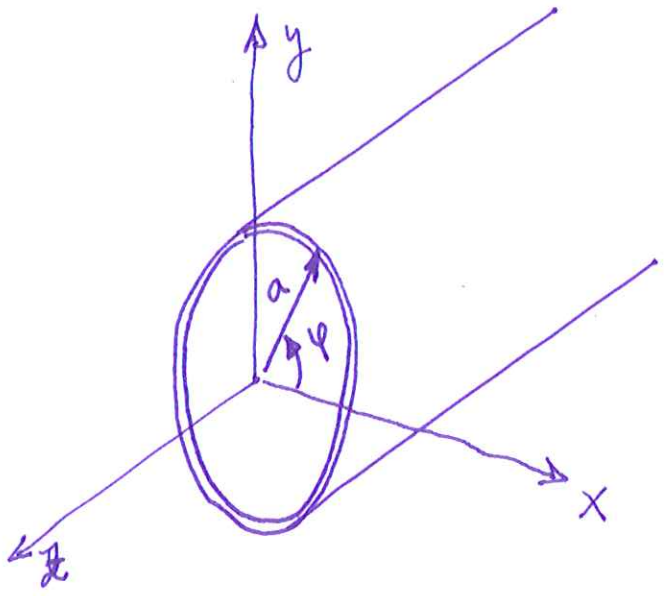
Guías Conductoras Sección Circular.



De nuevo, de la ec. de las Ondas EM en medios materiales:

$$\nabla^2 \vec{E} + \omega^2 \varepsilon \mu \vec{E} + j\omega\sigma\mu \vec{E} = 0$$

En el interior de la guía $\sigma = 0$, quedando

$$\nabla^2 \vec{E} + \omega^2 \varepsilon \mu \vec{E} = 0$$

La solución a esa ec. es una onda que se propaga en $+z$

$$\vec{E}(\rho,\varphi,z) = E(\rho,\varphi)\cdot e^{-j\beta z}$$

Sustituyendo en la ec. y teniendo en cuenta que el Laplaciano de una función en coord. cilíndricas es:

$$\nabla^2 f = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial f}{\partial\rho}\right) + \frac{1}{\rho^2}\frac{\partial^2 f}{\partial\varphi^2} + \frac{\partial^2 f}{\partial z^2}$$

La ecuación queda:

$$\frac{\partial^2 E}{\partial\rho^2} + \frac{1}{\rho}\frac{\partial E}{\partial\rho} + \frac{1}{\rho^2}\frac{\partial E}{\partial\varphi^2} + \beta^2 E + \omega^2\varepsilon\mu E = 0$$

Con el Laplaciano podemos considerar: $\nabla^2 E = (\nabla^2_{\rho\varphi} + \nabla^2_z) E$

Sustituyendo en la ec llegamos a que:

$$E_\rho = \frac{-j}{\underbrace{(\omega^2\mu\varepsilon - \beta^2)}_{K_c^2}} \left[\beta \frac{\partial E_z}{\partial \rho} + \frac{\omega\mu}{\rho} \frac{\partial H_z}{\partial \varphi} \right]$$

$$E_\varphi = \frac{-j}{K_c^2} \left[-\frac{\beta}{\rho} \frac{\partial E_z}{\partial \varphi} + \omega\mu \frac{\partial H_z}{\partial \rho} \right]$$

$$H_\rho = \frac{j}{K_c^2} \left[\frac{\omega\varepsilon}{\rho} \frac{\partial E_z}{\partial \varphi} - \beta \frac{\partial H_z}{\partial \rho} \right]$$

$$H_\varphi = \frac{-j}{K_c^2} \left[\omega\varepsilon \frac{\partial E_z}{\partial \rho} + \frac{\beta}{\rho} \frac{\partial H_z}{\partial \varphi} \right]$$

Lo que nos lleva a que: Calculando E_z y H_z obtenemos el resto de las componentes de campo eléctrico y magnético.

Jugando con estas expresiones llegamos a:

$$\nabla^2 E_z + (\omega^2\mu\varepsilon - \beta^2) E_z = 0$$

En cuya resolución empleamos el método de separación de variables

$$E_z(\rho, \varphi) = R(\rho) \cdot \Phi(\varphi)$$

$$\frac{\partial^2 E_z}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial E_z}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 E_z}{\partial \varphi^2} + \underbrace{(\omega^2 \mu \varepsilon - \beta^2)}_{K_c^2} E_z = 0$$

Sustituyendo $E_z = R(\rho) \cdot \Phi(\varphi)$ y operando, se tiene:

$$\underbrace{\rho^2 \frac{1}{R}\frac{d^2 R}{d\rho^2} + \rho \frac{dR}{d\rho} + \rho^2 K_c^2}_{\text{Solo depende de } \rho} = \underbrace{-\frac{1}{\Phi}\frac{d^2\Phi}{d\varphi^2}}_{\text{Solo depende de } \varphi}$$

La única de forma de cumplirse esto es que ambos lados sean iguales a una constante que llamaremos m^2

$$\begin{cases} \rho^2 \frac{1}{R}\frac{d^2 R}{d\rho^2} + \rho \frac{dR}{d\rho} + \rho^2 K_c^2 = m^2 \\ -\frac{1}{\Phi}\frac{d^2\Phi}{d\varphi^2} = m^2 \end{cases}$$

Las ecuaciones a resolver son entonces:

$$\begin{cases} \boxed{\frac{d^2 R}{d\rho^2} + \frac{1}{\rho}\frac{dR}{d\rho} + \left(K_c^2 - \frac{m^2}{\rho^2}\right) R = 0} \Rightarrow \text{Soluciones F. Bessel.} \\ \boxed{\frac{d^2\Phi}{d\varphi^2} + m^2 \Phi = 0} \longrightarrow \text{Soluciones tipo "sen" "cos"} \end{cases}$$

$$R = A\, J_m(K_c \cdot \rho) + B\, N_m(K_c \cdot \rho)$$

$$\Phi = C \cos m\varphi + D \operatorname{sen} m\varphi$$

J_m : funciones de Bessel (1^a especie)

N_m : funciones de Neumann (Bessel de 2^a especie)

Modos TM

$$E_z(\rho,\varphi) = R(\rho)\cdot\Phi(\varphi) = \left[A J_m(k_c\rho) + B N_m(k_c\rho)\right]\left[C\cos m\varphi + D \,\text{sen}\, m\varphi\right]$$

Aplicamos las condiciones de contorno:

* $E_z(\rho = a) = 0 \Rightarrow J_m(k_c\rho) = 0 \Rightarrow$ Ceros de la F. Bessel. $X_{m,n}$

* El campo ha de ser finito en todos los puntos $\Rightarrow B = 0$ pues las F. Neumann son discont. en $\rho = 0$.

* Por simplificación tomaremos $D = 0$ (Aunque algunos libros prefieren no hacerlo (Balanis))

Quedando:

$$E_z(\rho,\varphi) = \overset{A\cdot C}{A}\cdot J_m(k_c\cdot\rho)\cdot\cos m\varphi$$

La condición que nos lleva a los ceros de la función de Bessel implica:

$$k_c\cdot a = X_{m,n}$$ siendo a el radio de la guía.

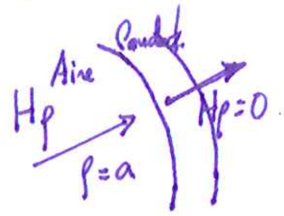
$$\sqrt{\omega^2\mu\varepsilon}\cdot a = X_{m,n}$$

$$\boxed{f_{c_{m,n}} = \frac{X_{m,n}}{2\pi a\sqrt{\mu\varepsilon}}} \Rightarrow$$ Frecuencia de corte del modo $TM_{m,n}$

Modos TE

$$H_z(\rho,\varphi) = \mathbb{B}\; J_m(K_c\cdot\rho)\cdot \cos m\varphi$$

Donde una de las condiciones de contorno, obligaba a que la componente H_ρ fuera cero en $\rho = a$



$$H_\rho(\rho=a)=0 \;\Rightarrow\; \left.\frac{\partial H_z}{\partial\rho}\right]_{\rho=a} = 0$$

Ya que

$$H_\rho = \frac{j}{K_c^2}\left[\frac{\omega\varepsilon}{\rho}\cancel{\frac{\partial E_z}{\partial\varphi}} - \beta\frac{\partial H_z}{\partial\rho}\right]$$

Modo TE ($E_z = 0$)

El hecho de que $\left.\dfrac{\partial H_z}{\partial\rho}\right]_{\rho=a} = 0$ lleva a considerar como solución, los "ceros" de la "derivada de la función de Bessel"

$$J'_m(K_c\rho) = 0 \;\Rightarrow\; \boxed{X'_{m,n}}$$

ceros de la derivada de la función de Bessel de orden m

Con lo que:

$$K_c\cdot\rho = X'_{m,n}$$

$$\boxed{f_{c_{m,n}} = \frac{X'_{m,n}}{2\pi a\sqrt{\mu\varepsilon}}}$$

Modos TE ($H_z = 0$) Balanis

$$E_\rho = -A_{mn} \frac{m}{\varepsilon \rho} J_m(\beta_\rho \cdot \rho) \left[-C_2 \operatorname{sen} m\phi + D_2 \cos m\phi \right] e^{-j\beta_z \cdot z}$$

$$E_\phi = A_{mn} \frac{\beta_\rho}{\varepsilon} J'_m(\beta_\rho \cdot \rho) \left[C_2 \cos m\phi + D_2 \operatorname{sen} m\phi \right] e^{-j\beta_z \cdot z}$$

$$E_z = 0$$

$$H_\rho = -A_{mn} \frac{\beta_\rho \beta_z}{\omega \mu \varepsilon} J'_m(\beta_\rho \cdot \rho) \left[C_2 \cos m\phi + D_2 \operatorname{sen} m\phi \right] e^{-j\beta_z \cdot z}$$

$$H_\phi = -A_{mn} \frac{m\beta_z}{\omega \mu \varepsilon} \frac{1}{\rho} J_m(\beta_\rho \cdot \rho) \left[-C_2 \operatorname{sen} m\phi + D_2 \cos m\phi \right] e^{-j\beta_z \cdot z}$$

$$H_z = -j A_{mn} \frac{\beta_\rho^2}{\omega \mu \varepsilon} J_m(\beta_\rho \cdot \rho) \left[C_2 \cos m\phi + D_2 \operatorname{sen} m\phi \right] e^{-j\beta_z \cdot z}$$

Modos TM ($H_z = 0$) Balanis.

$$E_z = -j B_{mn} \frac{\beta_\rho^2}{\omega\mu\varepsilon} J_m(\beta_\rho \rho) \left[C_2 \cos(m\phi) + D_2 \operatorname{sen}(m\phi) \right] e^{-j\beta_z z}$$

$$E_\rho = -\cancel{j} B_{mn} \frac{\beta_\rho \beta_z}{\omega\mu\varepsilon} J_m'(\ ) \left[C_2 \cos m\phi + D_2 \operatorname{sen} m\phi \right] e^{-j\beta_z z}$$

$$E_\phi = - B_{mn} \frac{m \beta_z}{\omega\mu\varepsilon\rho} J_m(\ ) \left[-C_2 \operatorname{sen} m\phi + D_2 \cos m\phi \right] e^{-j\beta_z z}$$

donde $\beta_\rho = \frac{X_{mn}}{a}$ $\qquad$ $\beta_z = \sqrt{\omega^2\mu\varepsilon - \frac{X^2}{a^2}} = \underbrace{\beta}_{\sqrt{\omega^2\mu\varepsilon}} \sqrt{1 - \left(\frac{\beta_c}{\beta}\right)^2}$

en el Ramo es β

$$H_\rho = B_{mn} \frac{m}{\mu} \frac{1}{\rho} J_m(\beta_\rho \rho) \left[-C_2 \operatorname{sen} m\phi + D_2 \cos m\phi \right] e^{-j\beta_z z}$$

$$H_\phi = - B_{mn} \frac{\beta_\rho}{\mu} J_m'(\beta_\rho \rho) \left[C_2 \cos m\phi + D_2 \operatorname{sen} m\phi \right] e^{-j\beta_z z}$$

$$H_z = 0$$

REPRESENTACION GRAFICA DE LAS FUNCIONES DE BESSEL

funciones de Neumann

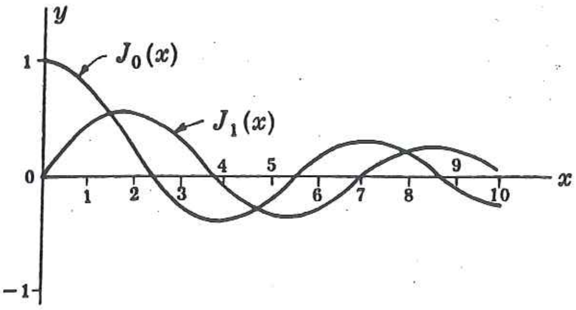


Fig. 24-1

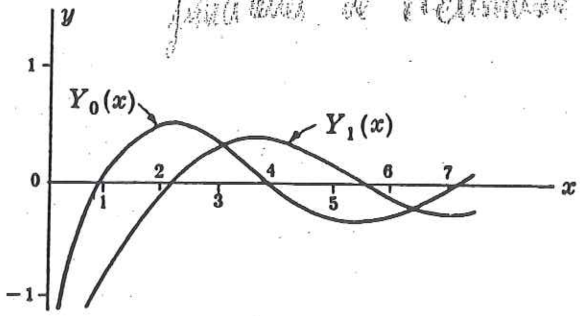


Fig. 24-2

función de Bessel modificada

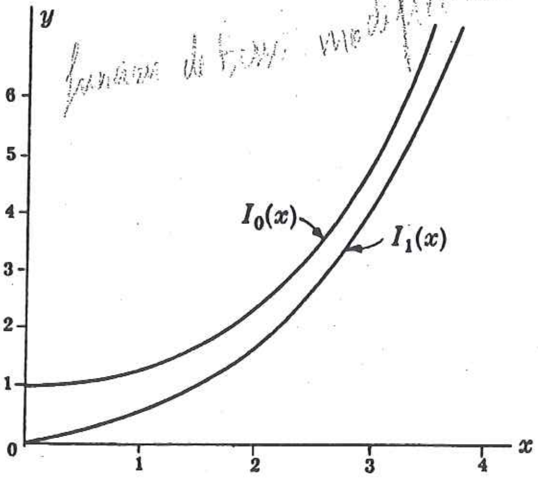


Fig. 24-3

funciones de Bessel

(2ª solución de E.B.M.

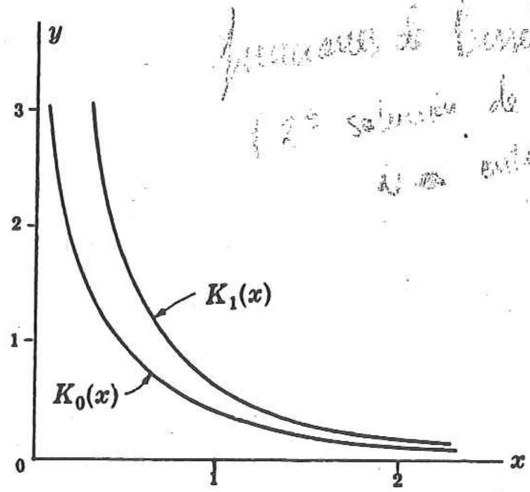


Fig. 24-4

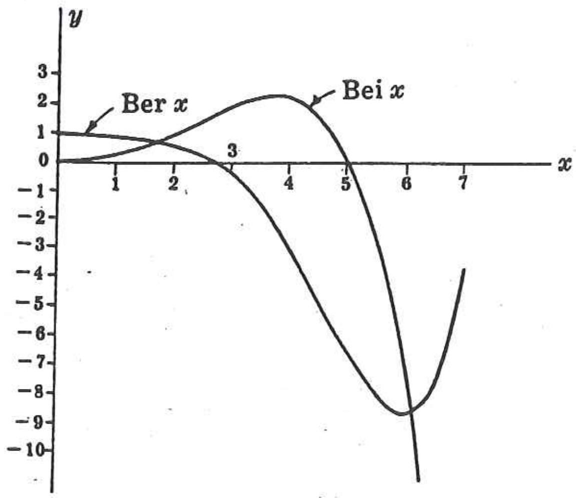


Fig. 24-5

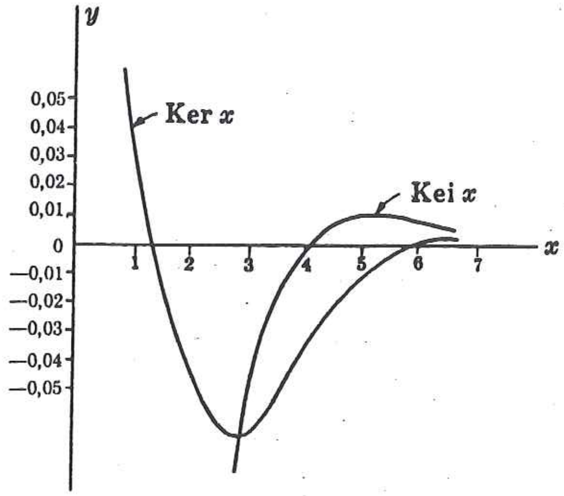


Fig. 24-6

TE

TABLE 9-1
Zeroes χ'_{mn} of derivative $J'_m(\chi'_{mn}) = 0$ ($n = 1, 2, 3, \ldots$) of the Bessel function $J_m(x)$

	$m = 0$	$m = 1$	$m = 2$	$m = 3$	$m = 4$	$m = 5$	$m = 6$	$m = 7$	$m = 8$	$m = 9$	$m = 10$	$m = 11$
$n = 1$	3.8318	1.8412	3.0542	4.2012	5.3175	6.4155	7.5013	8.5777	9.6474	10.7114	11.7708	12.826
$n = 2$	7.0156	5.3315	6.7062	8.0153	9.2824	10.5199	11.7349	12.9324	14.1155	15.2867	16.4479	17.600
$n = 3$	10.1735	8.5363	9.9695	11.3459	12.6819	13.9872	15.2682	16.5294	17.7740	19.0046	20.2230	21.430
$n = 4$	13.3237	11.7060	13.1704	14.5859	15.9641	17.3129	18.6375	19.9419	21.2291	22.5014	23.7607	25.008
$n = 5$	16.4706	14.8636	16.3475	17.7888	19.1960	20.5755	21.9317	23.2681	24.5872	25.8913	27.1820	28.460

TM

TABLE 9-2
Zeroes χ_{mn} of $J_m(\chi_{mn}) = 0$ ($n = 1, 2, 3, \ldots$) of Bessel function $J_m(x)$

	$m = 0$	$m = 1$	$m = 2$	$m = 3$	$m = 4$	$m = 5$	$m = 6$	$m = 7$	$m = 8$	$m = 9$	$m = 10$	$m = 11$
$n = 1$	2.4049	3.8318	5.1357	6.3802	7.5884	8.7715	9.9361	11.0864	12.2251	13.3543	14.4755	15.5898
$n = 2$	5.5201	7.0156	8.4173	9.7610	11.0647	12.3386	13.5893	14.8213	16.0378	17.2412	18.4335	19.6160
$n = 3$	8.6537	10.1735	11.6199	13.0152	14.3726	15.7002	17.0038	18.2876	19.5545	20.8071	22.0470	23.2759
$n = 4$	11.7915	13.3237	14.7960	16.2235	17.6160	18.9801	20.3208	21.6415	22.9452	24.2339	25.5095	26.7733
$n = 5$	14.9309	16.4706	17.9598	19.4094	20.8269	22.2178	23.5861	24.9349	26.2668	27.5838	28.8874	30.1791

05/12/12 III

Atenuación (por pérdidas en conductores)

Modos TE

$$\alpha_{c_{TE_{m,n}}} = \frac{R_s}{a \cdot \eta \cdot \sqrt{1-\left(\frac{f_c}{f}\right)^2}} \left[\left(\frac{f_{c_{m,n}}}{f}\right)^2 + \frac{m^2}{(X'_{m,n})^2 - m^2} \right] \; Np/m$$

Modos TM

$$\alpha_{c_{TM_{m,n}}} = \frac{R_s}{a \cdot \eta \cdot \sqrt{1-\left(\frac{f_c}{f}\right)^2}} \quad Np/m$$

Modos $TE_{0,m}$

Ventajas:

Observar cómo su atenuación disminuye con las altas frecuencias.
Se emplean en transporte de señal de alta frecuencia.

Atenuación guía rectangular ≈ 120 dB/Km. (WR90 de Cu)
Atenuación fibra óptica ≈ 0.5 dB/Km (1.3μm)
Atenuación guía circular ≈ 1.5 dB/Km.

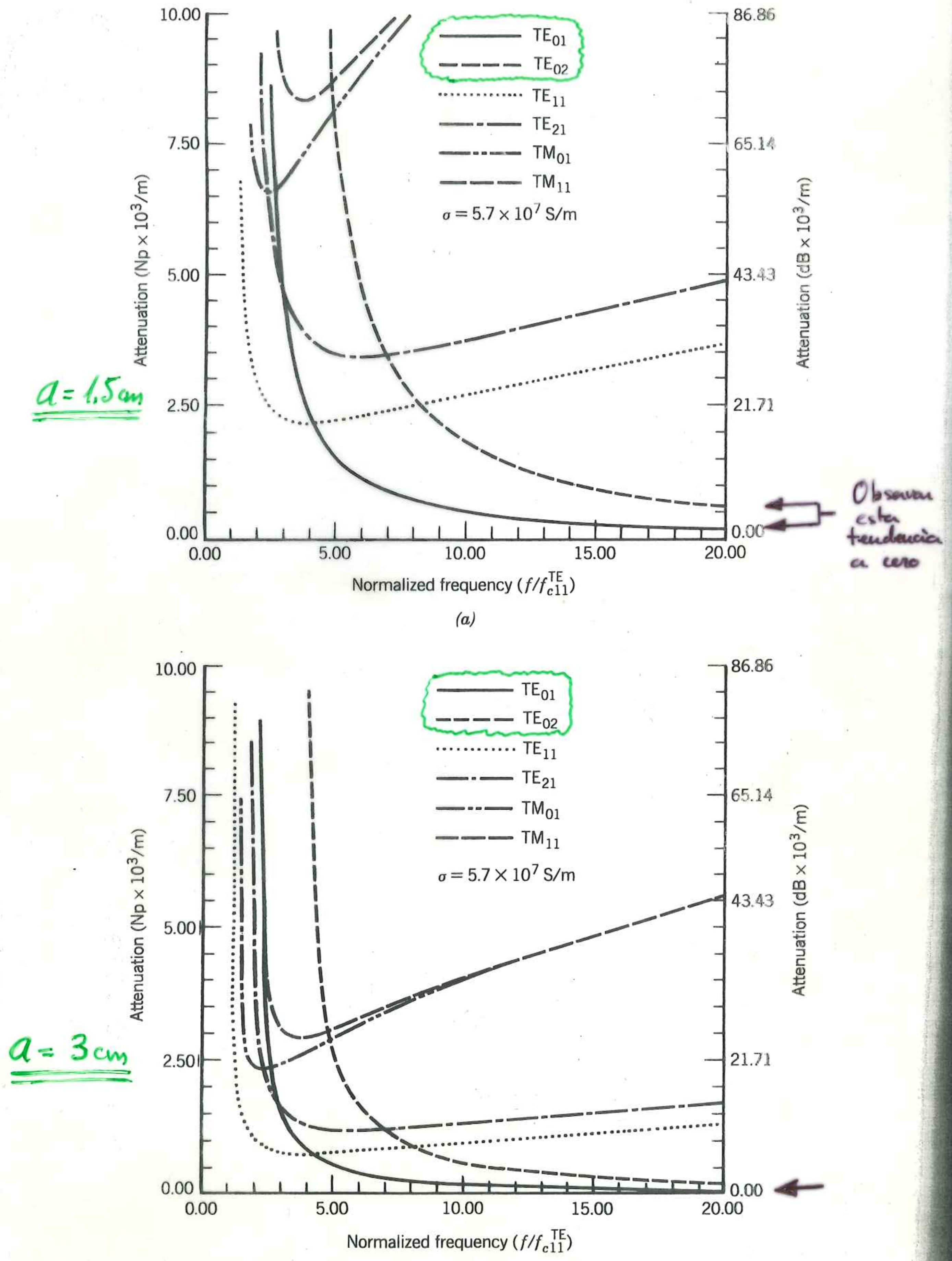
Inconvenientes:

No es el modo dominante.

05/12/12 IV

Atenuación (por pérdidas en dieléctricos)

$$\alpha_d = \frac{\underbrace{k}_{=\omega\cdot\sqrt{\varepsilon\mu}} \cdot \frac{\varepsilon''}{\varepsilon'}}{2\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$$



(a)

(b)

FIGURE 9-4 Attenuation for TE^z_{mn} and TM^z_{mn} modes in a circular waveguide. (a) $a = 1.5$ cm. (b) $a = 3$ cm.

Guías de ondas Circulares (radio : a)

(Resumen)

	$TE_{m,n}$	$TM_{m,n}$
K_c = (Balanis) $\beta_c = \beta_p$	$\frac{X'_{m,n}}{a}$ → Ceros de las Funciones Derivadas de Bessel.	$\frac{X_{m,n}}{a}$ Ceros de las funciones de Bessel
f_c	$\frac{X'_{m,n}}{2\pi a\sqrt{\mu\varepsilon}}$	$\frac{X_{m,n}}{2\pi a\sqrt{\mu\varepsilon}}$
λ_c	$\frac{2\pi a}{X'_{m,n}}$	$\frac{2\pi a}{X_{m,n}}$
$\beta_z\ (f \geq f_c)$ constante de fase	$\beta\sqrt{1-\left(\frac{f_c}{f}\right)^2}$	→ igual
$\lambda_g\ (f \geq f_c)$ long. de onda de la guía.	$\frac{\lambda}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$	→ igual
$u_p\ (f \geq f_c)$	$\frac{u}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$	→ igual.
$Z\ (f \geq f_c)$ Impedancia de la onda	$\frac{\eta}{\sqrt{1-\left(\frac{f_c}{f}\right)^2}}$	$\eta\sqrt{1-\left(\frac{f_c}{f}\right)^2}$

TABLE 9-3
Summary of TE^z_{mn} and TM^z_{mn} mode characteristics of circular waveguide

	$TE^z_{mn}\begin{pmatrix} m = 0,1,2,\ldots, \\ n = 1,2,3,\ldots \end{pmatrix}$	$TM^z_{mn}\begin{pmatrix} m = 0,1,2,3,\ldots, \\ n = 1,2,3,4,\ldots \end{pmatrix}$
E^+_ρ	$-A_{mn}\dfrac{m}{\varepsilon\rho}J_m(\beta_\rho\rho)[-C_2\sin(m\phi) + D_2\cos(m\phi)]e^{-j\beta_z z}$	$-B_{mn}\dfrac{\beta_\rho\beta_z}{\omega\mu\varepsilon}J'_m(\beta_\rho\rho)[C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$
E^+_ϕ	$A_{mn}\dfrac{\beta_\rho}{\varepsilon}J'_m(\beta_\rho\rho)[C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$	$-B_{mn}\dfrac{m\beta_z}{\omega\mu\varepsilon}\dfrac{1}{\rho}J_m(\beta_\rho\rho)[-C_2\sin(m\phi) + D_2\cos(m\phi)]e^{-j\beta_z z}$
E^+_z	0	$-jB_{mn}\dfrac{\beta_\rho^2}{\omega\mu\varepsilon}J_m(\beta_\rho\rho)[C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$
H^+_ρ	$-A_{mn}\dfrac{\beta_\rho\beta_z}{\omega\mu\varepsilon}J'_m(\beta_\rho\rho)[C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$	$B_{mn}\dfrac{m}{\mu}\dfrac{1}{\rho}J_m(\beta_\rho\rho)[-C_2\sin(m\phi) + D_2\cos(m\phi)]e^{-j\beta_z z}$
H^+_ϕ	$-A_{mn}\dfrac{m\beta_z}{\omega\mu\varepsilon}\dfrac{1}{\rho}J_m(\beta_\rho\rho)[-C_2\sin(m\phi) + D_2\cos(m\phi)]e^{-j\beta_z z}$	$-B_{mn}\dfrac{\beta_\rho}{\mu}J'_m(\beta_\rho\rho)[-C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$
H^+_z	$-jA_{mn}\dfrac{\beta_\rho^2}{\omega\mu\varepsilon}J_m(\beta_\rho\rho)[C_2\cos(m\phi) + D_2\sin(m\phi)]e^{-j\beta_z z}$	0
$'$	$\dfrac{\partial}{\partial(\beta_\rho\rho)}$	
$\beta_c = \beta_\rho$	$\dfrac{\chi'_{mn}}{a}$	$\dfrac{\chi_{mn}}{a}$
f_c	$\dfrac{\chi'_{mn}}{2\pi a\sqrt{\mu\varepsilon}}$	$\dfrac{\chi_{mn}}{2\pi a\sqrt{\mu\varepsilon}}$
λ_c	$\dfrac{2\pi a}{\chi'_{mn}}$	$\dfrac{2\pi a}{\chi_{mn}}$

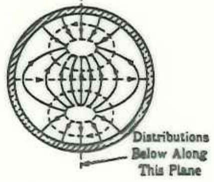
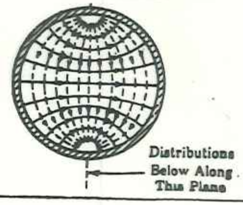
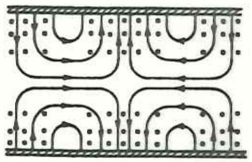
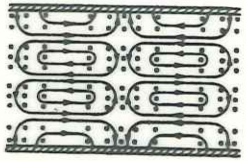
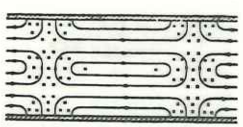
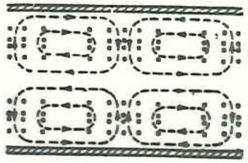
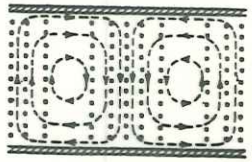
TABLE 9-3 *(Continued).*

	$TE^z_{mn}\begin{pmatrix} m = 0,1,2,\ldots, \\ n = 1,2,3,\ldots \end{pmatrix}$	$TM^z_{mn}\begin{pmatrix} m = 0,1,2,3,\ldots, \\ n = 1,2,3,4,\ldots \end{pmatrix}$
$\beta_z\ (f \geq f_c)$	$\beta\sqrt{1-\left(\dfrac{f_c}{f}\right)^2} = \beta\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}$	
$\lambda_g\ (f \geq f_c)$	$\dfrac{\lambda}{\sqrt{1-\left(\dfrac{f_c}{f}\right)^2}} = \dfrac{\lambda}{\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}}$	
$v_p\ (f \geq f_c)$	$\dfrac{v}{\sqrt{1-\left(\dfrac{f_c}{f}\right)^2}} = \dfrac{v}{\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}}$	
$Z_w\ (f \geq f_c)$	$\dfrac{\eta}{\sqrt{1-\left(\dfrac{f_c}{f}\right)^2}} = \dfrac{\eta}{\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}}$	$\eta\sqrt{1-\left(\dfrac{f_c}{f}\right)^2} = \eta\sqrt{1-\left(\dfrac{\lambda}{\lambda_c}\right)^2}$
$Z_w\ (f \leq f_c)$	$j\dfrac{\eta}{\sqrt{\left(\dfrac{f_c}{f}\right)^2 - 1}} = j\dfrac{\eta}{\sqrt{\left(\dfrac{\lambda}{\lambda_c}\right)^2 - 1}}$	$-j\eta\sqrt{\left(\dfrac{f_c}{f}\right)^2 - 1} = -j\eta\sqrt{\left(\dfrac{\lambda}{\lambda_c}\right)^2 - 1}$
α_c	$\dfrac{R_s}{a\eta\sqrt{1-\left(\dfrac{f_c}{f}\right)^2}}\left[\left(\dfrac{f_c}{f}\right)^2 + \dfrac{m^2}{(\chi'_{mn})^2 - m^2}\right]$	$\dfrac{R_s}{a\eta}\dfrac{1}{\sqrt{1-\left(\dfrac{f_c}{f}\right)^2}}$

Fíjense en la dirección de las líneas de E.
BAJA ATENUACIÓN

Similar al TE_{10} en guías rectangulares

Table 8.9
Summary of Wave Types for Circular Guides[a]

Wave Type	TM_{01}	TM_{02}	TM_{11}	TE_{01}	TE_{11}
Field distributions in cross-sectional plane, at plane of maximum transverse fields					
Field distributions along guide					
Field components present	E_z, E_r, H_ϕ	E_z, E_r, H_ϕ	$E_z, E_r, E_\phi, H_r, H_\phi$	H_z, H_r, E_ϕ	$H_z, H_r, H_\phi, E_r, E_\phi$
p_{nl} or p'_{nl}	2.405	5.52	3.83	3.83	1.84
$(k_c)_{nl}$	$\frac{2.405}{a}$	$\frac{5.52}{a}$	$\frac{3.83}{a}$	$\frac{3.83}{a}$	$\frac{1.84}{a}$
$(\lambda_c)_{nl}$	$2.61a$	$1.14a$	$1.64a$	$1.64a$	$3.41a$
$(f_c)_{nl}$	$\frac{0.383}{a\sqrt{\mu\varepsilon}}$	$\frac{0.877}{a\sqrt{\mu\varepsilon}}$	$\frac{0.609}{a\sqrt{\mu\varepsilon}}$	$\frac{0.609}{a\sqrt{\mu\varepsilon}}$	$\frac{0.293}{a\sqrt{\mu\varepsilon}}$
Attenuation due to imperfect conductors	$\frac{R_S}{a\eta}\frac{1}{\sqrt{1-(f_c/f)^2}}$	$\frac{R_S}{a\eta}\frac{1}{\sqrt{1-(f_c/f)^2}}$	$\frac{R_S}{a\eta}\frac{1}{\sqrt{1-(f_c/f)^2}}$	$\frac{R_S}{a\eta}\frac{(f_c/f)^2}{\sqrt{1-(f_c/f)^2}}$	$\frac{R_S}{a\eta}\frac{1}{\sqrt{1-(f_c/f)^2}}\left[\left(\frac{f_c}{f}\right)^2+0.420\right]$

[a] Electric field lines are shown solid and magnetic field lines are dashed.

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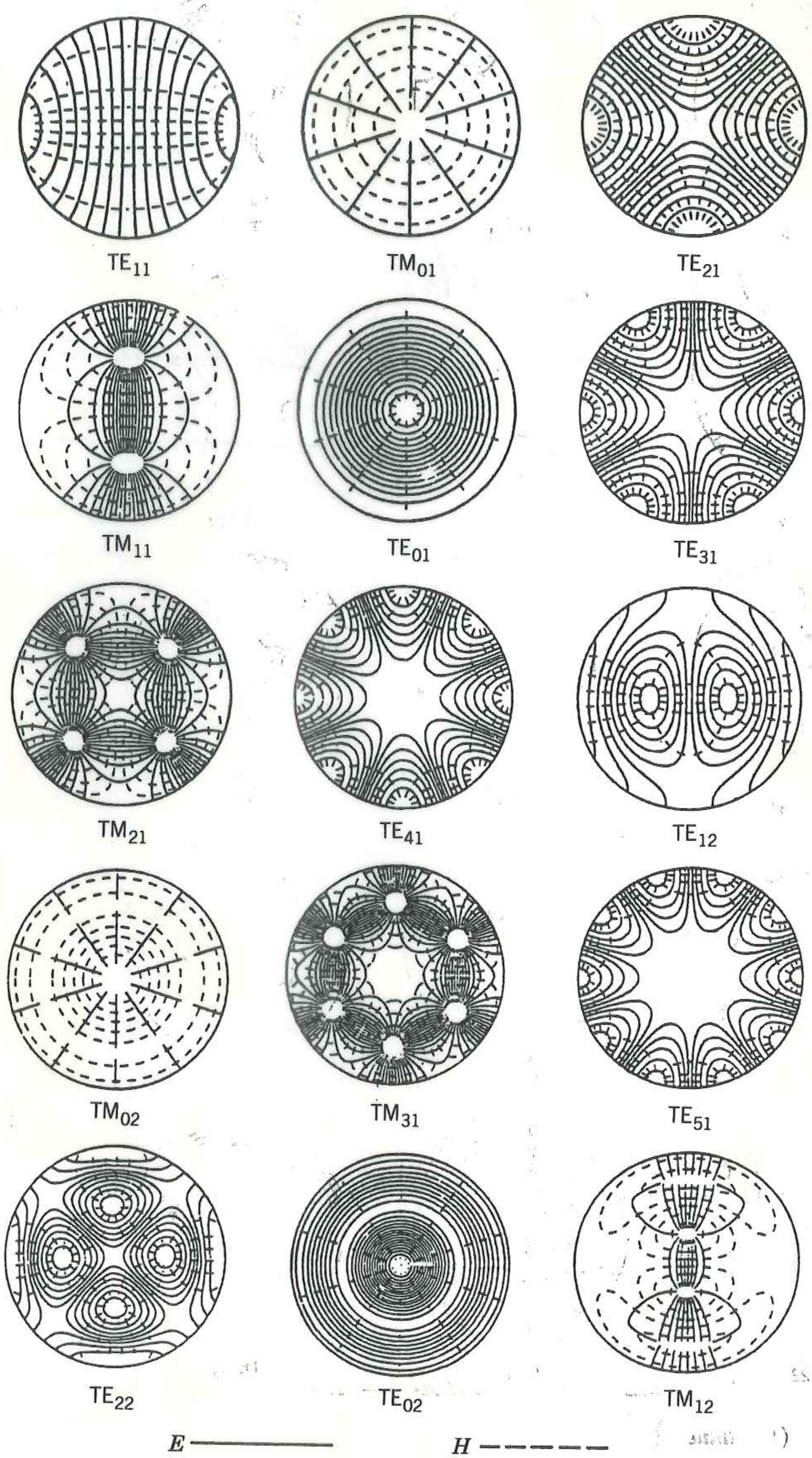

FIGURE 9-2 Field configurations of first 30 TE^z and/or TM^z modes in a circular waveguide. (*Source:* C. S. Lee, S. W. Lee, and S. L. Chuang, "Plot of modal field distribution in rectangular and circular waveguides," *IEEE Trans. Microwave Theory Tech.*, © 1966, IEEE.)

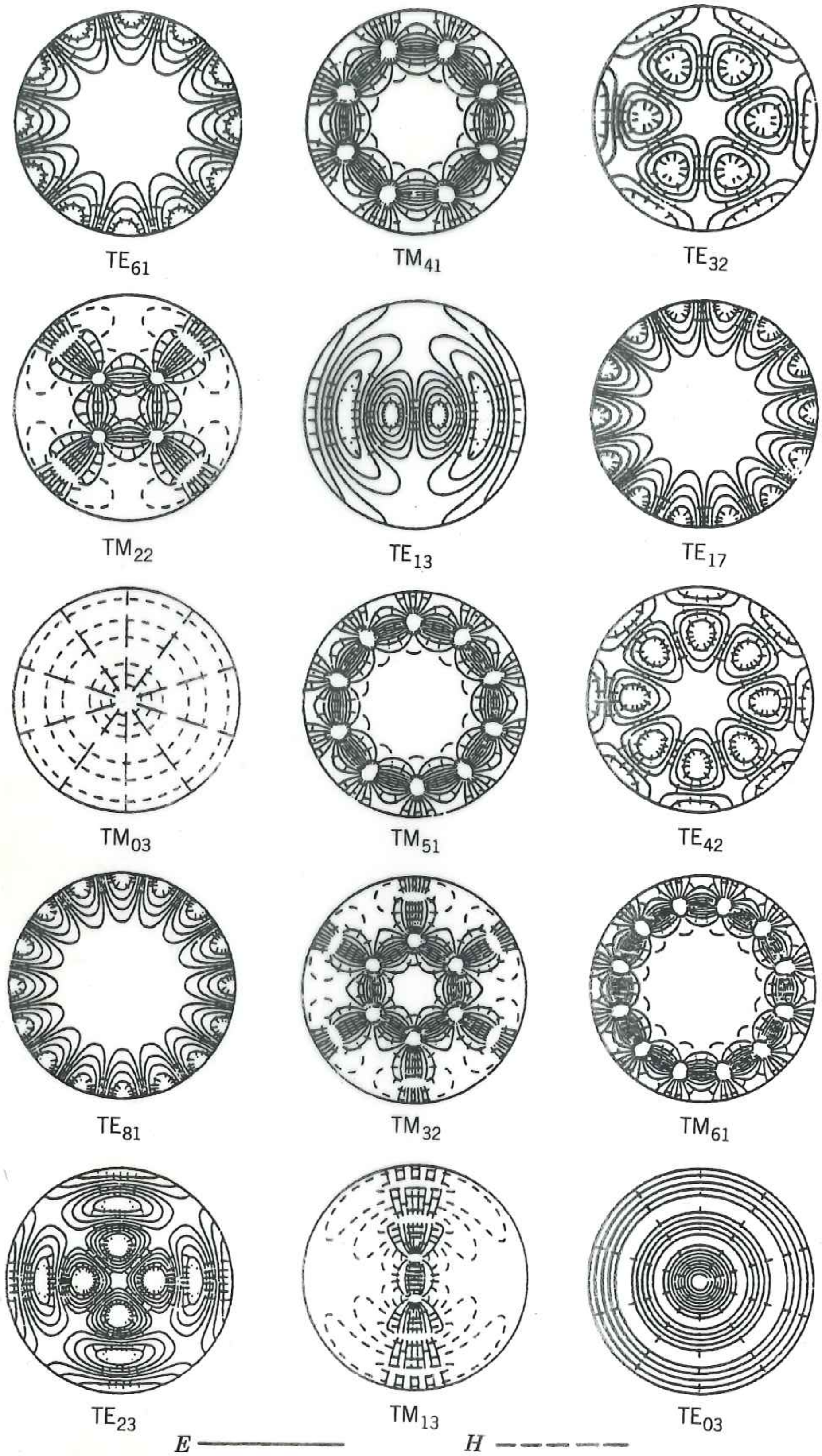

FIGURE 9-2 (*Continued*).