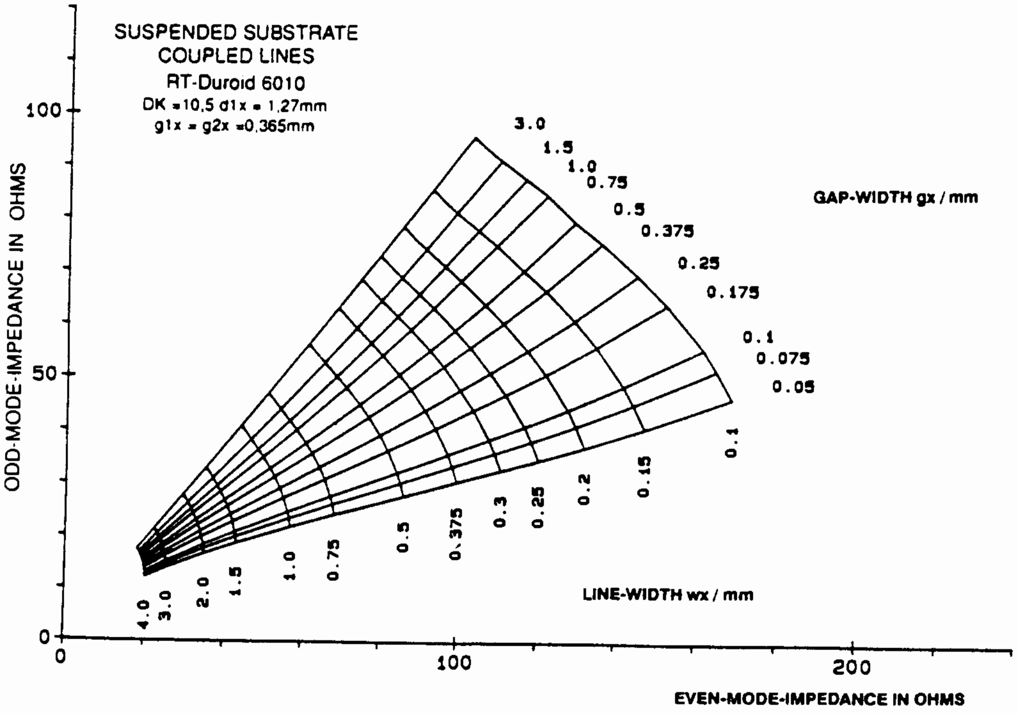


Figure 15. Even- and odd-mode impedances of suspended substrate coupled lines (substrate, RT 6010).

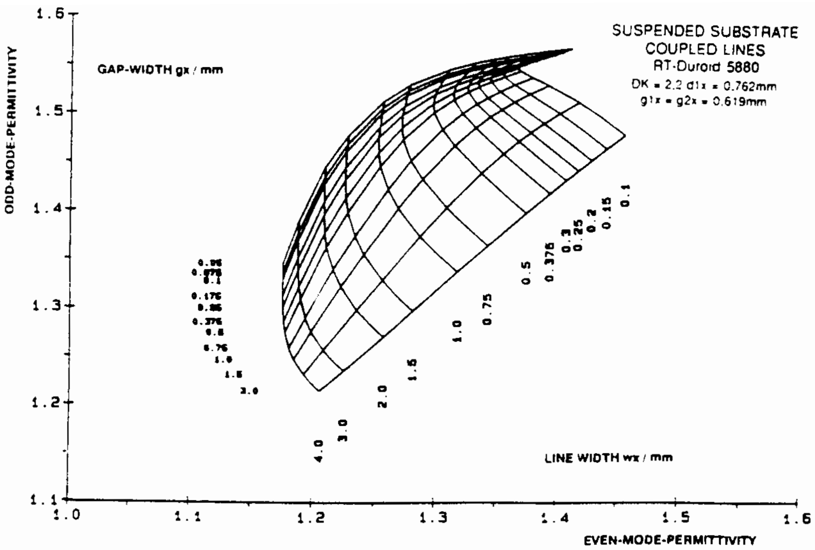


Figure 16. Even- and odd-mode permittivities of suspended substrate coupled lines (substrate: RT 5880).

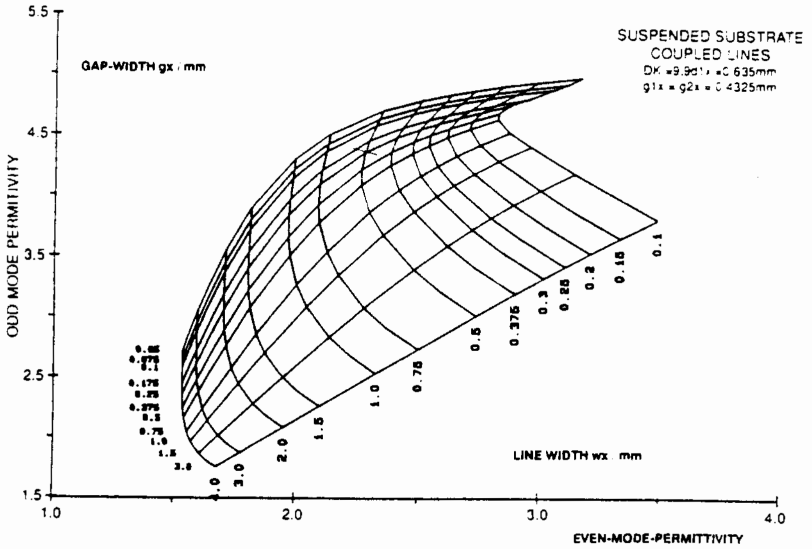


Figure 17. Even- and odd-mode permittivities of suspended substrate coupled lines (substrate: AL 203).

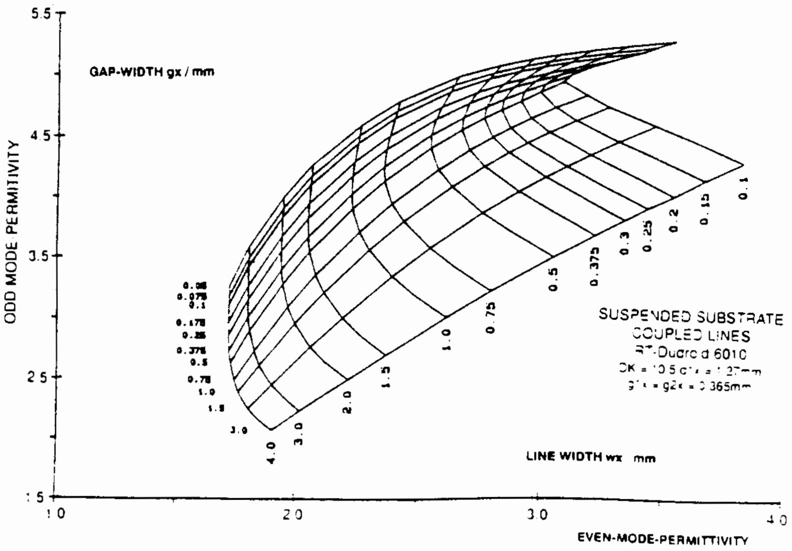


Figure 18. Even- and odd-mode permittivities of suspended substrate coupled lines (substrate: RT 6010).

Ομοεπίπεδος Κυματοδηγός (CPW : Coplanar Waveguide)
(Collin σελ. 175-)

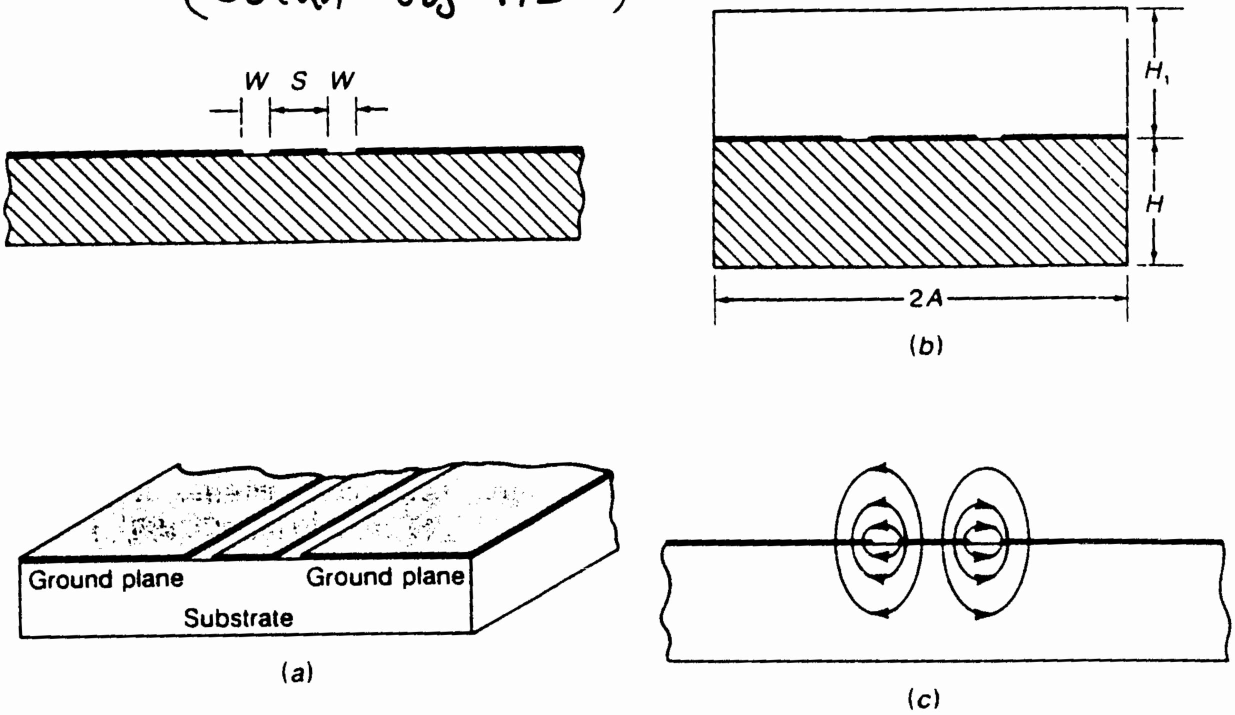


FIGURE 3.35
(*a*) Basic coplanar transmission line; (*b*) a shielded coplanar transmission line; (*c*) electric field distribution.

Ορθογωνικός Κυματοδηγός με ράχες.

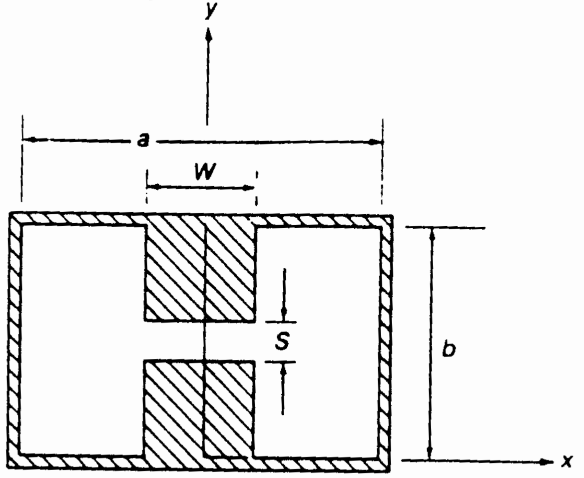


FIGURE 3.46
Ridge waveguide.

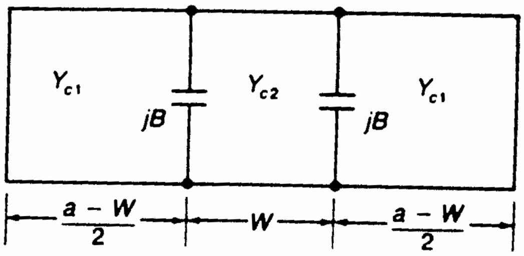


FIGURE 3.47
Equivalent transmission-line circuit of cro
section of ridge waveguide.

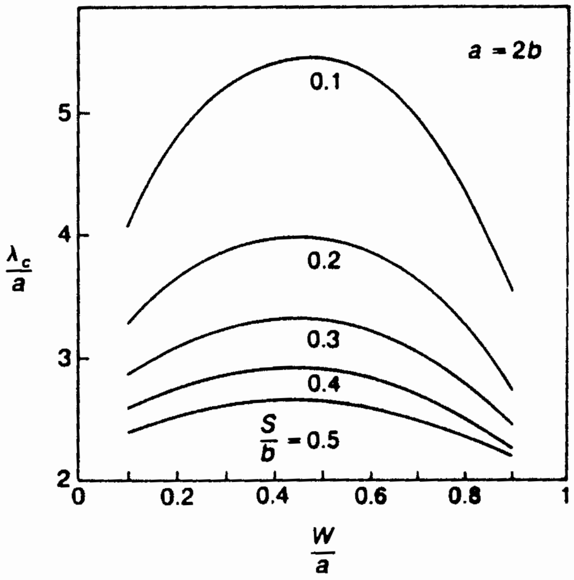


FIGURE 3.48
Normalized cutoff wavelength λ_c/a for a ridge waveguide.

Τοποθέτηση Ομοαξονικών Συνδετήρων σε μικροταινιακό κύκλωμα

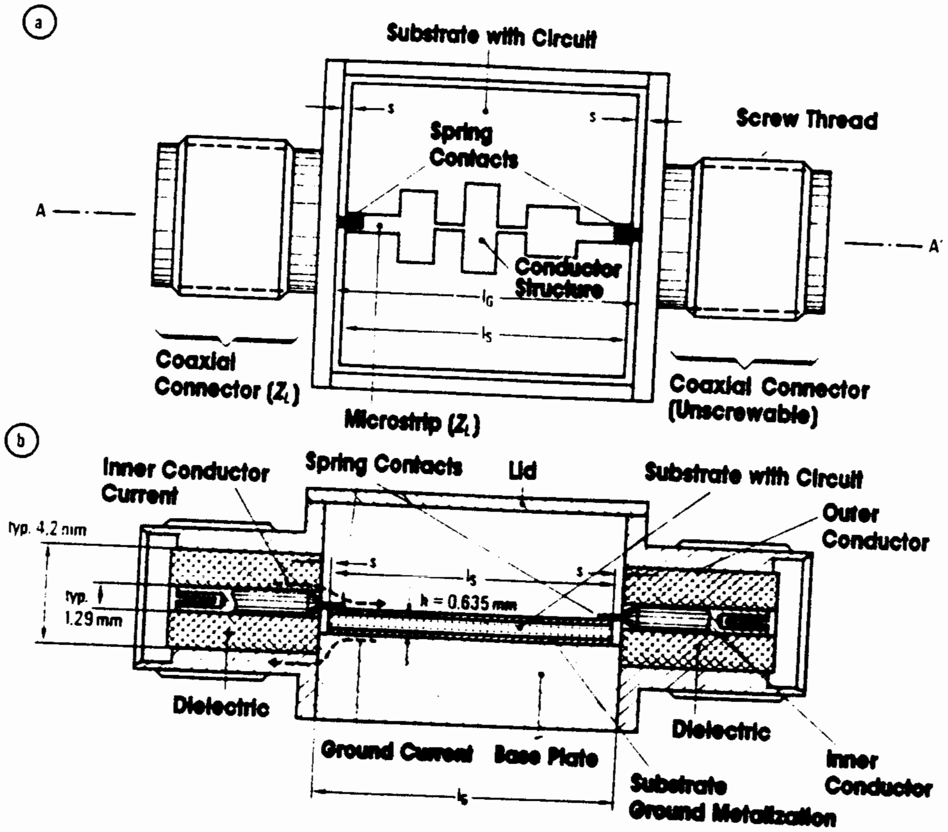
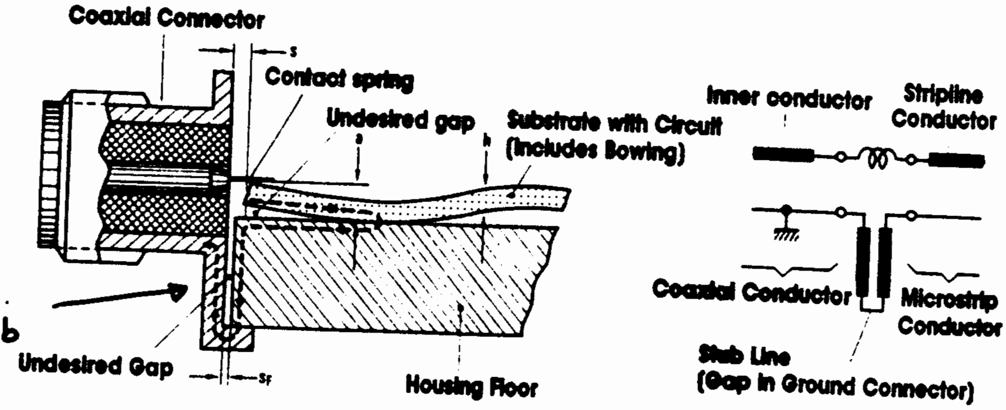


Fig. 1.32 Schematic of a housing for a microstrip circuit with two coaxial connectors: (a) without lid; (b) cross section.

Προβλήματα Διασυνδέσεων:



Κακή σύνδεση.
→ Παρασιτικό stub

Fig. 1.33 Action of a bend in the substrate and a split in the ground for a real coaxial-microstrip transition.

Πρέπει:

- Να ελαχιστοποιούνται οι ασυνέχειες του πεδίου
- Να εξασφαλίζεται ο ελάχιστος δρόμος ροής ρεύματος
- Να αποφεύγονται οι διαφορετικοί συντελεστές θερμικής διαστολής

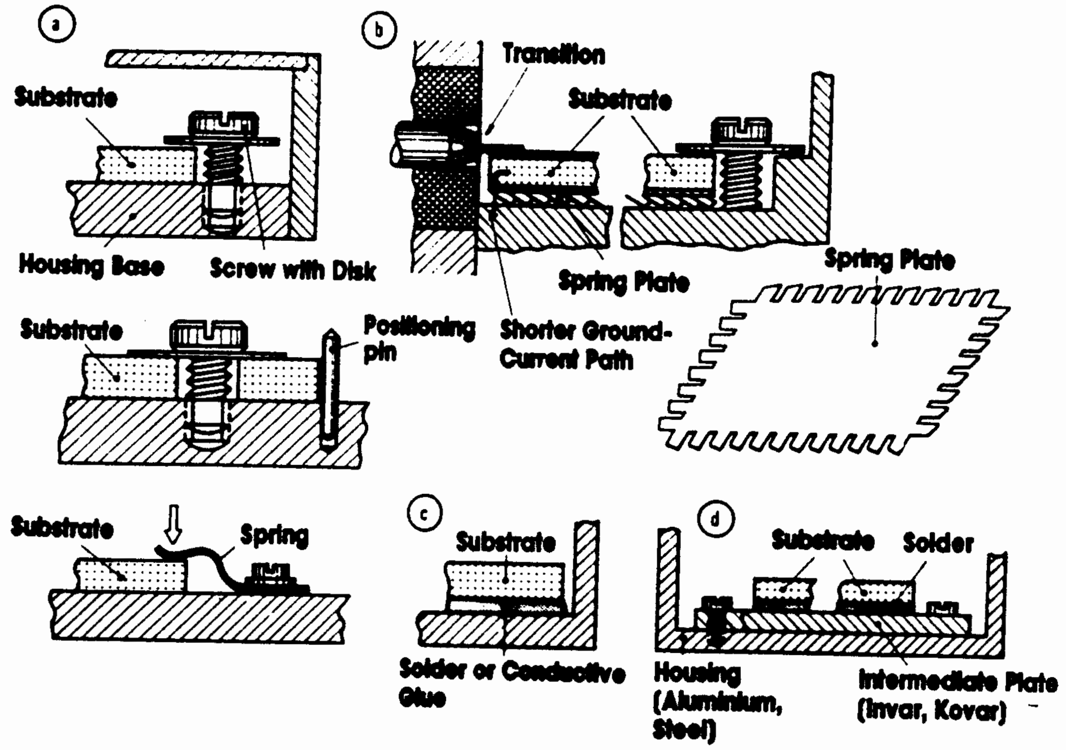


Fig. 1.34 Possible methods of mounting substrate in housing: (a) clamping; (b) clamping with spring plate; (c) soldering or gluing with conductive paste; (d) soldering onto an intermediate invar plate.

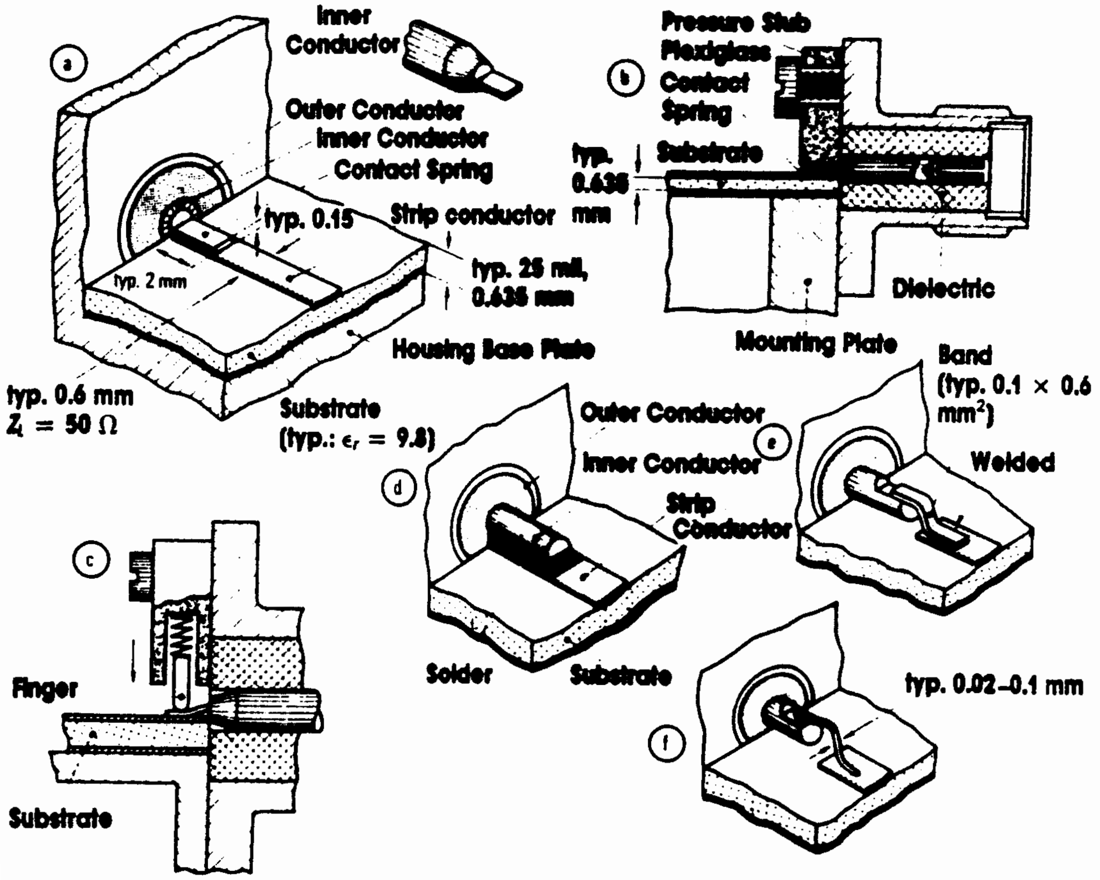


Fig. 1.35 Possibilities for inner-conductor connectors: (a) gluing with spring; ($f \leq 18$ GHz); (b) as in (a), but with plastic pressure stub; (c) as in (a), but with spring-loaded finger; (d) soldered inner conductor ($f \leq 1$ GHz); (e) welded strip ($f \leq 0.5$ GHz); (f) welded wire ($f \leq 0.2$ GHz).

Διασύνδεση Ομοαξονικού και μικροταινιακής γραμμής

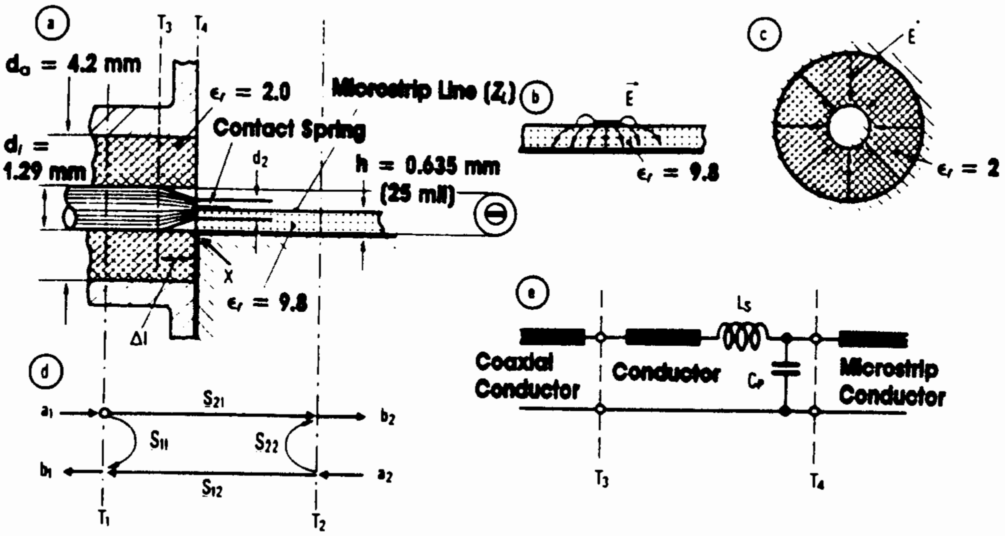


Fig. 1.37 Transition from SMA-coaxial line to microstrip line, electrical properties: (a) cross section; (b) electrical field pattern of microstrip line; (c) field pattern of coaxial line; (d) general scattering coefficients $\underline{S}_{ij}$ of a transition; (e) equivalent circuit of a compensated transition as shown in (a).

Διασυνδέσεις
χαμηλών
απωλειών

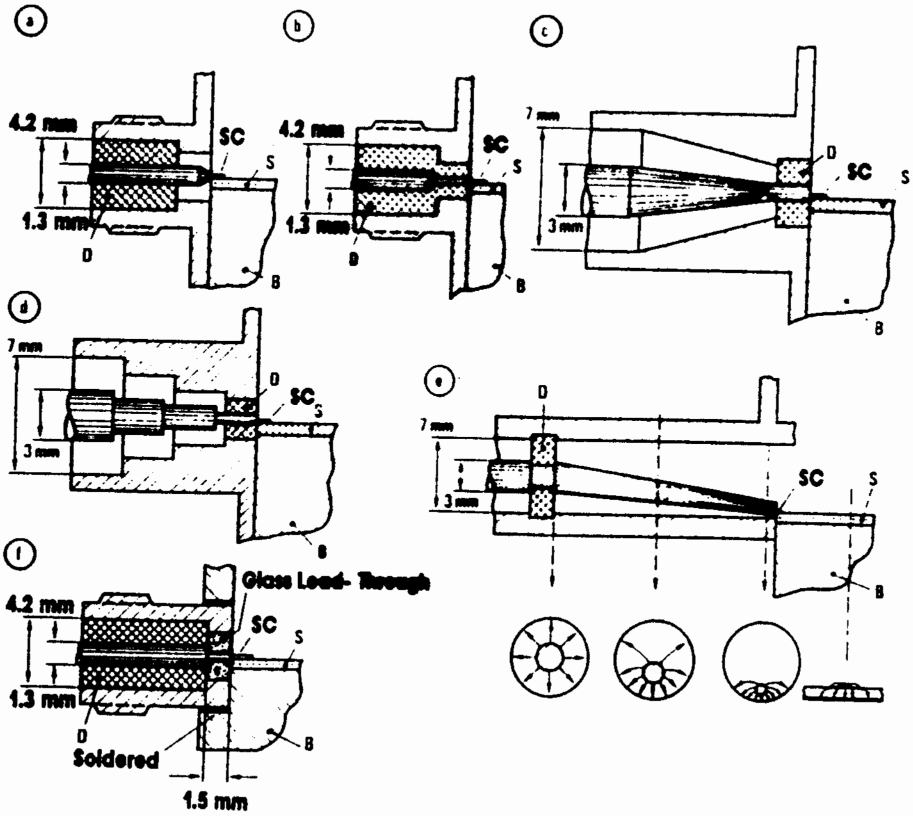


Fig. 1.38 Other types of low-reflection transitions from 3/7 coaxial line (d_{in} = 3 mm, d_{out} = 7 mm) or SMA coaxial line (d_{in} = 1.3 mm, d_{out} = 4.2 mm) to microstrip line on ceramic substrate, S (thickness 25 mil = 0.635 mm, ϵ_r = 9.8); SC = inner conductor spring contact; B = housing base plate: (a) with intermediate air conductor; (b) with stepped cross-section matching sections; (c) with continuous cross-section matching; (d) multistepped; (e) eccentric coaxial transition (after [1.319]); (f) hermetically sealed (D = dielectric)

Διασύνδεση ορθογωνικού κυματοδηγού - Μικροταινιακής Γραμμής

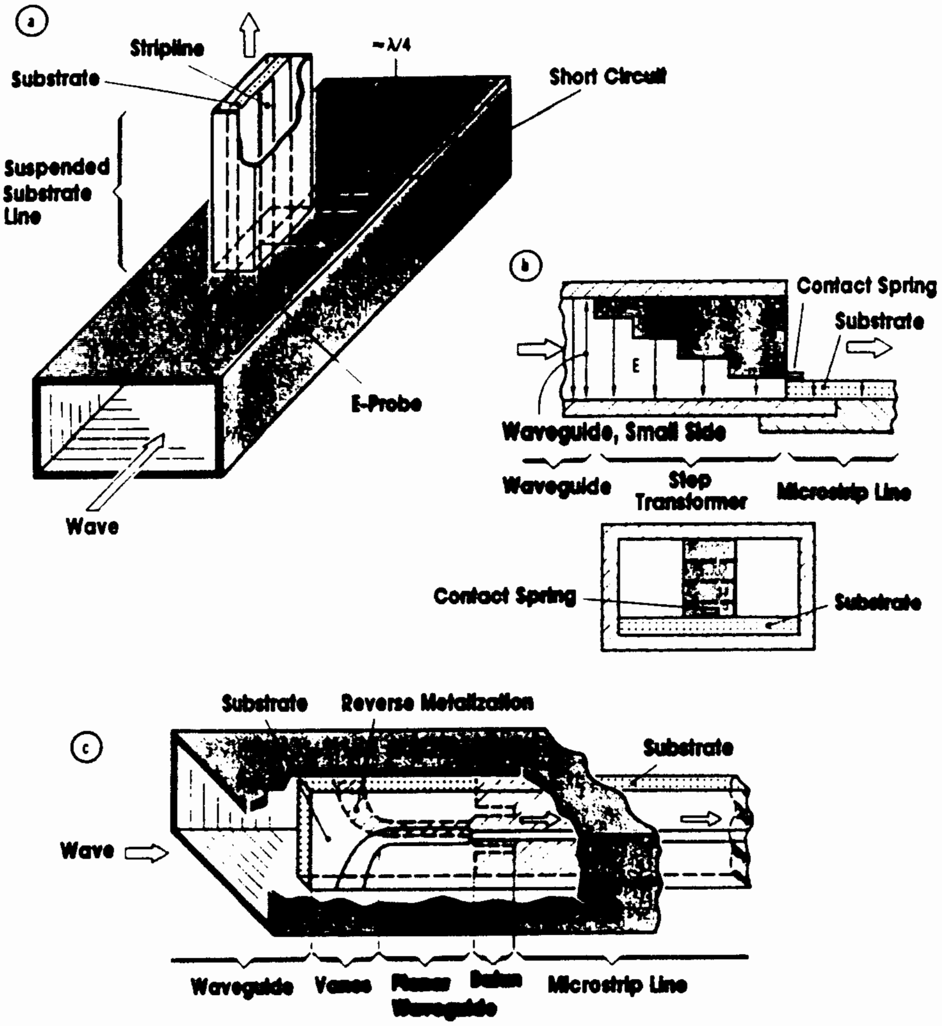
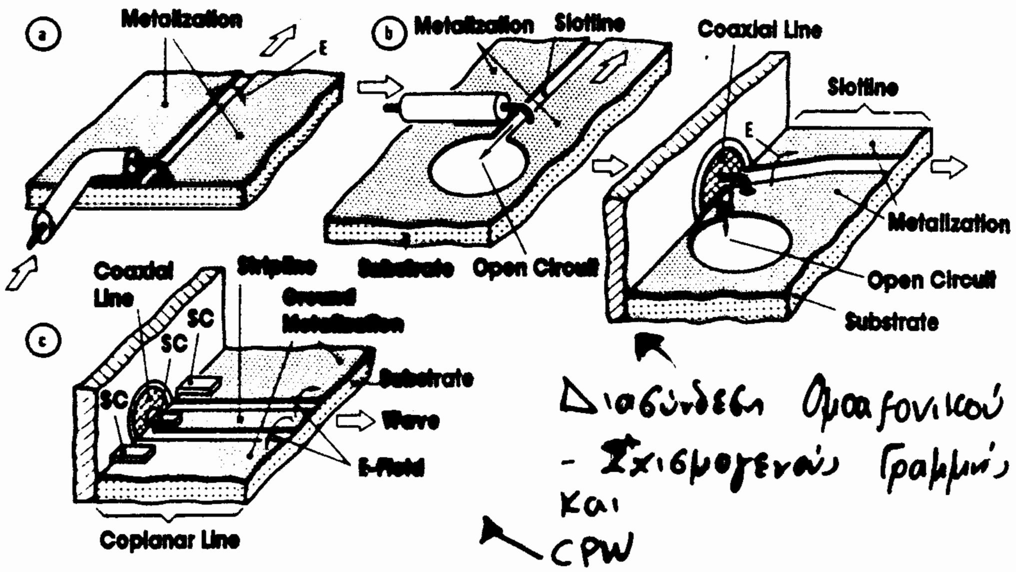


Fig. 1.40 Transitions from rectangular waveguide to stripline conductors: (a) E-field probe coupling via suspended-substrate line (after [1.347]); (b) step-transformer transition to microstrip line (after [1.30]); (c) transition to microstrip line (after [1.329, 1.330]).



Διασύνδεση Ομοαξονικού -
- Σχισμογενούς Γραμμής
και
CPW

Fig. 1.41 Transitions from coaxial to slotline and coplanar line: (a) slotline transition at substrate edge [1.349, 1.350]; (b) slotline transition with open circuit [1.351]; (c) coplanar line transition (SC = spring contacts for inner conductor and grounds).