Microstrip Patch Antennas

EE-4382/5306 - Antenna Engineering

Outline

- Introduction
  - Basic Characteristics
  - Feeding Methods
- Rectangular Patch
  - Transmission-Line Model
  - Conductance and Input Impedance
  - Matching Techniques
  - Fields
  - Directivity
- Quality Factor, Bandwidth, and Efficiency
- Antennas for Mobile Communications
  - Planar Inverted-F Antenna
  - Slot Antenna
  - Inverted-F Antenna

Introduction

Microstrip Antennas - Introduction

A microstrip patch antenna is a metallic strip or patch mounted on a dielectric layer (substrate) over a ground plane.
Useful for high performance in extreme applications: aircraft, satellite, missiles, cellphones and electronic devices.

PROS:
They are low profile, conformable, simple and inexpensive to manufacture, mechanically robust, and very versatile

CONS:
Low efficiency, low power, high Q, poor polarization purity, poor scanning properties, spurious radiation, very narrow frequency bandwidth, still large dimensions at high frequencies

TABLE 14.1 Typical substrates and their parameters

Company	Substrate	Thickness (mm)	Frequency (GHz)	ε_r	$\tan\delta$
Rogers Corporation	Duroid®5880	0.127 1.575 3.175	0 – 40	2.20	0.0009
	RO 3003		0 – 40	3.00	0.0010
	RO 3010		0 – 10	10.2	0.0022
	RO 4350	0.168 0.508 1.524	0 – 10	3.48	0.0037
-	FR4	0.05 – 100	0.001	4.70	-
DuPont	HK 04J	0.025	0.001	3.50	0.005
Isola	IS 410	0.05 – 3.2	0.1	5.40	0.035
Arlon	DiClad 870	0.091	0 – 10	2.33	0.0013
Polyflon	Polyguide	0.102	0 – 10	2.32	0.0005
Neltec	NH 9320	3.175	0 – 10	3.20	0.0024
Taconic	RF-60A	0.102	0 – 10	6.15	0.0038

Basic characteristics

Rectangular Microstrip Antenna

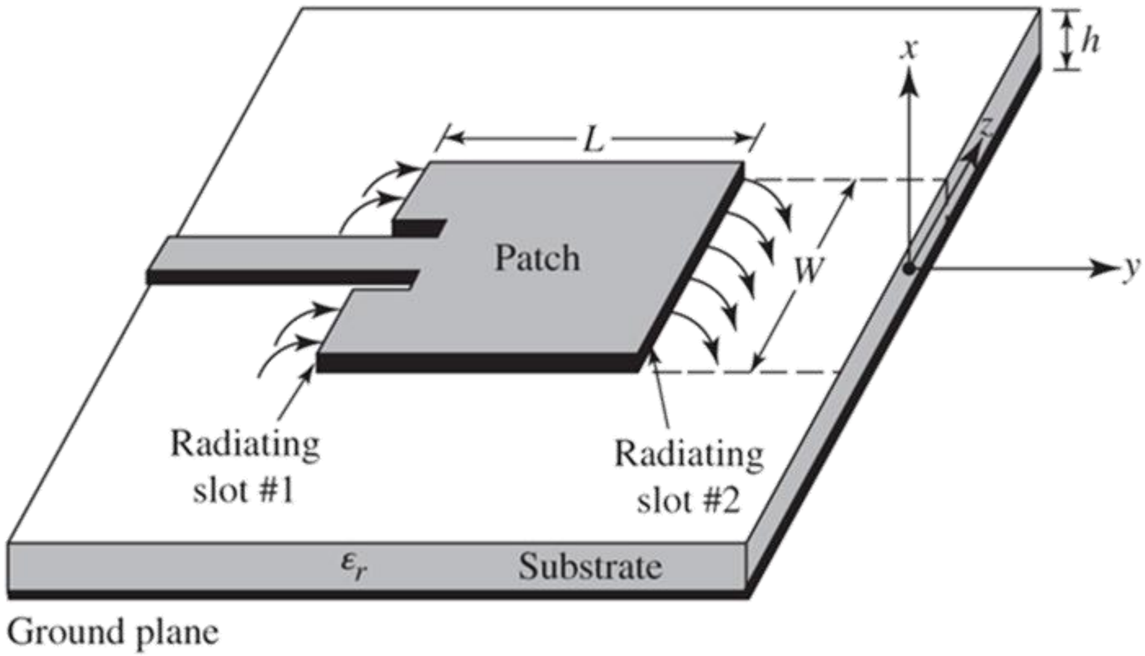


Fig. 14.1a

$$\frac{\lambda_0}{3} < \mathrm{L} < \frac{\lambda_0}{2}$$

$$2.2 \leq \epsilon_r \leq 12$$

W is tuned to get desired impedance

Coordinate System For Each Radiating Slot

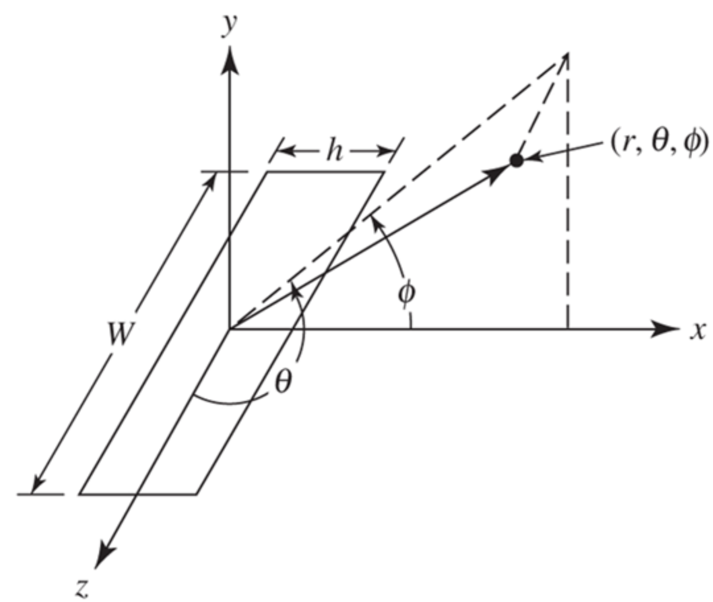
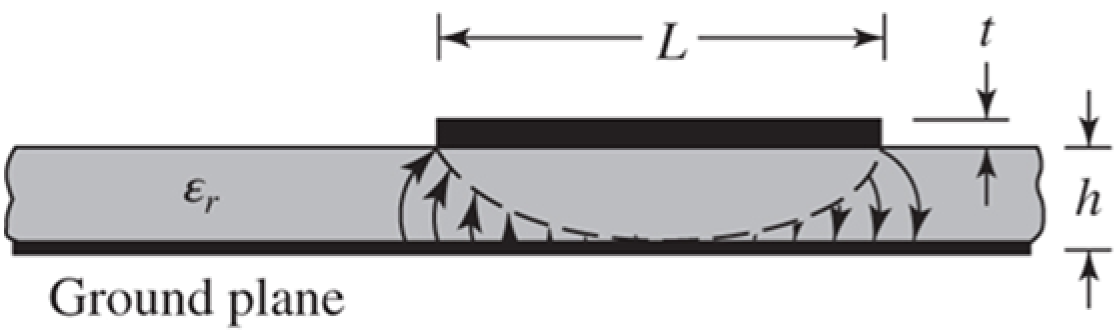


Fig. 14.1c

Chapter 14
Microstrip Antennas

Basic characteristics

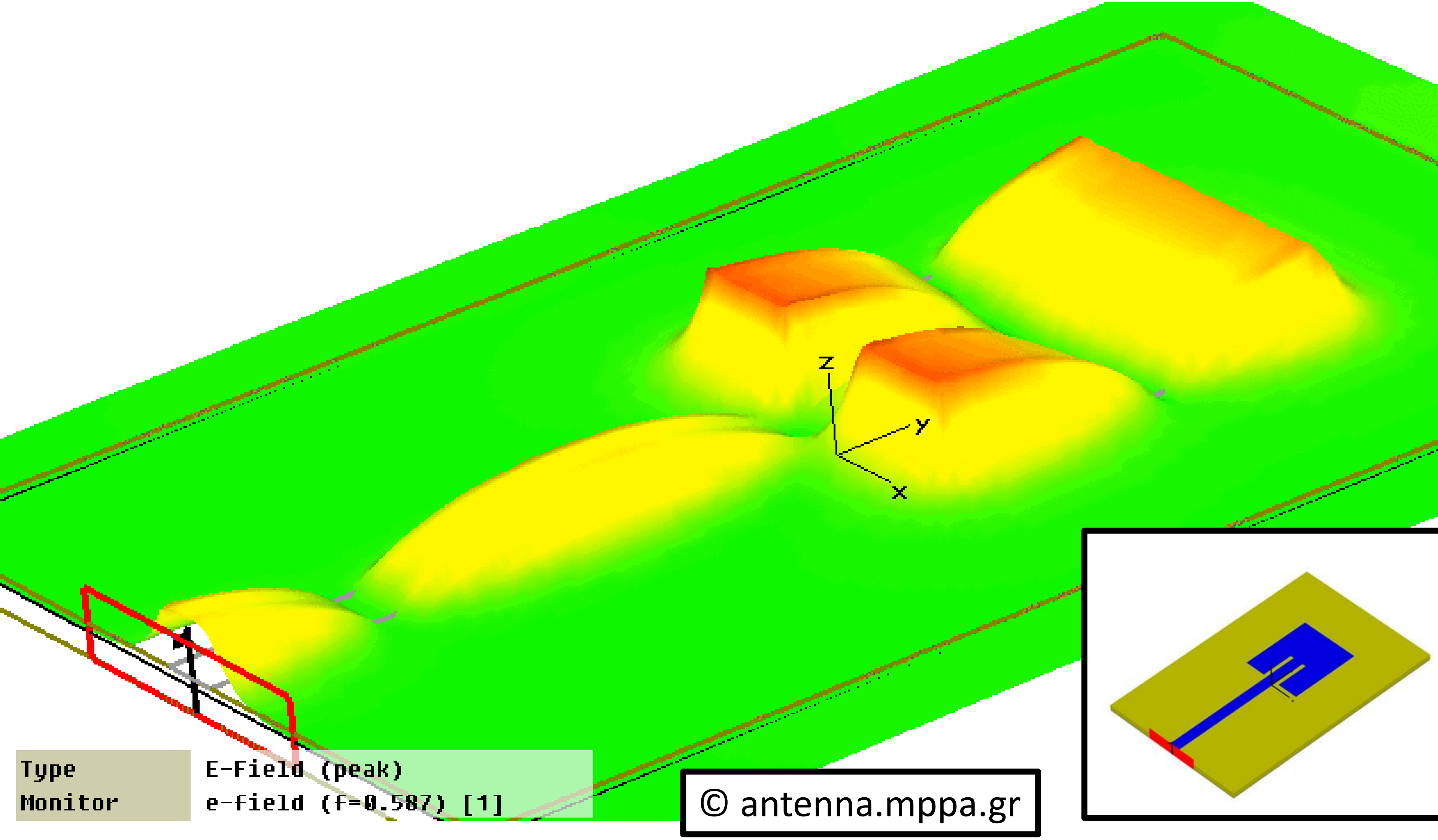
Side View



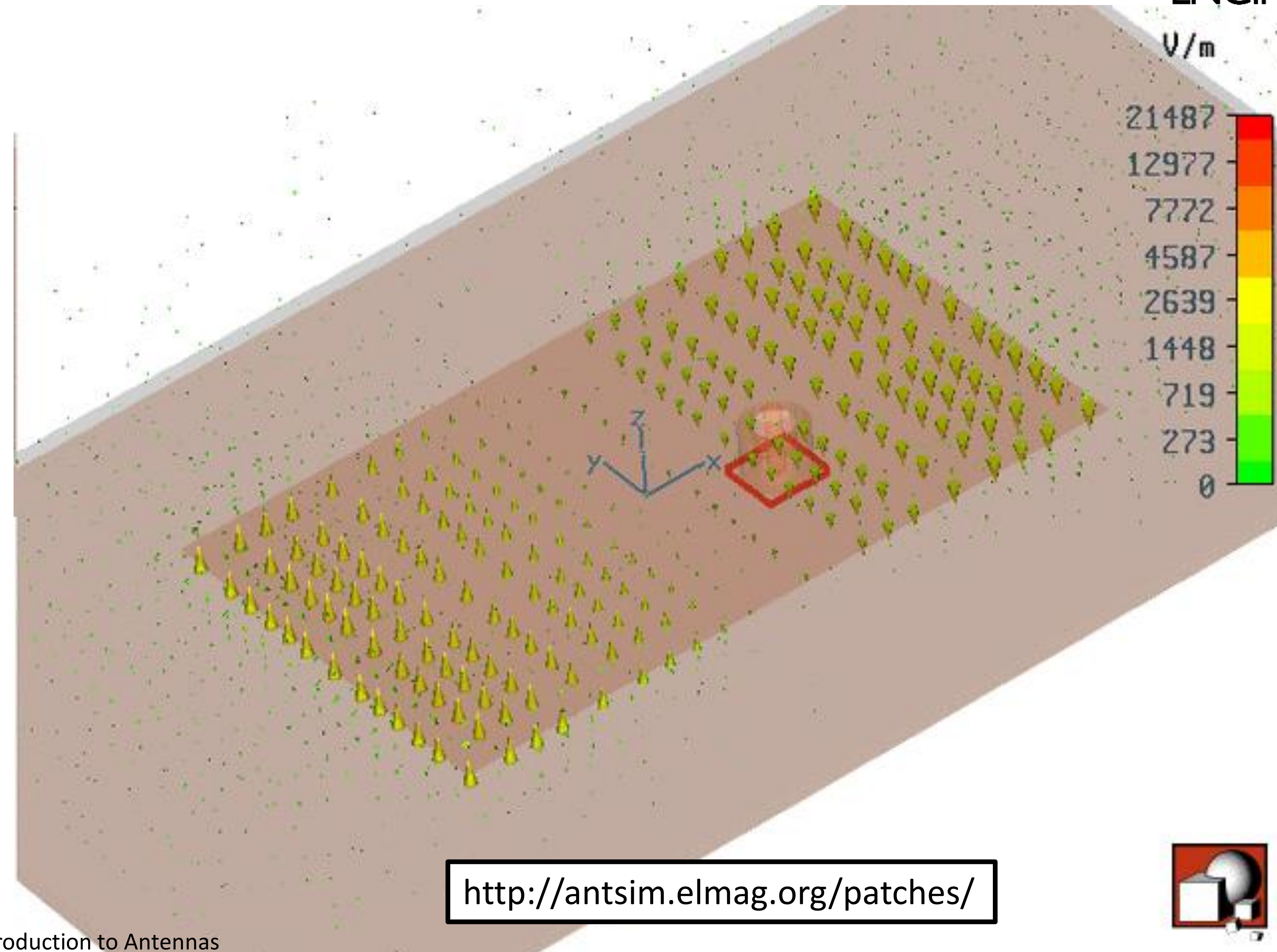
$$t \ll \lambda_0$$
$$h \ll \lambda_0$$
$$(0.003\lambda_0 \le h \le 0.05\lambda_0)$$

Fig. 14.1b

Basic Characteristics

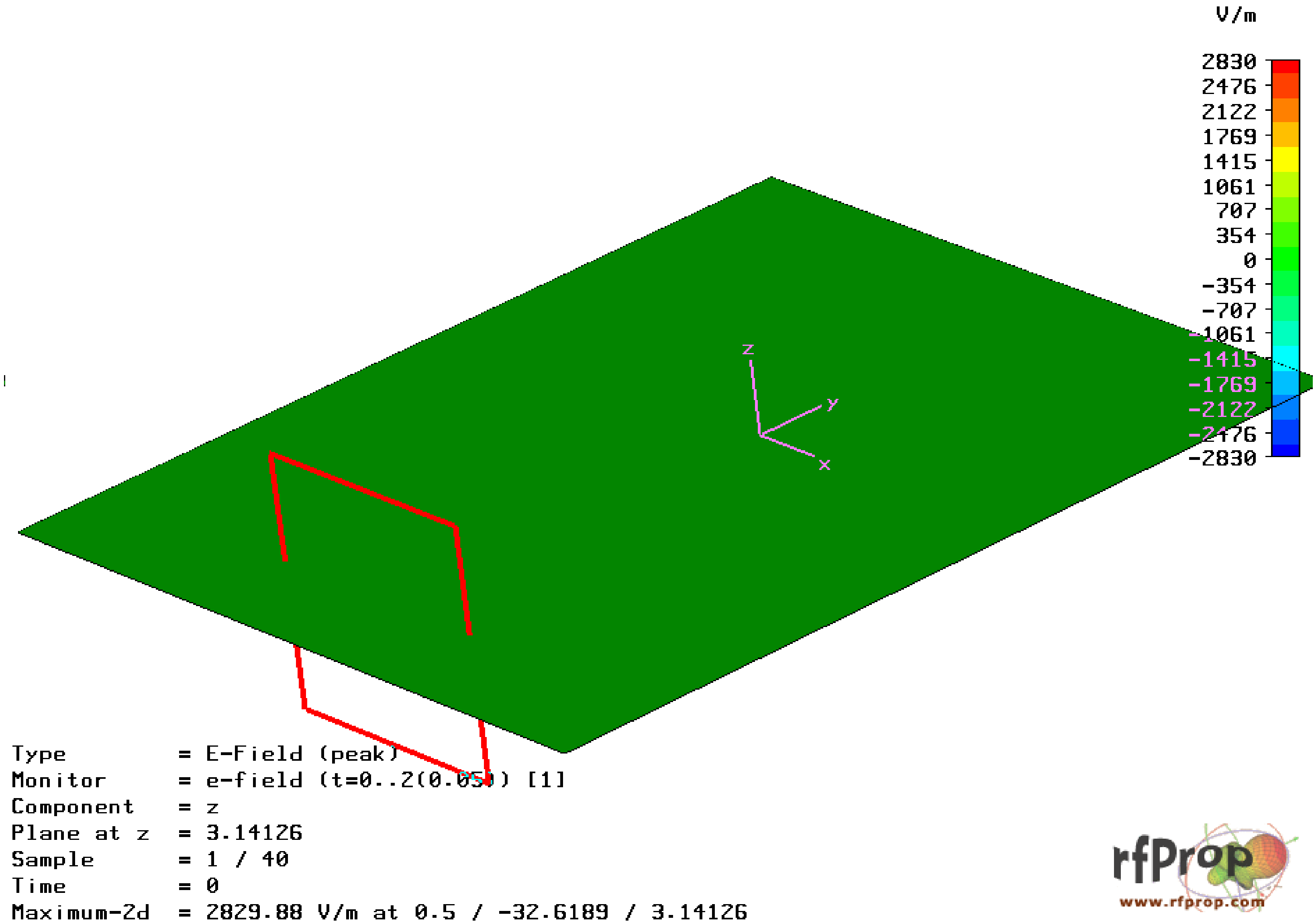


Basic Characteristics



http://antsim.elmag.org/patches/

Basic Characteristics



Basic characteristics

Patches of Various Shapes

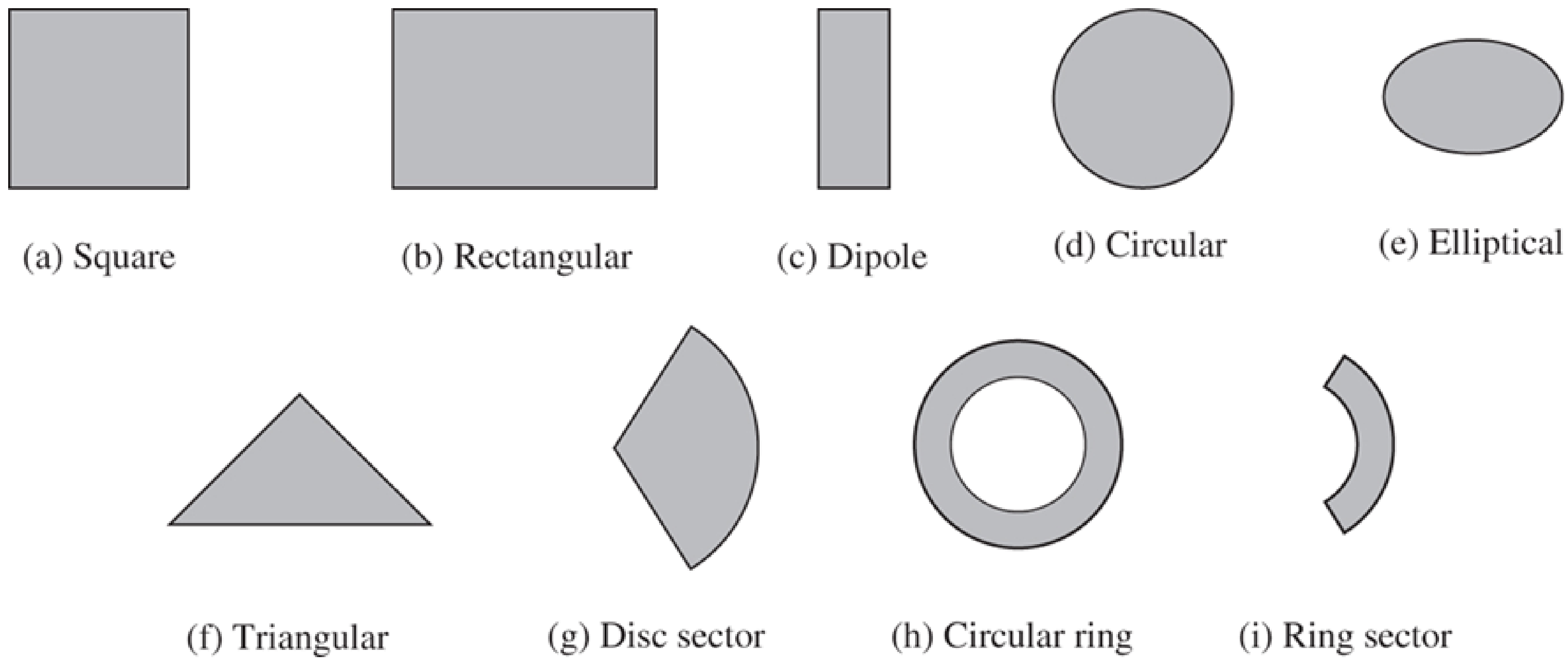


Fig. 14.2

Feeding Methods

Microstrip Feed Line

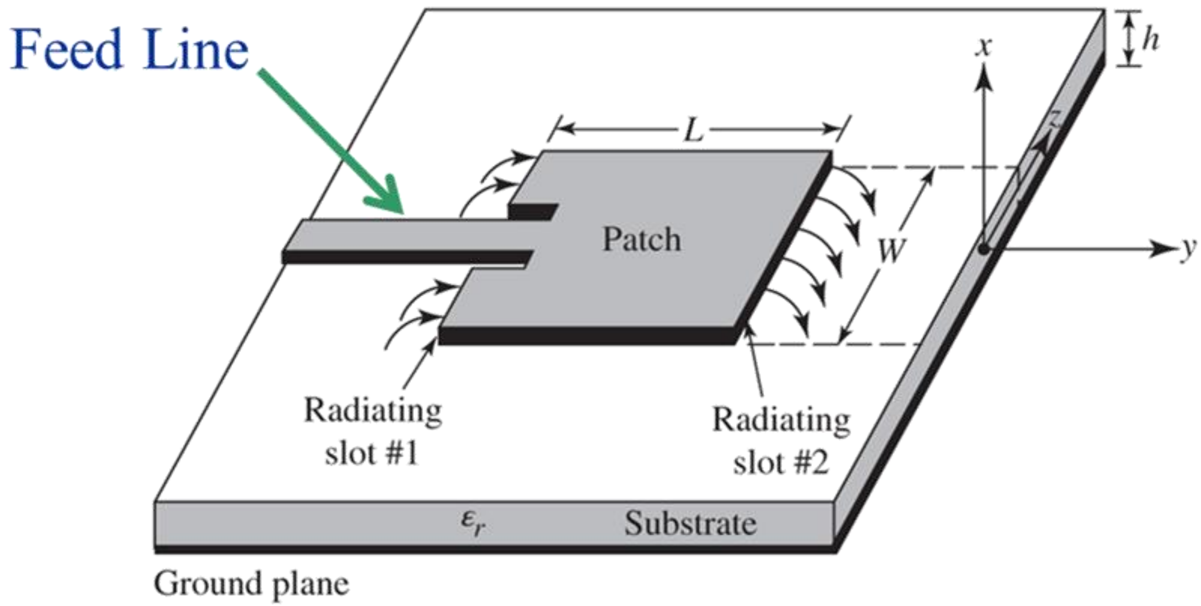
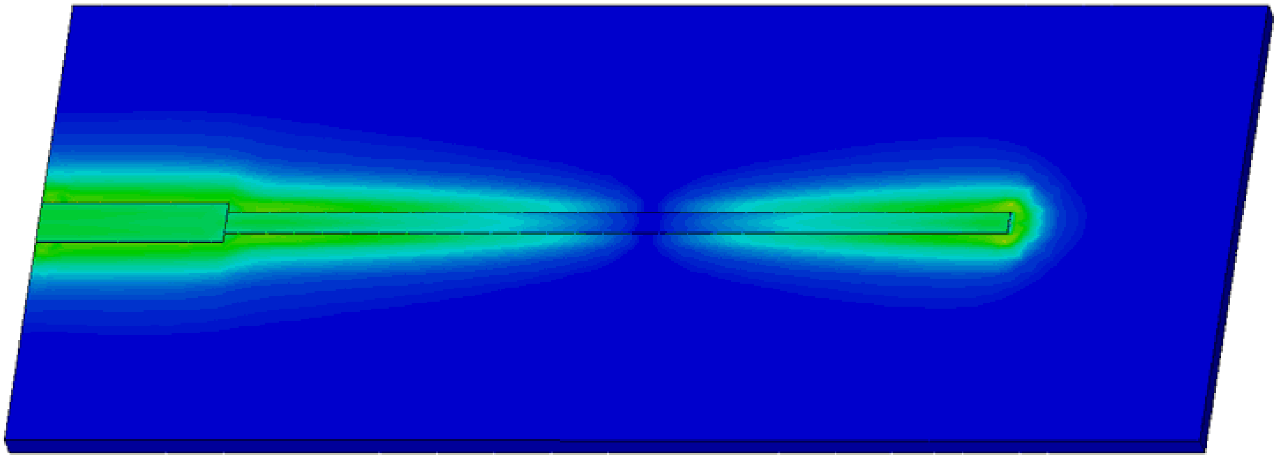
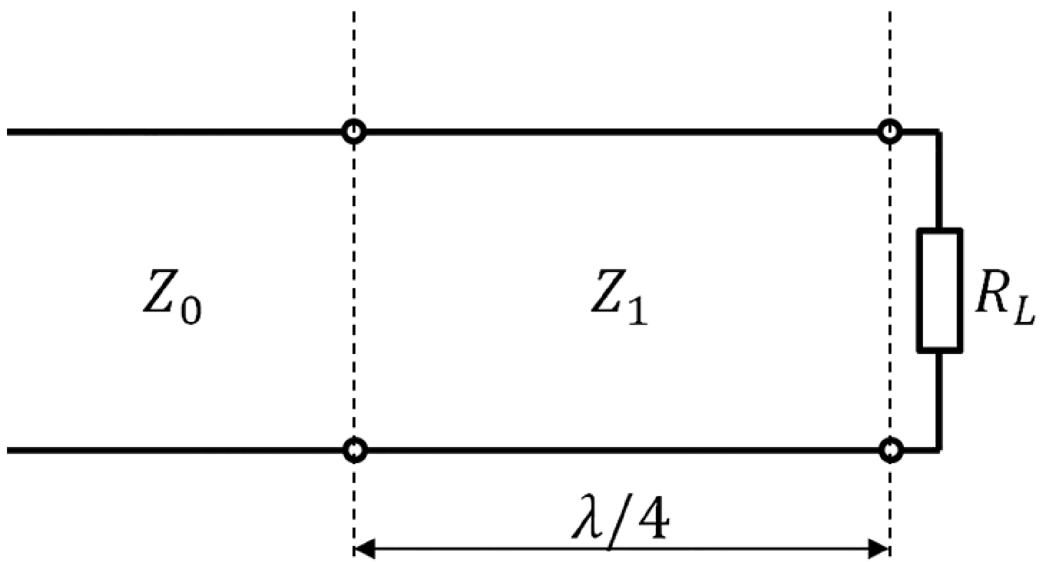


Fig. 14.3a

- Easy to fabricate
- Simple to match
- Low spurious radiation
- Narrow bandwidth
- Good for low h

Quarter Wave Transformer





$$\boxed{Z_1 = \sqrt{Z_0 R_L}}$$

https://www.cst.com/academia/examples/quarter-wave-transformer

Feeding Methods

Coaxial Feed Line

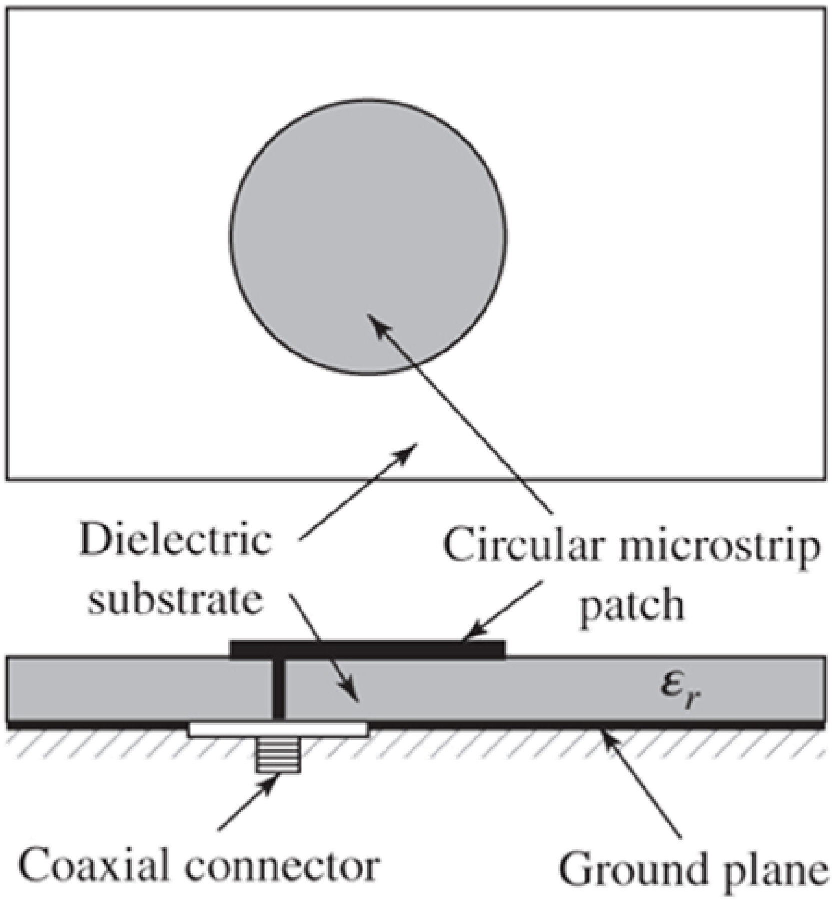


Fig. 14.3b

- Easy to fabricate
- Simple to match
- Low spurious radiation
- Matching is easily done by changing feed position
- Narrow Bandwidth
- Difficult to model & simulate

Feeding Methods

Aperture-Coupled Feed

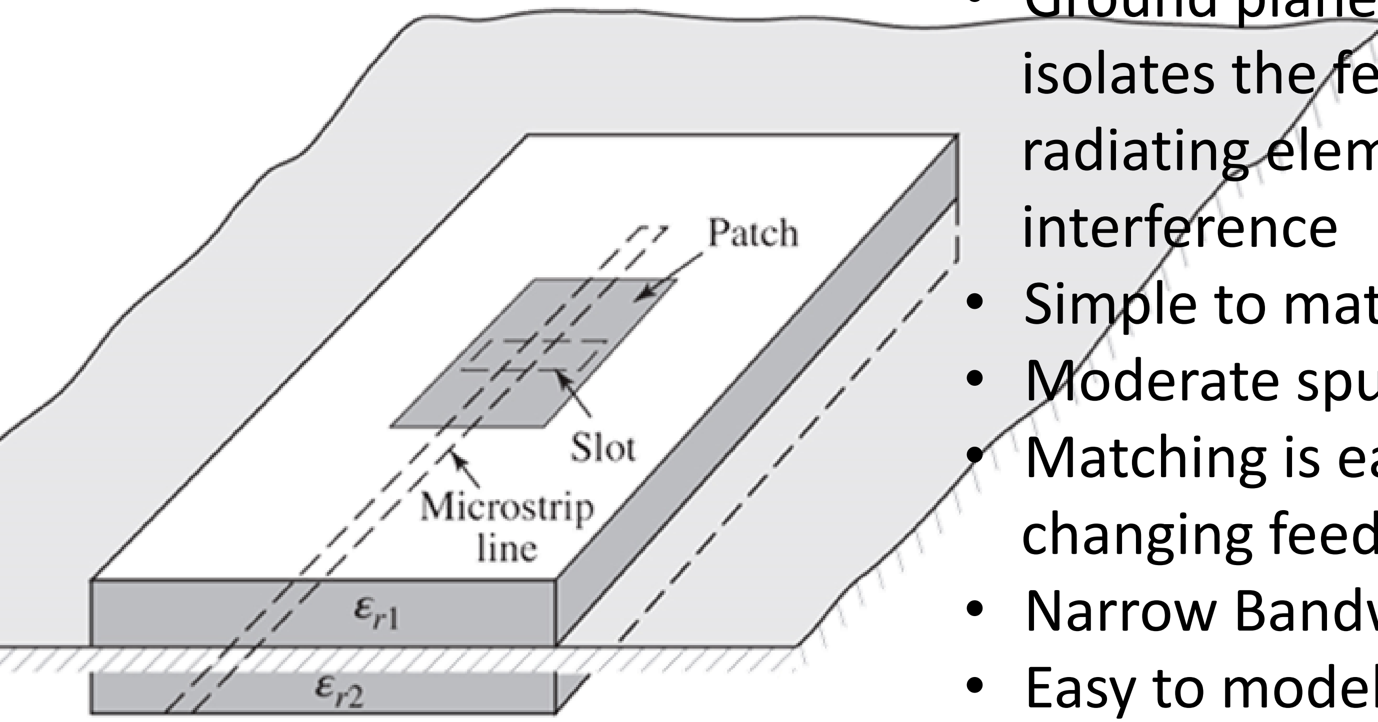


Fig. 14.3c

- Ground plane between substrates isolates the feed from the radiating element, minimizing interference
- Simple to match
- Moderate spurious radiation
- Matching is easily done by changing feed position
- Narrow Bandwidth
- Easy to model & simulate
- Most difficult to fabricate
- Independent optimization of feed and radiating element

Feeding Methods

Proximity-Coupled Feed

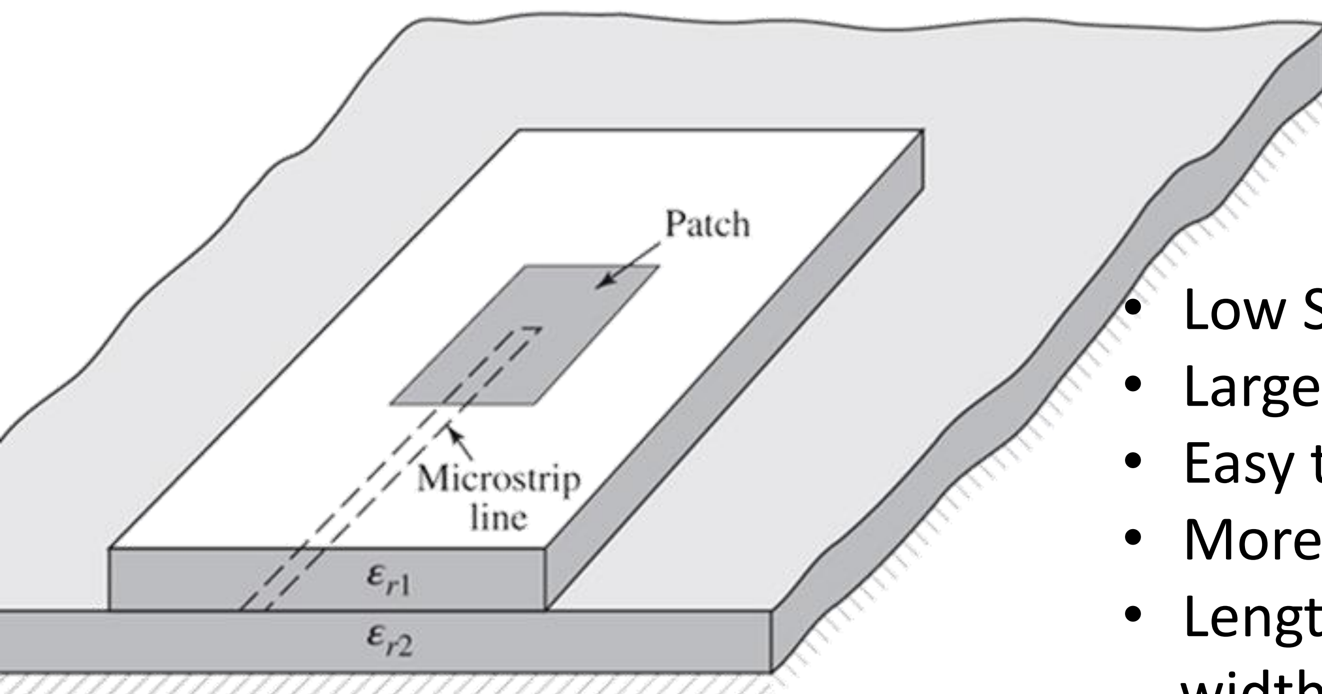


Fig. 14.3d

- Low Spurious Radiation
- Largest Bandwidth
- Easy to model & simulate
- More difficult to fabricate
- Length of feeding stub and width-to-line ratio of patch can control match

Rectangular Patch

Rectangular Patch Analysis

The rectangular patch is the most widely used configuration for microstrip patch antennas.

Transmission-Line Model
It is the easiest approach to model and analyze the microstrip patch antenna. It is also less accurate, but gives a good physical insight.

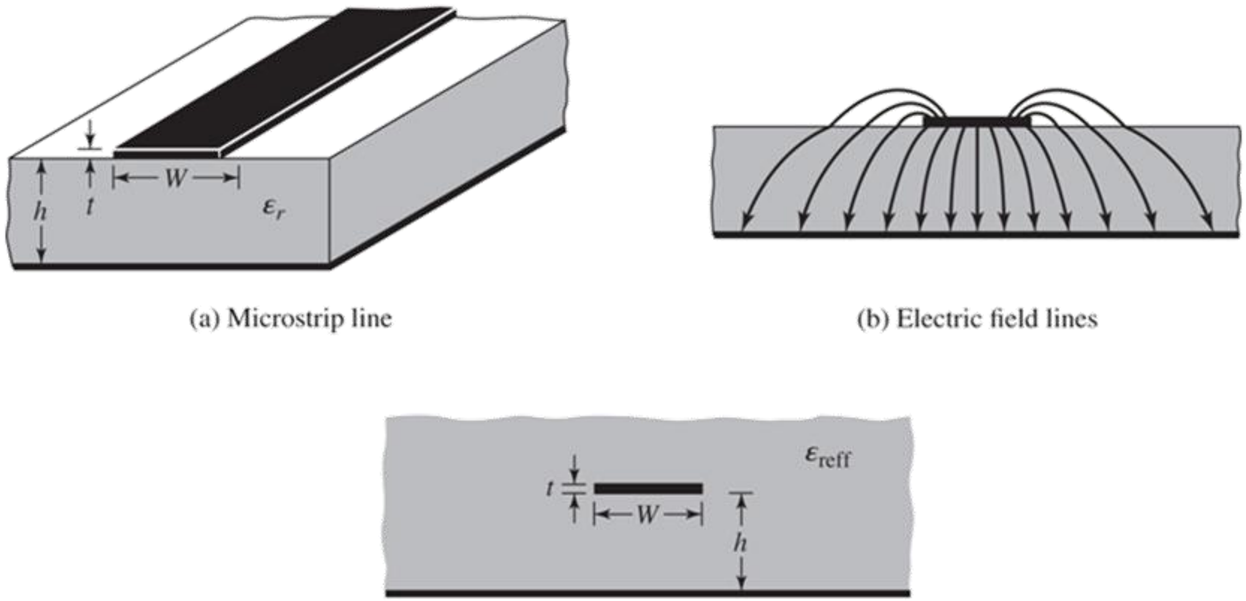
EM Cavity Model
It is more complex than the transmission line model, and it is more accurate. It also gives physical insight.

Full-Wave Model
It is the most accurate, versatile, and easiest to simulate of all three models. It is also the most complex and has less physical insight.

Transmission-Line Model

The transmission-line model represents the microstrip antenna by two slots, separated by a low-impedance Z_c transmission line of length L.

Looking at a cross section of the antenna (x-y plane), this is effectively a non-homogeneous transmission line. Fringing effects make the microstrip line look wider than it is. Effective dielectric constant is introduced to account for this.



(a) Microstrip line

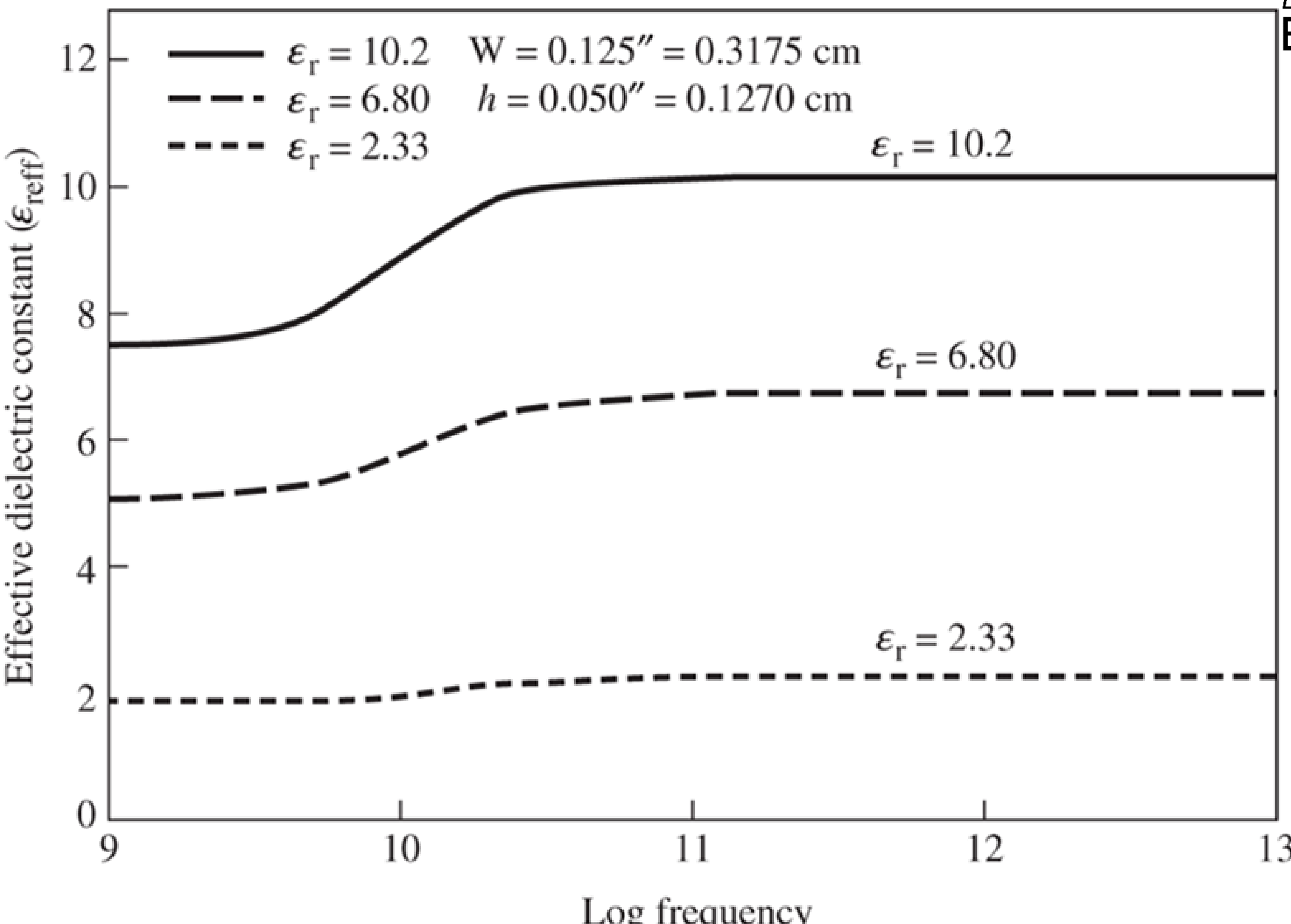
(b) Electric field lines

(c) Effective dielectric constant

Fig. 14.5

Chapter 14
Microstrip Antennas

Fringing Effects -Effective dielectric



Static Values

$$\epsilon_{reff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2}\left[1 + 12\,\frac{h}{w}\right]^{-\frac{1}{2}}$$

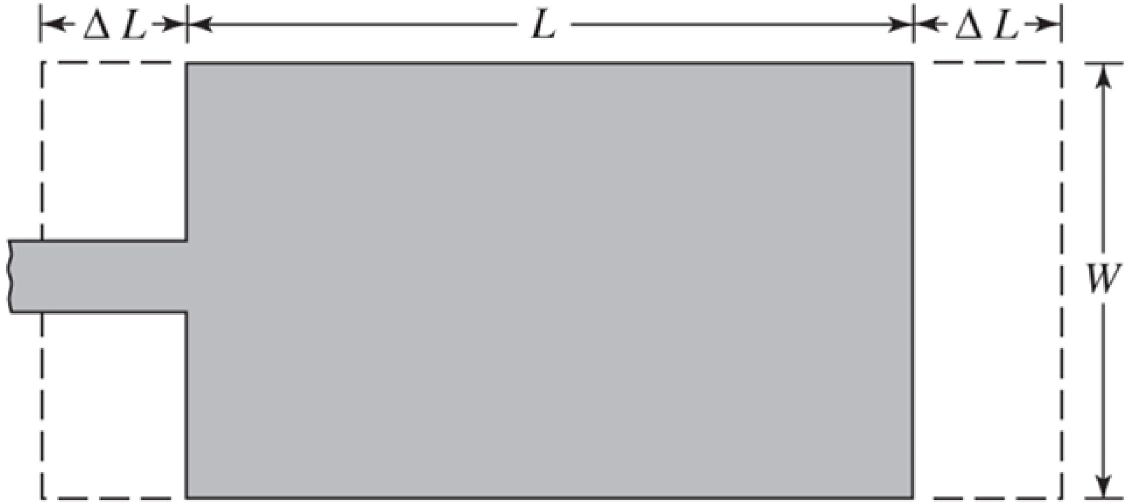
Effective Length, Resonant Frequency, and Effective Width

Because of the fringing effects, the patch of the antenna is electrically longer than the physical dimensions. We take care of this by adding an electrical distance ΔL which is a function of the effective dielectric constant ϵ_{reff} and width-to-height ratio $\frac{W}{h}$

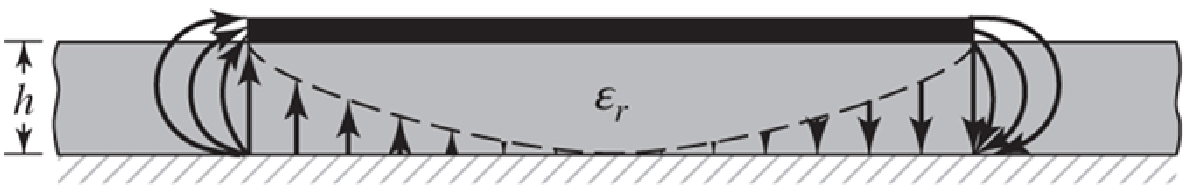
$$\frac{\Delta L}{h} = 0.412\frac{\left(\epsilon_{reff} + 0.3\right)\left(\frac{W}{h} + 0.264\right)}{\left(\epsilon_{reff} - 0.258\right)\left(\frac{W}{h} + 0.8\right)}$$

$$L_{eff} = L + \Delta L$$

Effective Length, Resonant Frequency, and Effective Width



(a) Top view



(b) Side view

Fig. 14.7

Chapter 14
Microstrip Antennas

Effective Length, Resonant Frequency, and Effective Width

The resonant frequency in the dominant TM_{010} mode is

$$f_{r_{010}} = \frac{1}{2L\sqrt{\epsilon_r}\sqrt{\mu_0\epsilon_0}} = \frac{c_0}{2L\sqrt{\epsilon_r}}$$

Accounting for fringing effects,

$$f_{rc_{010}} = \frac{1}{2L_{eff}\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} = \frac{1}{2(L+2\Delta L)\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}}$$

$$= q\,\frac{1}{2L\sqrt{\epsilon_r}\sqrt{\mu_0\epsilon_0}} = q\,\frac{c_0}{2L\sqrt{\epsilon_r}}$$

$$q = \frac{f_{rc_{010}}}{f_{r_{010}}}$$

Rectangular Antenna Design

This procedure assumes we know the dielectric constant of the substrate ϵ_r , the resonant frequency f_r , and the height of the substrate h.

1. Determine W

$$W = \frac{1}{2f_r\sqrt{\mu_0\epsilon_0}}\sqrt{\frac{2}{\epsilon_r + 1}} = \frac{c_0}{2f_r}\sqrt{\frac{2}{\epsilon_r + 1}}$$

2. Determine the effective dielectric constant ϵ_{reff}
3. Determine the extension of ΔL
4. Determine the actual length L of the patch

$$L = \frac{1}{2f_r\sqrt{\epsilon_{reff}}\sqrt{\mu_0\epsilon_0}} - 2\Delta L$$

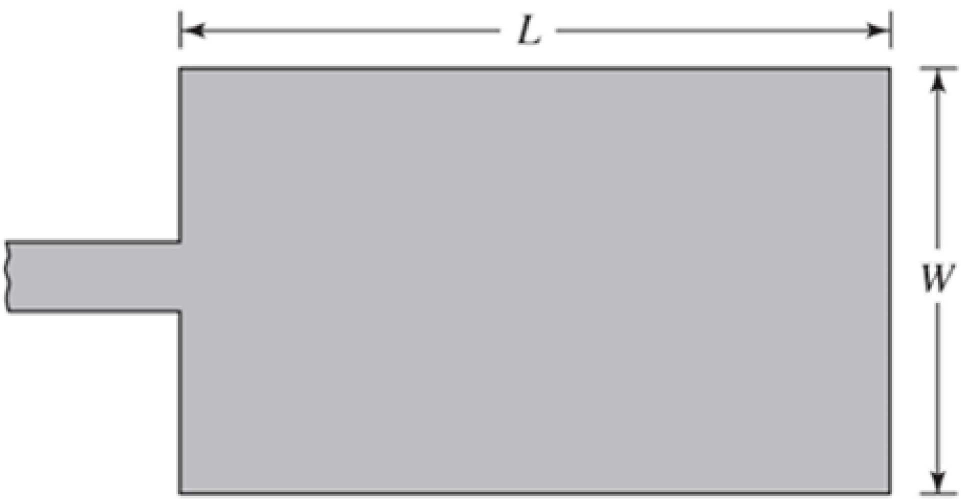
Approximate lengths of the microstrip vary between $(0.47 - 0.49)\frac{\lambda_0}{\sqrt{\epsilon_r}}$

Rectangular Patch Design - Example

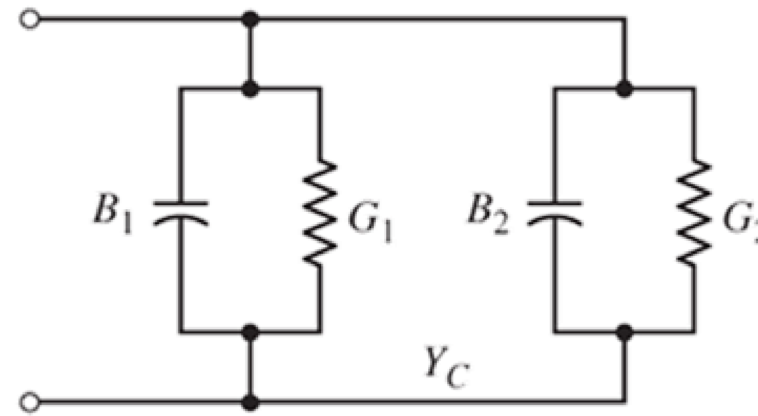
Design a rectangular microstrip antenna using a substrate (RT/Duroid 5880) with dielectric constant of 2.2, $h = 0.1588 \text{ cm}$ and resonant frequency of 10 GHz.

Rectangular Antenna Conductance and Input Impedance

Rectangular Patch and Equivalent Circuit



(a) Rectangular patch

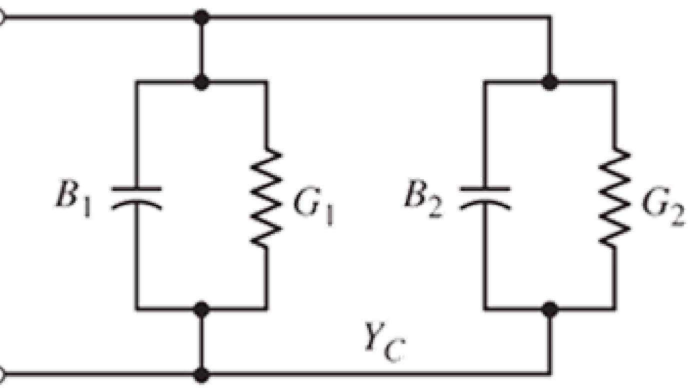


(b) Transmission model equivalent

Fig. 14.9

Conductance and Input Impedance

$$Y_1 = G_1 + jB_1$$



(b) Transmission model equivalent

$$G_1 = \frac{W}{120\lambda_0}\left[1 - \frac{1}{24}(k_0 h)^2\right] \qquad \frac{h}{\lambda_0} < \frac{1}{10}$$

$$B_1 = \frac{W}{120\lambda_0}\left[1 - 0.636\ln(k_0 h)\right] \qquad \frac{h}{\lambda_0} < \frac{1}{10}$$

$$Y_2 = Y_1, \qquad G_2 = G_1, \qquad B_2 = B_1$$

Conductance and Input Impedance

At resonance

$$\tilde{Y}_2 = \tilde{G}_2 + j\tilde{B}_2 = G_1 - jB_1$$

$$Y_{in} = Y_1 + \tilde{Y}_2 = 2G_1$$

$$\boxed{Z_{in} = R_{in} = \frac{1}{Y_{in}} = \frac{1}{2G_1}}$$

This formula does not take into account mutual effects between the slots.

Conductance and Input Impedance

To take into account mutual effects between the slots, we introduce G_{12}

$$\boxed{R_{in} = \frac{1}{2(G_1 \pm G_{12})}}$$

where '+' is used with odd (antisymmetric) resonant voltage distribution beneath the patch and between the slots and '–' is used for modes with even (symmetric) resonant voltage distribution.

$$G_{12} = \frac{1}{|V_0|^2} Re\left[\iint_S E_1 \times H_2^* \cdot ds\right]$$

E_1 - E-field radiated by slot 1

H_1 - H-field radiated by slot 2

V_0 - Voltage across the slot

Conductance and Input Impedance

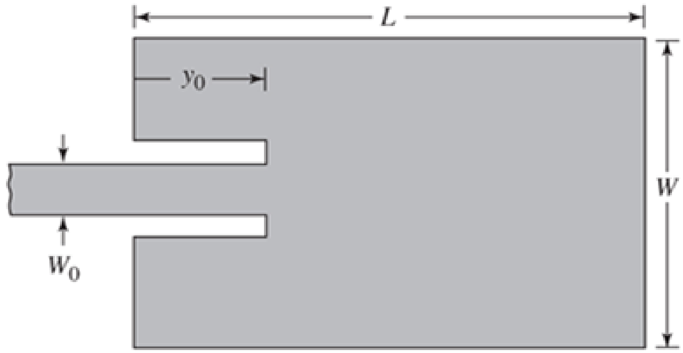
$$G_{12} = \frac{1}{120\pi^2} \int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)} \right]^2 J_0(k_0 L \sin(\theta)) \sin^3(\theta)\, d\theta$$

Where J_0 is the Bessel function of the first kind of order zero.

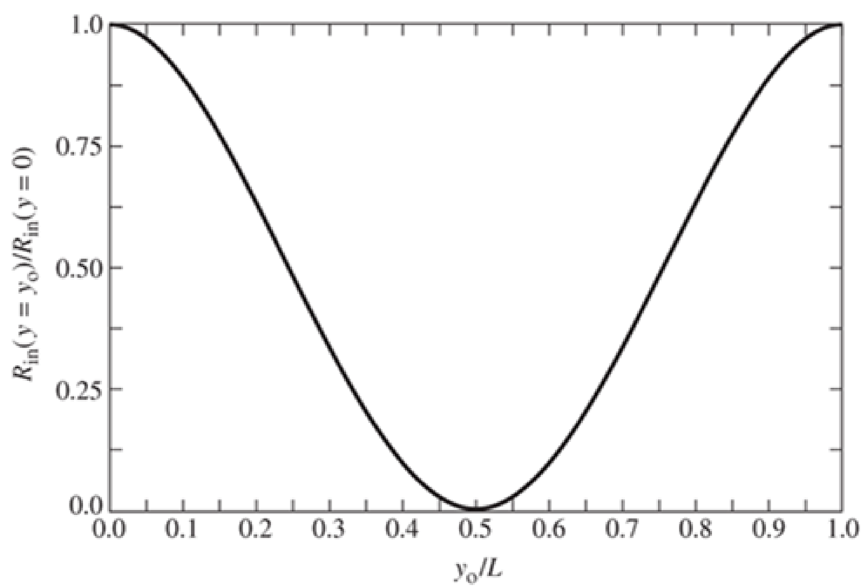
Patch Input Impedance- Example

A rectangular microstrip antenna has a width-to-height ratio of $\frac{W}{h} = 5$, where the width has half-wave resonant dimensions $W = \frac{\lambda_0}{2}$. Determine the input impedance of the antenna. Do not take into account mutual effects.

Matching Techniques – Inset feed



(a) Recessed microstrip-line feed



(b) Normalized input resistance

$$R_{in(y=y_0)} = R_{in(y=0)} \cos^2\left(\frac{\pi}{L} y_0\right)$$

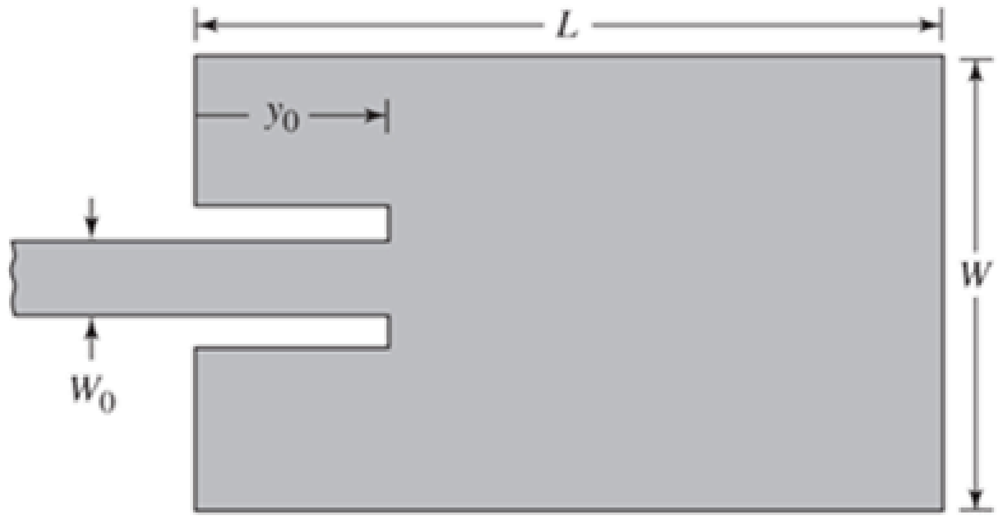
Fig. 14.11

Antenna Patch Design - Example

A square patch has an input resistance at resonance of $260\ \Omega$. Determine the inset feeding distance so that the input resistance is $50\ \Omega$.

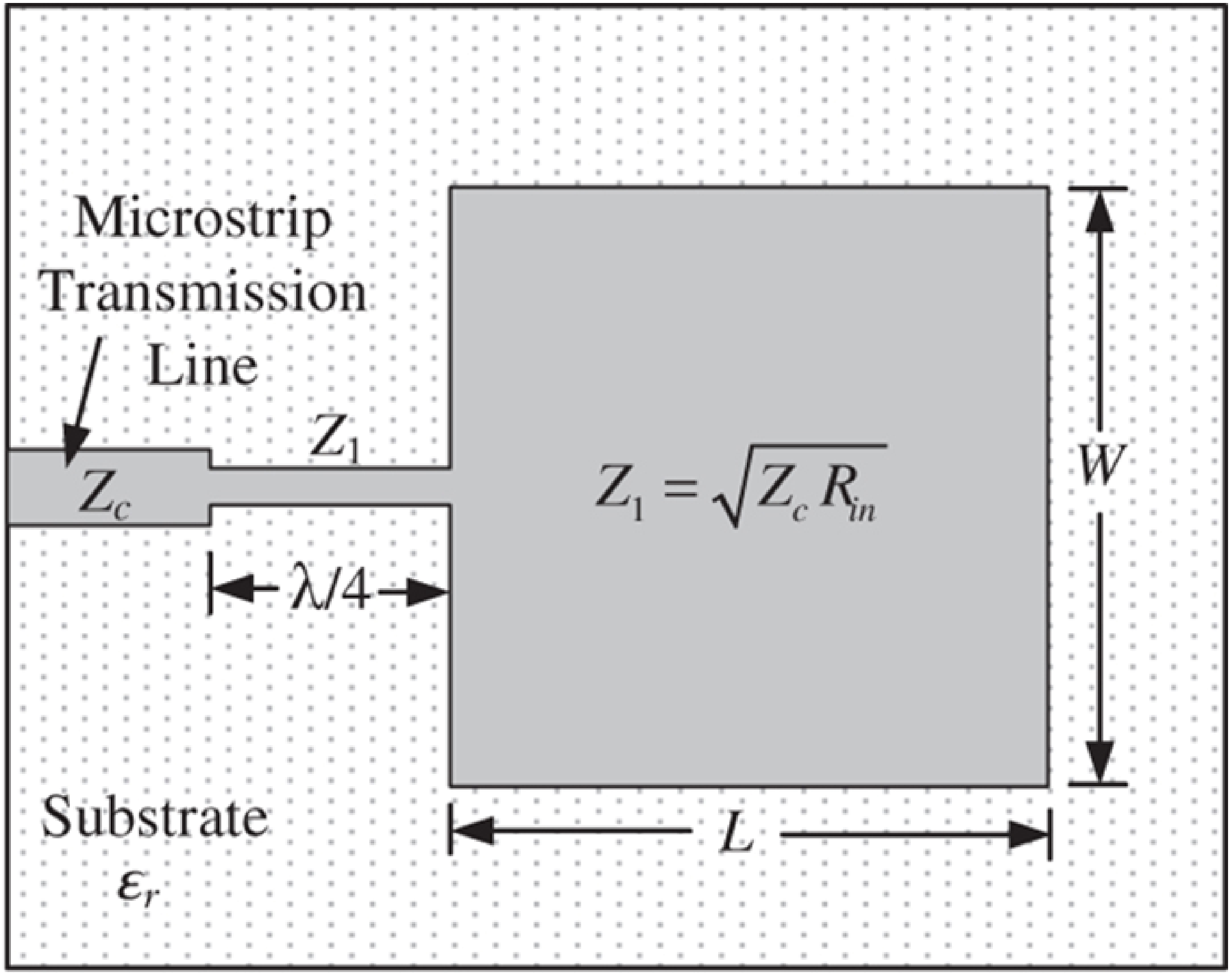
Now consider the feeding point to be $y_0 = 0.4L$. Determine the input resistance.

Microstrip Line Characteristic Impedance



$$
Z_c = \begin{cases} \dfrac{60}{\sqrt{\epsilon_{reff}}} \ln\left[\dfrac{8h}{W_0} + \dfrac{W_0}{4h}\right], & \dfrac{W_0}{h} \le 1 \\ \dfrac{120\pi}{\sqrt{\epsilon_{reff}}\left[\dfrac{W_0}{h} + 1.393 + 0.667\ln\left(\dfrac{W_0}{h} + 1.444\right)\right]}, & \dfrac{W_0}{h} > 1 \end{cases}
$$

Matching Techniques – Inset feed



(b) $\lambda/4$ impedance transformer

Fig. 14.12

Chapter 14
Microstrip Antennas

Rectangular Patch - Example

A microstrip antenna with overall dimensions of $L = 0.906$ cm and $W = 1.186$ cm, substrate with height $h = 0.1588$ cm and dielectric constant $\epsilon_r = 2.2$, is operating at 10 GHz. Find:

(a) The input impedance. Do not take into account mutual effects between slots.

(b) The position of the inset feed point where the input impedance is 50 ohms.

(c) Taking into account mutual effects and new calculations, the admittance between slots is calculated as $G_1 = 1.57 \times 10^{-3}, G_{12} = 6.1683 \times 10^{-4}$. Calculate the input impedance and the distance of the inset feed point. Compare with parts (a) and (b)

Rectangular Patch - Fields

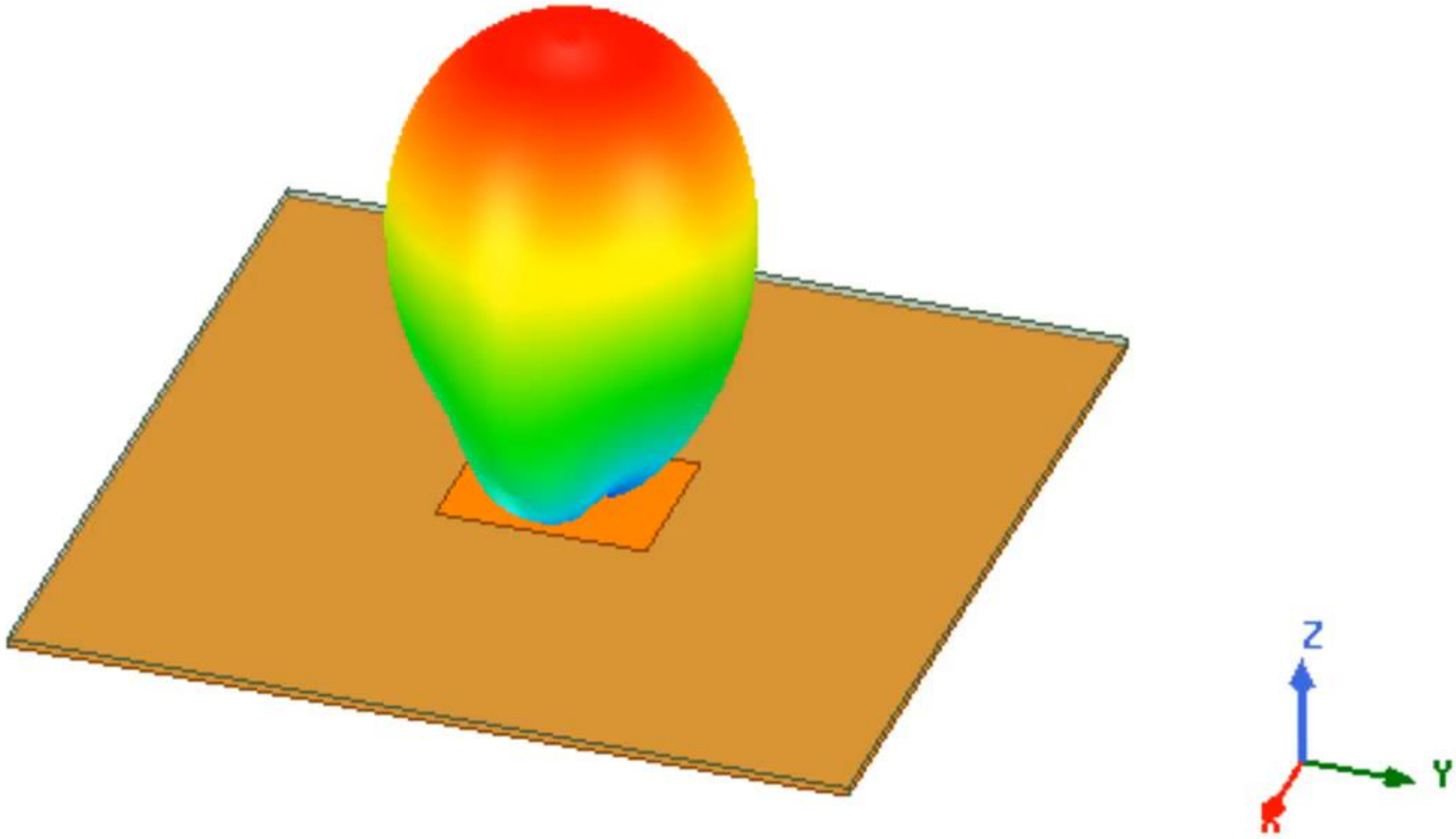
$$f(\theta,\phi) = \frac{\sin\left[\frac{kW}{2}\sin(\theta)\sin(\phi)\right]}{\frac{kW}{2}\sin(\theta)\sin(\phi)}\cos\left(\frac{kL}{2}\sin(\theta)\cos(\phi)\right)$$

$$F_E(\theta) = \cos\left(\frac{kL}{2}\sin(\theta)\right), \qquad \phi = 0°$$

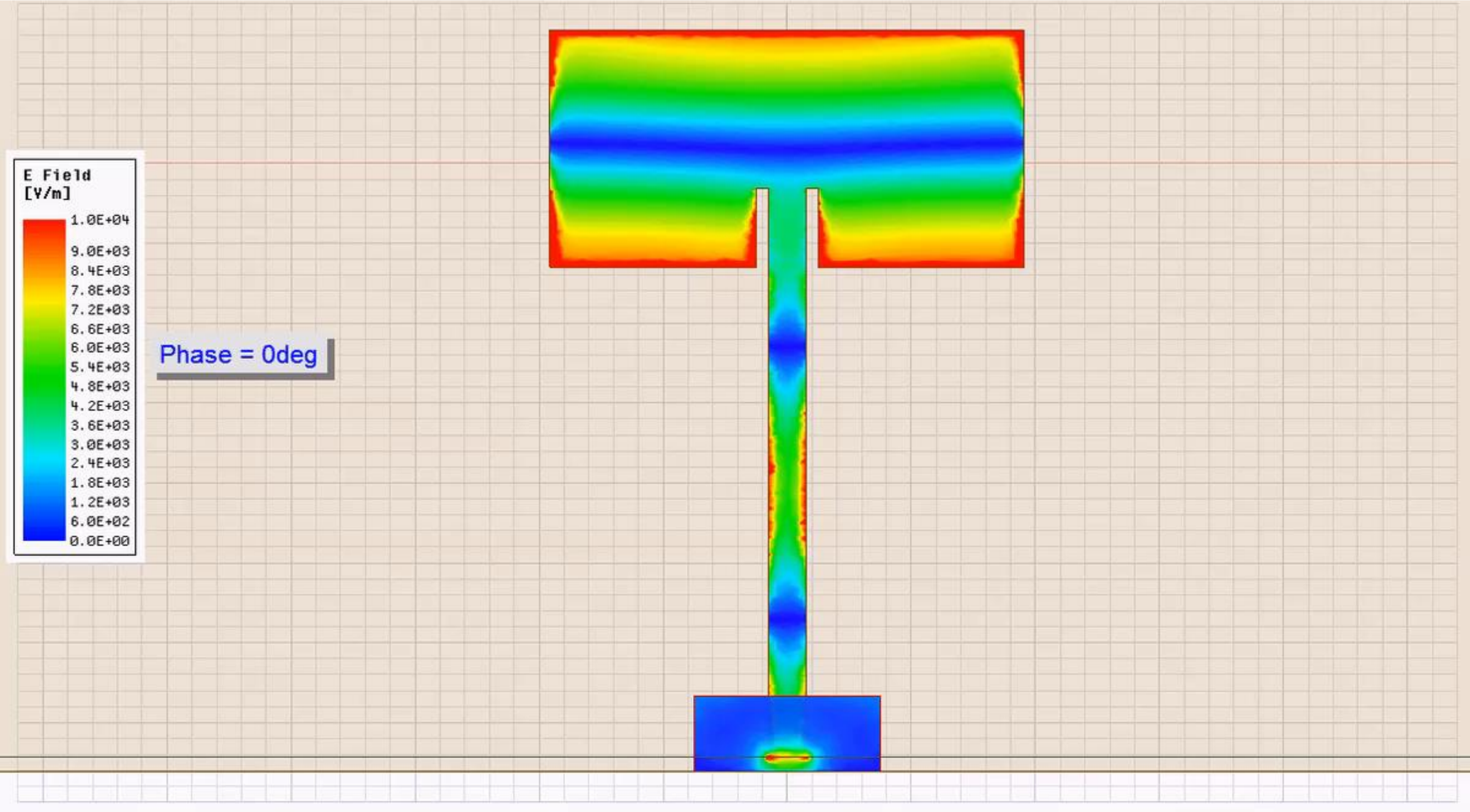
$$F_H(\theta) = \cos(\theta)\frac{\sin\left(\frac{kW}{2}\sin(\theta)\right)}{\frac{kW}{2}\sin(\theta)}, \qquad \phi = 90°$$

Rectangular Patch - Fields

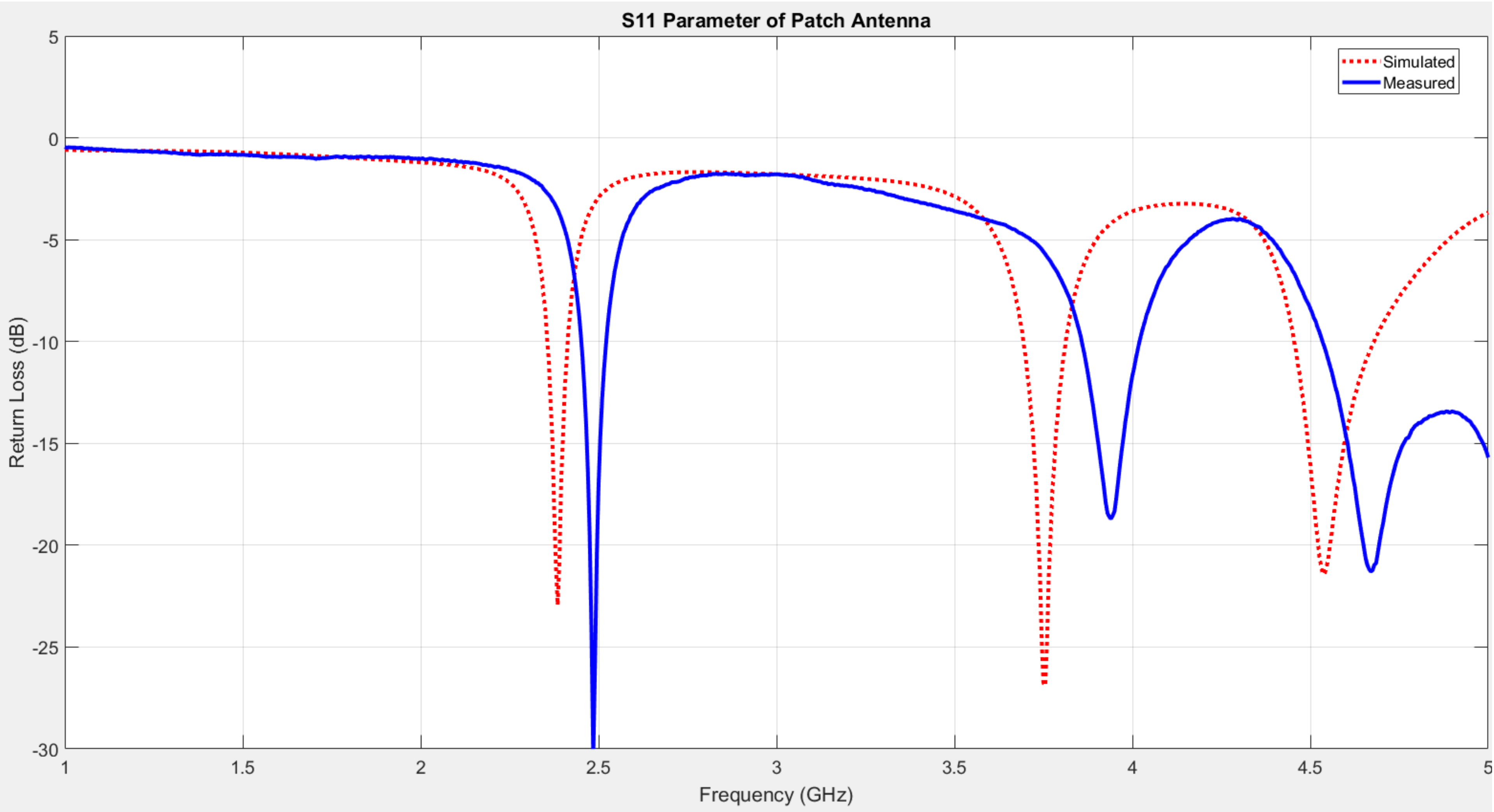
Radiation Efficiency: 36.72%



Rectangular Patch - Fields



Rectangular Patch Antenna Measurements & Simulation



Rectangular Patch - Directivity

$$D_0 = \frac{U_{max}}{U_0} = \frac{4\pi U_{max}}{P_{rad}}$$

Single Slot ($k_0 h \ll 1$)

$$U_{max} = \frac{|V_0|^2}{2\eta_0 \pi^2}\left(\frac{\pi W}{\lambda_0}\right)^2$$

$$P_{rad} = \frac{|V_0|^2}{2\eta_0 \pi^2} \int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)}\right]^2 \sin^3(\theta)\, d\theta$$

Two Slots ($k_0 h \ll 1$)

$$D_2 = \left(\frac{2\pi W}{\lambda_0}\right)^2 \frac{\pi}{I_2}$$

$$I_2 = \int_0^{\pi}\int_0^{\pi} \left[\frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)}\right]^2 \sin^3(\theta)\cos^2\left(\frac{k_0 L_e}{2}\sin(\theta)\sin(\phi)\right) d\theta d\phi$$

Quality Factor, Bandwidth, and Efficiency

Quality Factor

The quality factor, bandwidth, and efficiency are interrelated figures-of-merit, and cannot be independently optimized.

$$Q = \omega_r \frac{\text{Stored Energy}}{\text{Dissipated Power}}$$

The quality factor is representative of the antenna losses. These are radiation, conduction (ohmic), dielectric, and surface-wave losses.

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}}$$

Where

Q_t = Total Quality Factor
Q_{rad} = Quality Factor due to radiation (space-wave) losses.
Q_c = Quality Factor due to conduction (ohmic) losses.
Q_d = Quality Factor due to dielectric losses
Q_{sw} = Quality Factor due to surface waves (negligible for thin substrates)

Quality Factor

For very thin substrates $(k \ll h_0)$ of arbitrary shapes, there are approximate formulas to represent the quality factors.

$$Q_c = h\sqrt{\pi f \mu \sigma}$$

$$Q_d = \frac{1}{\tan(\delta)}$$

$$Q_{rad} = \frac{2\omega\epsilon_r}{h\, G_t/l} K$$

$$K = \frac{\iint_{area} |E|^2 dA}{\oint_{perimeter} |E|^2 dl}$$

For rectangular aperture in the dominant TM_{010}^x mode

$$K = \frac{L}{4}$$

$\frac{G_t}{l} = \frac{G_{rad}}{W}$ conductance per unit length of radiating aperture

Quality Factor – Bandwidth

The fractional bandwidth of the antenna is inversely proportional to the Q_t of the antenna

$$\frac{\Delta f}{f_0} = \frac{1}{Q_t}$$

$\frac{\Delta f}{f_0} =$ Fractional Bandwidth $\left(\frac{f_2 - f_1}{f_0}\right), f_0 = \left(\frac{f_1 + f_2}{2}\right)$

$$\frac{\Delta f}{f_0} = \frac{VSWR\ - 1}{Q_t\sqrt{VSWR}}$$

$$f_1 = \frac{f_0}{\sqrt{1 + 1/Q_t}}, f_2 = f_0\sqrt{1 + 1/Q_t}$$

An approximate expression of the bandwidth for $\mathrm{VSWR} \leq 2, |\Gamma| \leq \frac{1}{3}$,

$$\mathrm{BW} = 3.771\left[\frac{\epsilon_r - 1}{(\epsilon_r)^2}\right]\frac{h}{\lambda_0}\left(\frac{W}{L}\right)$$

Quality Factor – Dimensions and Bandwidth

CP: Single Feed For Nearly Sqare Patch [34]

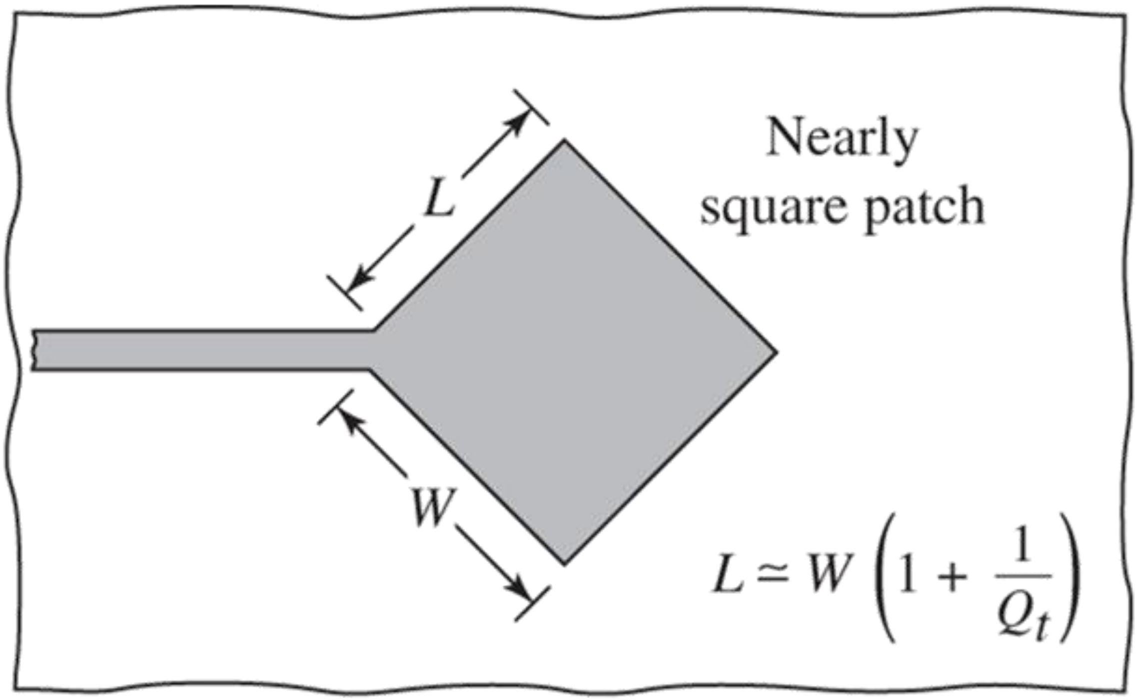


Fig. 14.35a

Quality Factor, Bandwidth, and Efficiency – Example

The fractional bandwidth at a center frequency of $10\ \mathrm{GHz}$ of a rectangular patch antenna whose substrate is RT/Duroid 5880 $(\epsilon_r = 2.2)$ with height $h = 0.1588\ \mathrm{cm}$ is about 5% for a VSWR of $2{:}\,1$. Within that bandwidth, find resonant frequencies associated with the two lengths of the rectangular patch antenna, and relative ratio of the two lengths.

Antennas for Mobile Communications

Planar Inverted F Antenna

3-D View

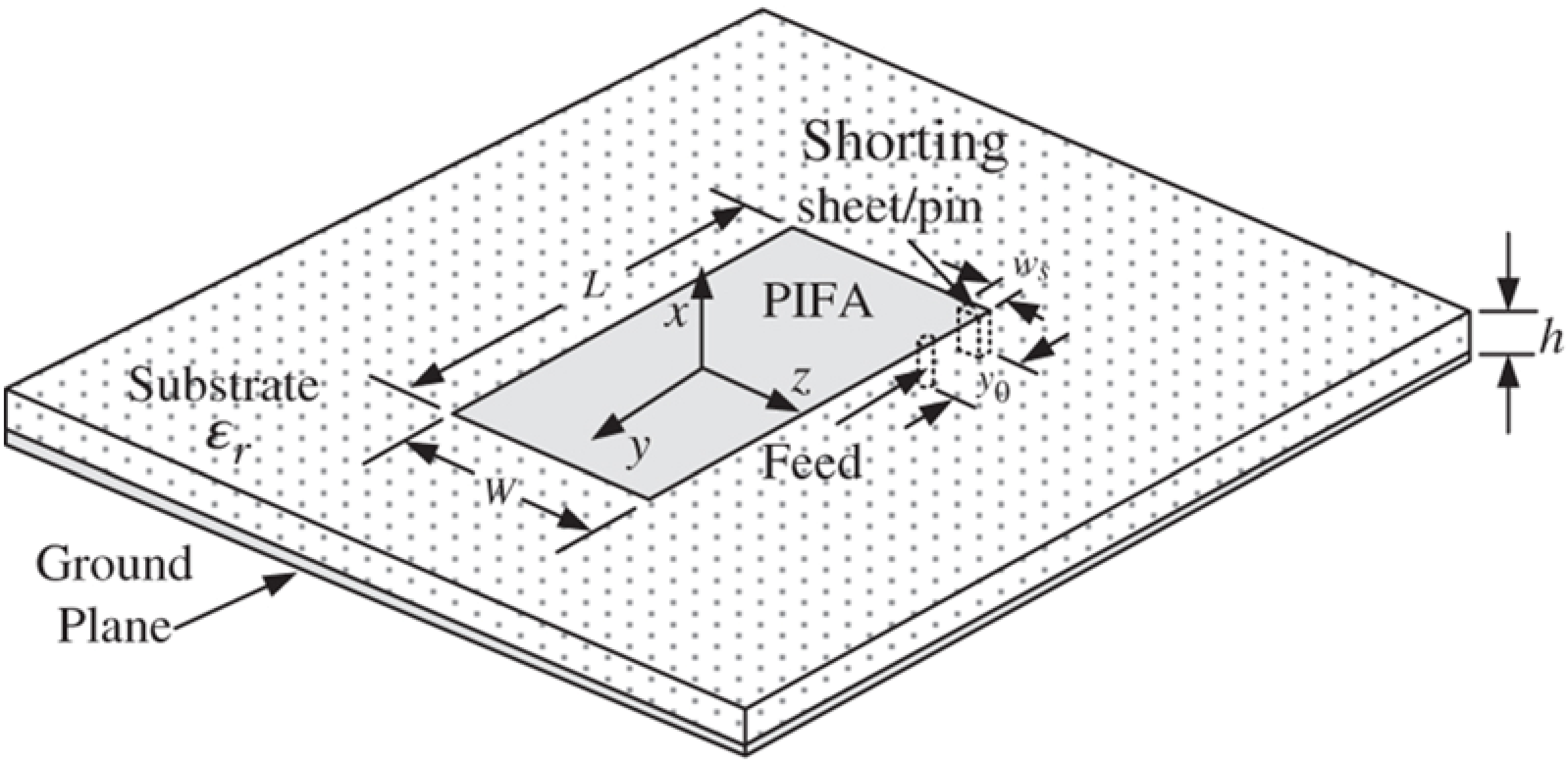


Fig. 14.46

Chapter 14
Microstrip Antennas

Planar Inverted F Antenna

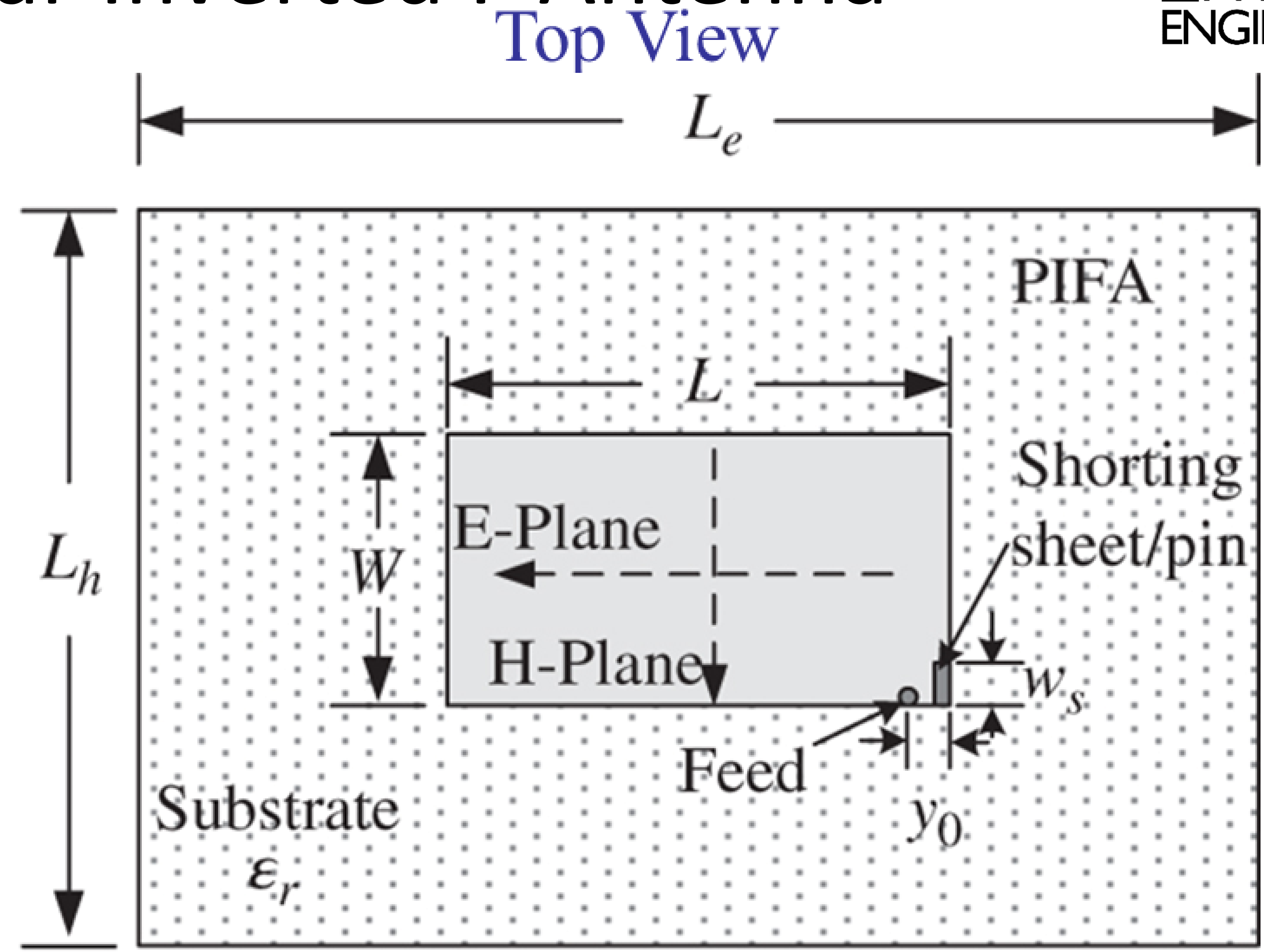


Fig. 14.46

Chapter 14
Microstrip Antennas

Planar Inverted F Antenna

Side View

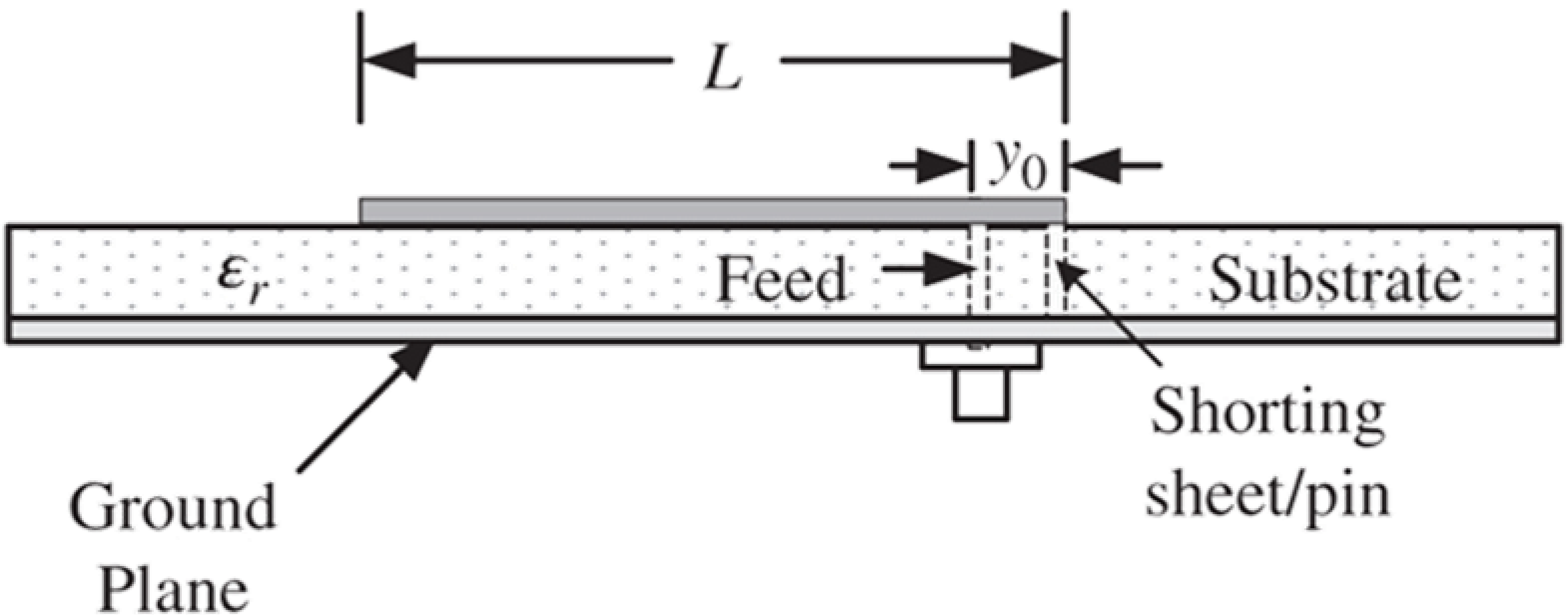
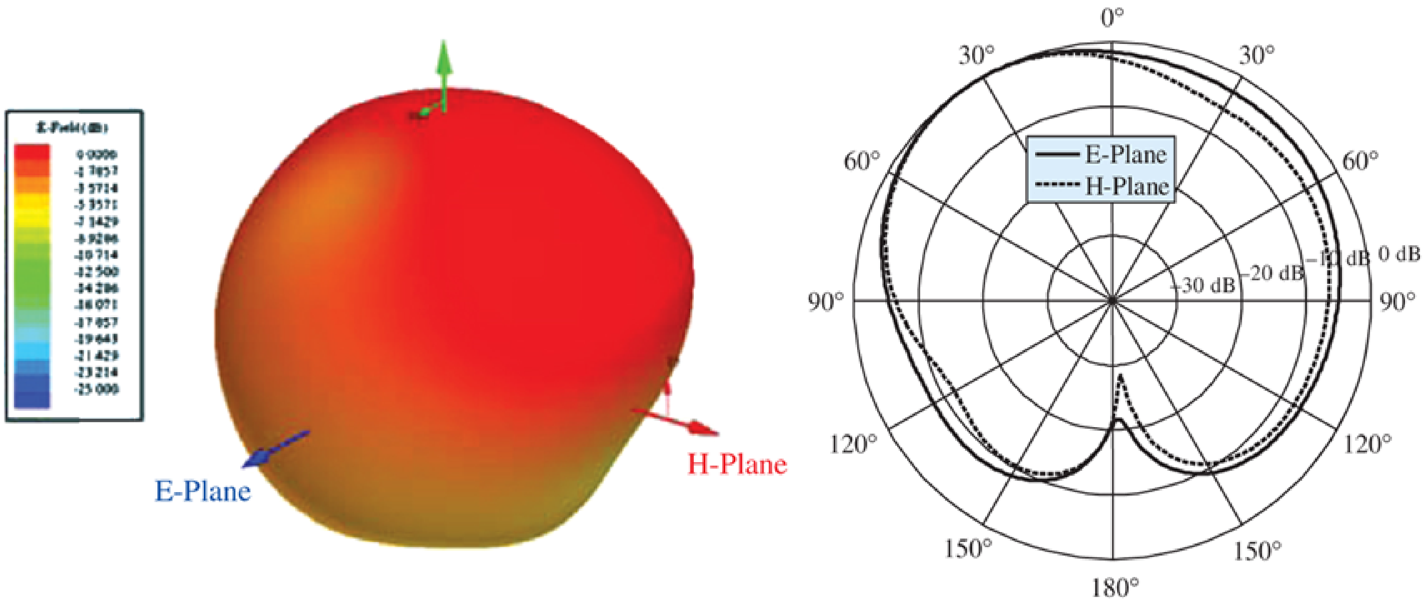


Fig. 14.46

Planar Inverted F Antenna

3-D and 2-D Patterns of PIFA



(a) 3-D (b) E-plane (solid) and H-plane (dashed)

Fig. 14.48

Chapter 14
Microstrip Antennas

Slot Antenna

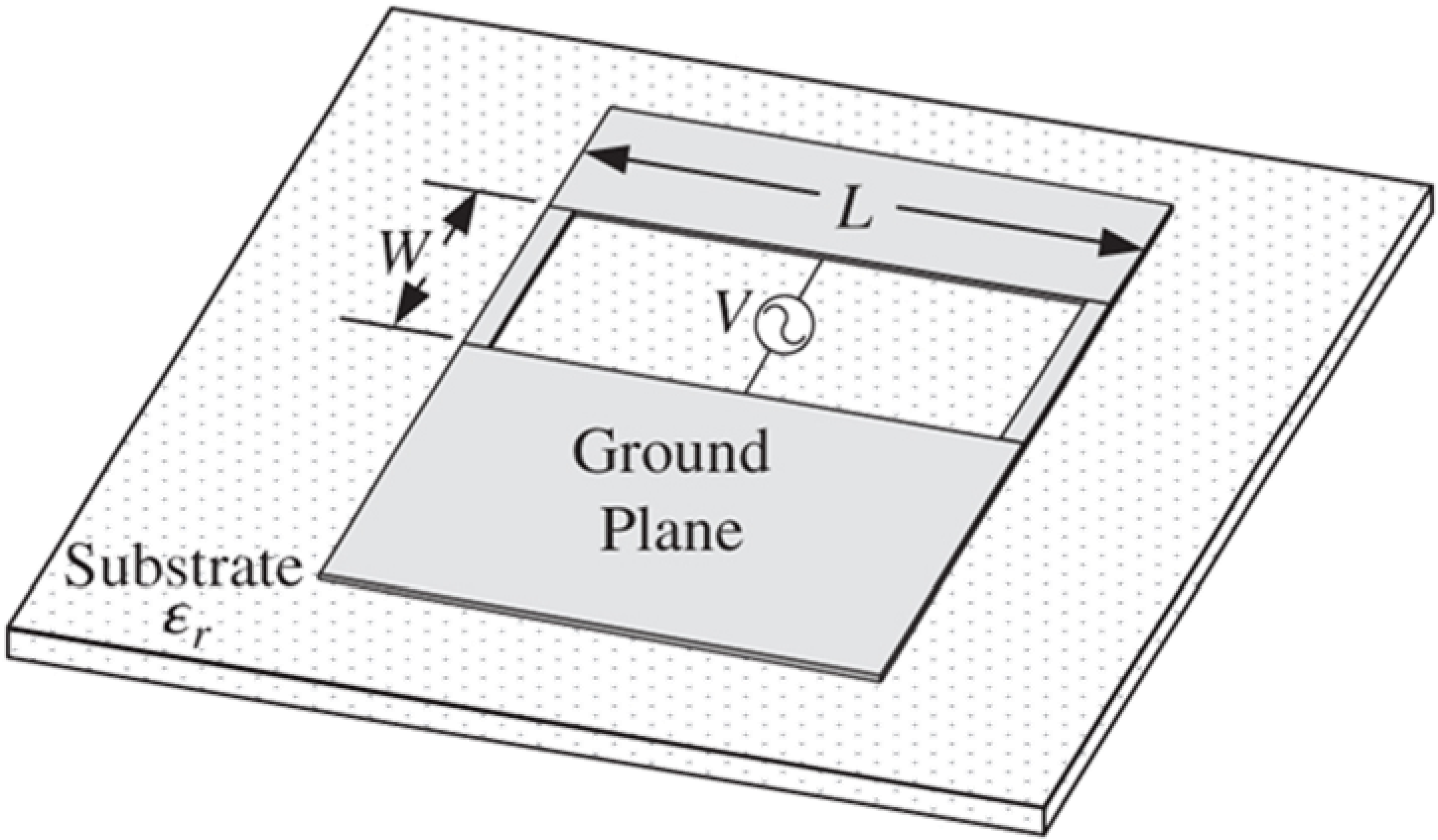


Fig. 14.49

Chapter 14
Microstrip Antennas

Inverted F Antenna

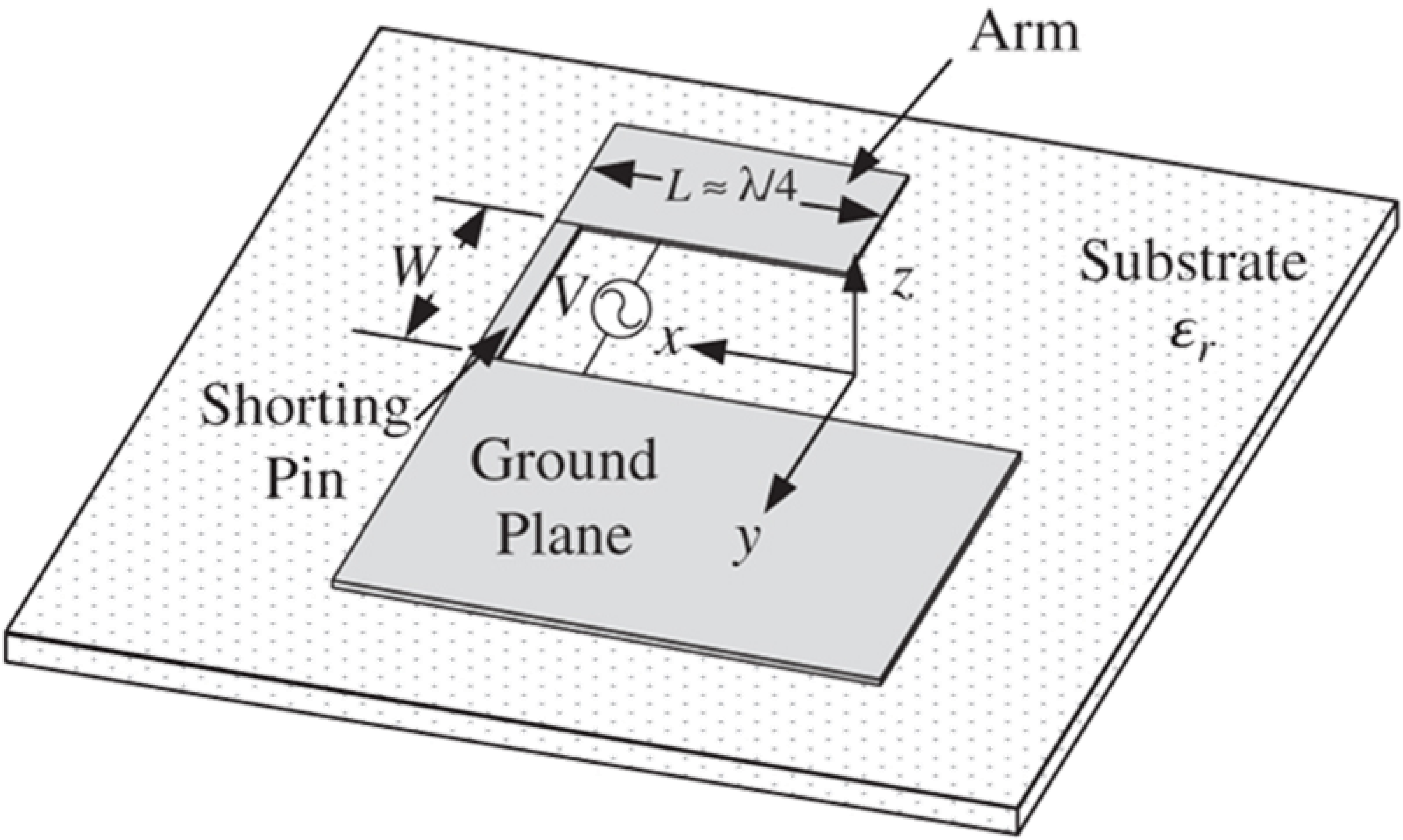


Fig. 14.51

Chapter 14
Microstrip Antennas

Inverted F Antenna

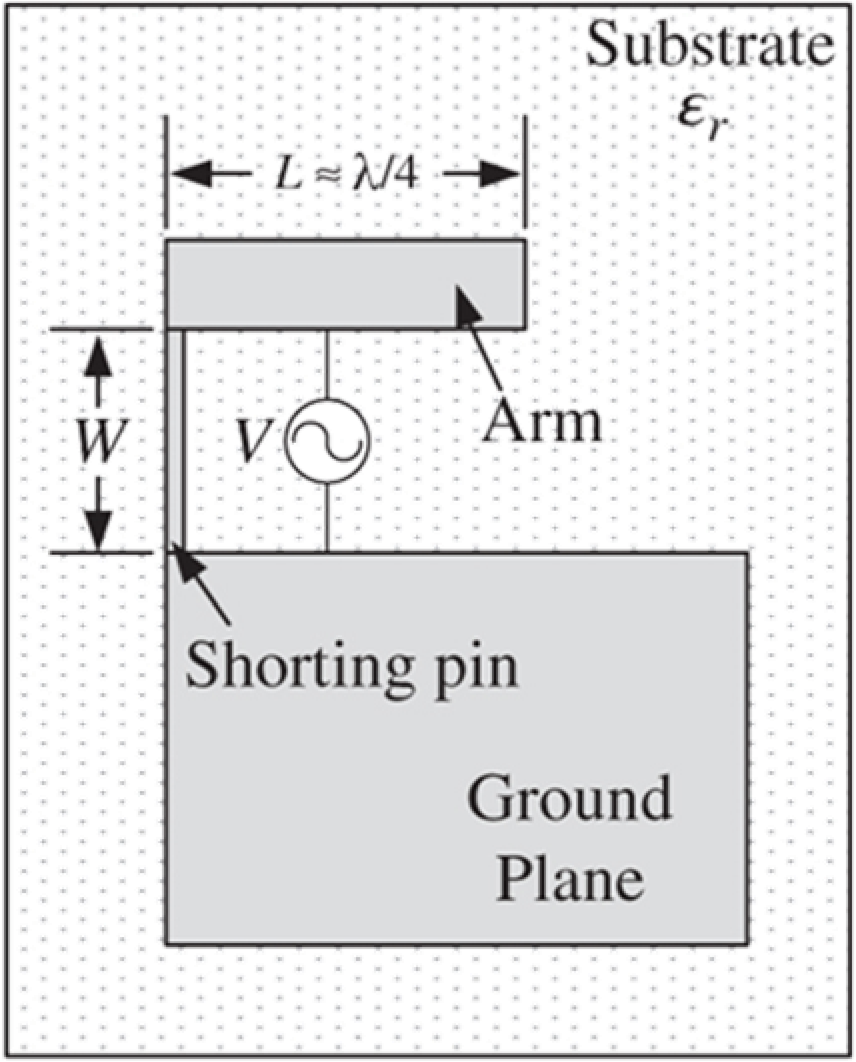
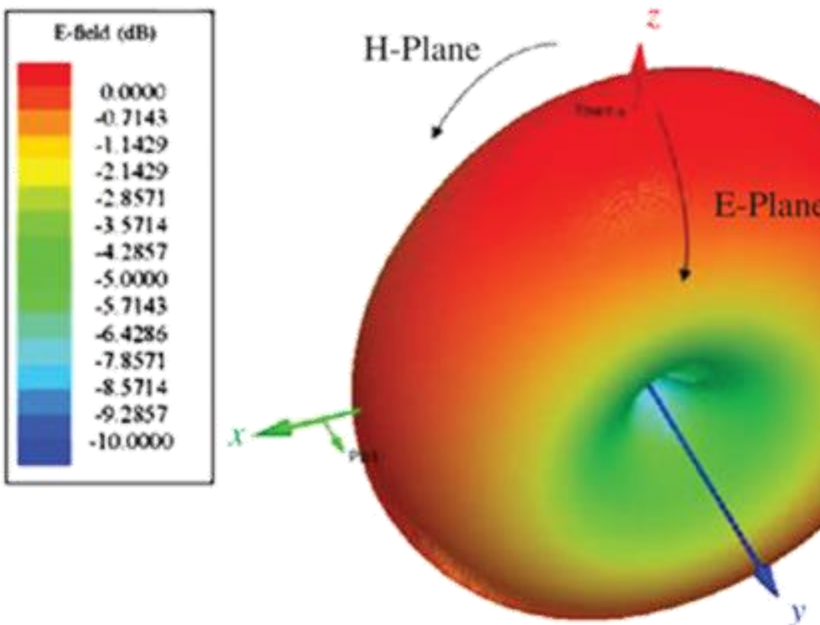


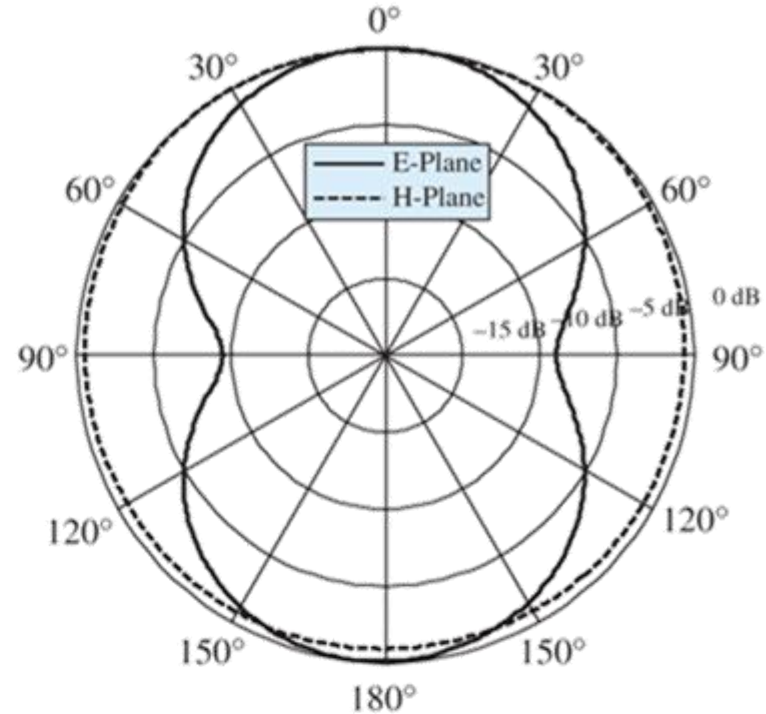
Fig. 14.51

Chapter 14
Microstrip Antennas

Inverted F Antenna



(a) 3-D



(b) E-plane (solid) and H-plane (dashed)

Fig. 14.53

Chapter 14
Microstrip Antennas

3D Inverted F Antenna

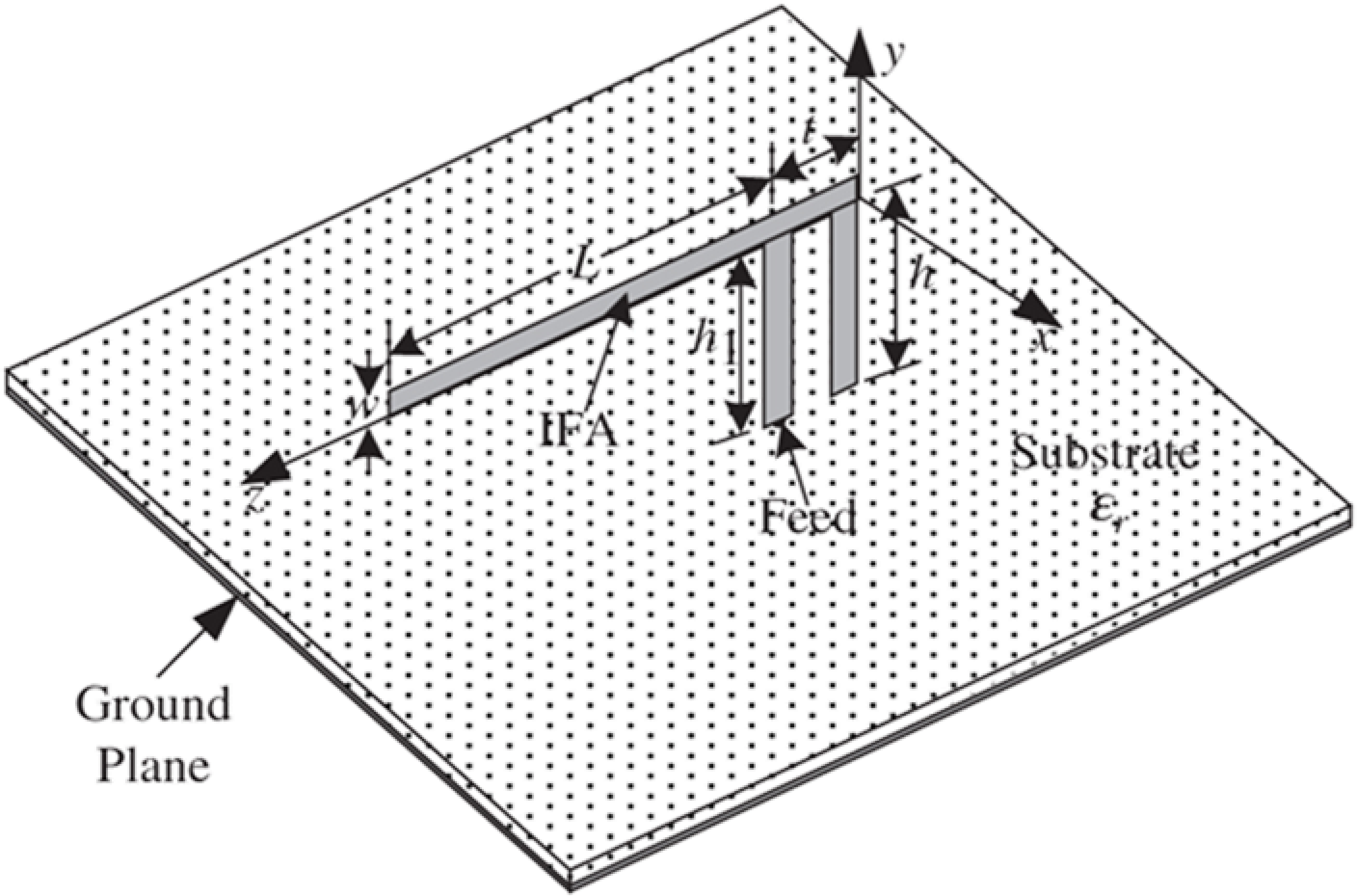


Fig. 14.54

Chapter 14
Microstrip Antennas

3D Inverted F Antenna

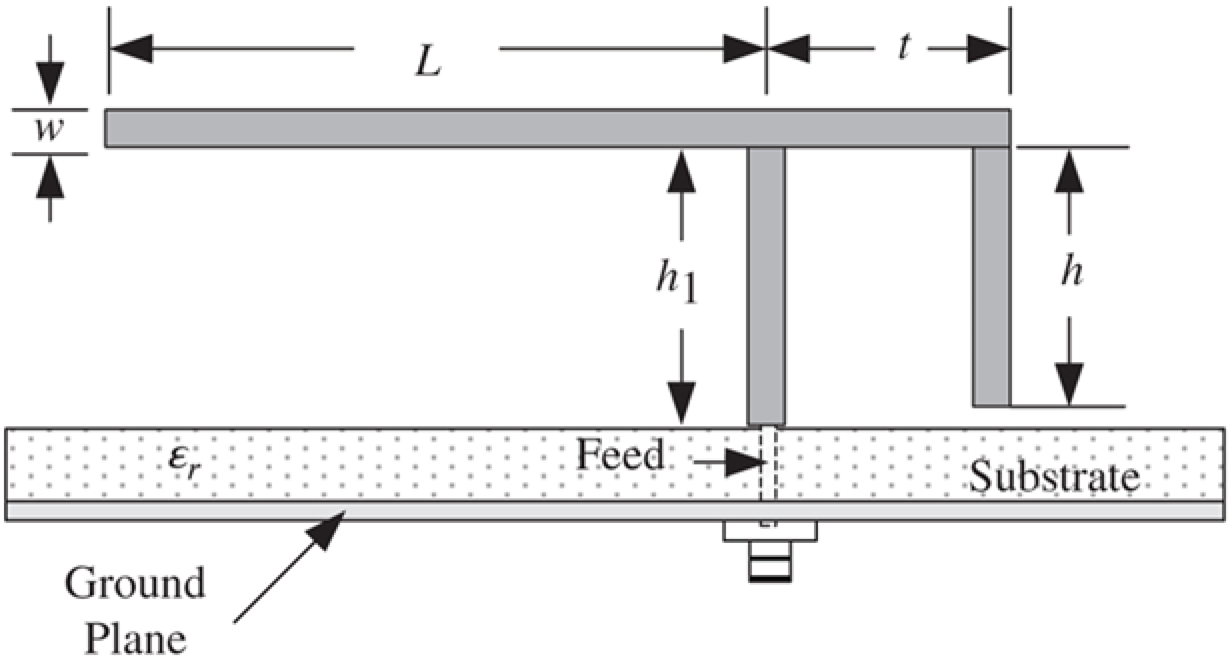


Fig. 14.54

Chapter 14
Microstrip Antennas