Spring 2019

EECE 588
Lecture 23

Prof. Wonbin Hong

A Design Example

- Now, let us design a 2.4 GHz patch antenna on a 1.5 mm thick RO4003C substrate with ε_r=3.4.
- Equations (1)-(4) show a summary of the design procedure:

$$W = \frac{3\times 10^8}{2\times 2.4\times 10^9}\sqrt{\frac{2}{3.4+1}} = 42.1mm \quad (1)$$

$$\varepsilon_{eff} = \frac{3.4+1}{2} + \frac{3.4-1}{2}\left\{1+12\frac{1.5}{W}\right\}^{-1/2} = 3.2 \quad (2)$$

$$\Delta L = h\times 0.412\frac{(3.2+0.3)\left(\frac{42.1}{1.5}+0.264\right)}{(3.2-0.258)\left(\frac{42.1}{1.5}+0.8\right)} = 1.5mm\times 0.48 = 0.72\,mm \quad (3)$$

$$L = \frac{\lambda}{2} - 2\Delta L = \frac{125}{2\sqrt{3.2}} - 2\times 0.72 = 33.5mm \quad (4)$$

POSTECH

A Design Example: Continued

- The dimensions of the patch antenna are L = 33.5 mm × W = 42.1 mm.
- Using the formulas presented in the previous slides, the input impedance of the antenna can be calculated.

$$R_{in} = \frac{1}{2G} = 416.7\,\Omega$$

- So, if we use a 50Ω microstrip line to feed the antenna, what should the recessed length be to achieve a match?

$$50 = 416.7\cos^2\left(\frac{\pi}{L}y_0\right) \qquad \frac{\pi}{L}y_0 = 1.22 \Rightarrow y_0 = 13\,mm$$

- A 50Ω microstrip line on this substrate has the width of 3.6 mm. You can calculate this using the formulas found in literature (such as those presented in Slide # 11or little software packages such as TXLINE by AWR*.

* TXLINE is available for download for Free from http://web.awrcorp.com/Usa/Products/Optional-Products/TX-Line/

A Design Example: Continued

- You can also use the formulas found in literature to calculate the characteristics impedance of the microstrip line.
- Some formulas are provided in Slide #10-12. Here is another formula:

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

- These formulas are usually obtained by solving the wave equation with the help of conformal mapping (which is a complex variable concept).

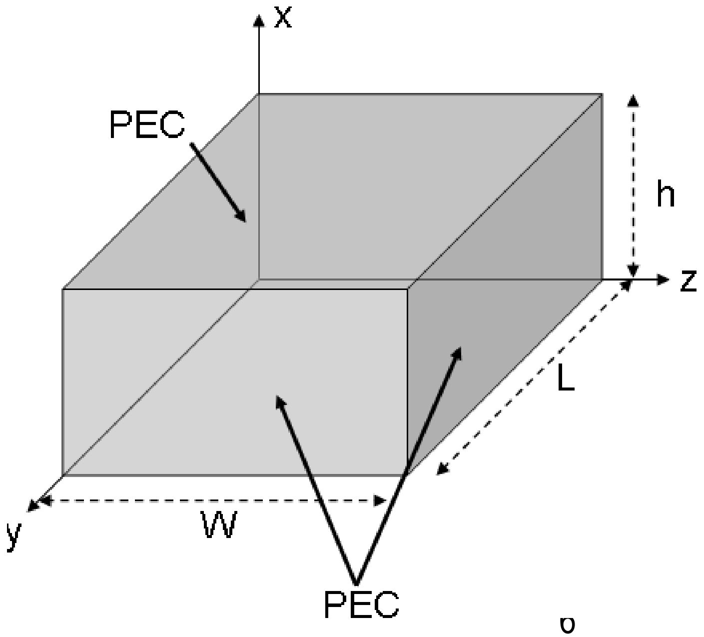
Patch Antenna Analysis

Patch Antenna Analysis:

The Cavity Technique

Cavity Method

- A close metallic box is an example of a traditional cavity resonator. This is shown in the figure below.
- The Helmholtz wave equation, with the appropriate boundary conditions, can be solved to obtain the modes of this resonator.
- Boundary conditions:
  - E_{tan}=0 at x=0, h.
  - E_{tan}=0 at z=0, W.
  - E_{tan}=0 at y=0, L.
  - Note that the tangential component of the electric field is zero at the boundary of a dielectric and a Perfect Electric Conductor (PEC).



POSTECH

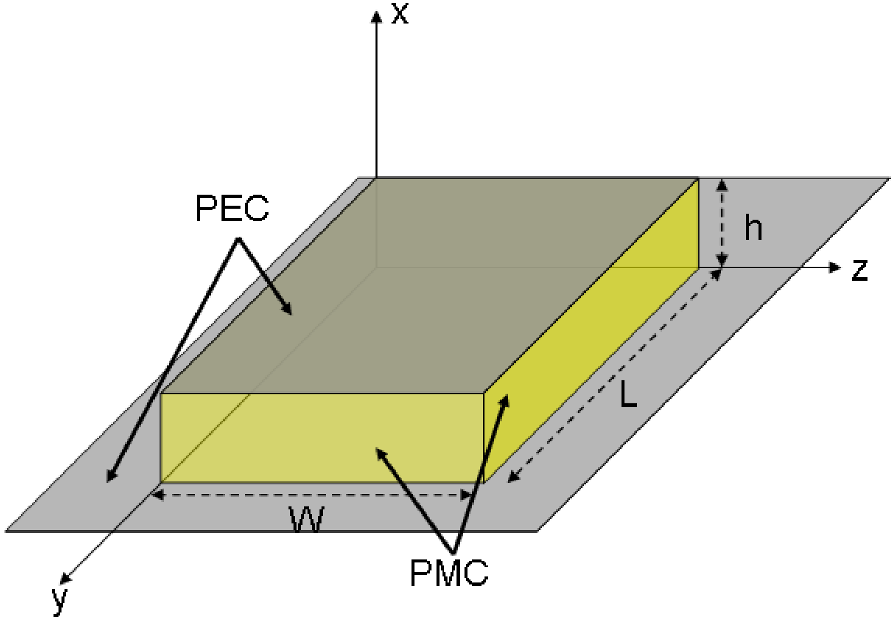
Cavity Method

- Solutions of this problem can be found in advanced EM books such as “Advanced Engineering Electromagnetics” by Balanis or “Time Harmonic Electromagnetic Fields” by Roger F. Harrington.
- Usually, the solutions are obtained in terms of TE (Transverse Electric) or TM (Transverse Magnetic) waves. In this case, we use TE_x and TM_x waves, where:
  - $TE_x \rightarrow E_x=0$
  - $TM_x \rightarrow H_x=0$
- A microstrip patch antenna can be considered as a rectangular cavity where the top and bottom walls are perfect electric conductors (PEC) and the side walls are perfect magnetic conductors (PMC).
- A PMC is dual of a PEC. i.e., the tangential component of magnetic field is zero on a PMC.

POSTECH

Cavity Method for Analyzing Patch Antennas

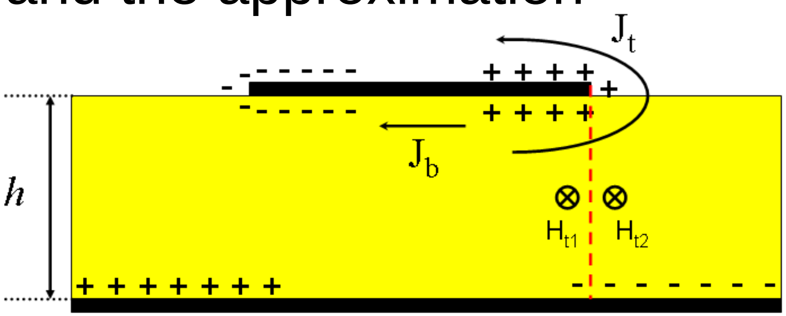
- Similar to a cavity with PEC walls, the wave equation must be solved in this case. The boundary conditions, however, are:
  - $E_y=E_z=0$ at $x=0$, h.
  - $H_x=H_z=0$ at $y=0$, L.
  - $H_x=H_y=0$ at $z=0$, W.
- Also note that this cavity is filled with a dielectric material with the dielectric constant of ε_r.
- Since $h<<\lambda$, the fields do not vary with x.
- Also, since $h<<\lambda$, the fringing fields can be ignored ➔ The E fields are normal to the surface of the patch ➔ No TE_x mode exist (since $E_x \neq 0$).



A patch antenna can be modeled using a cavity with Perfect Magnetic Conductor walls.

Cavity Method: Problems

- The tangential component of the magnetic field is not actually zero at the walls of the imaginary cavity but its value is small.
- The reason is very simple: Boundary condition requires that H_{t1}-H_{t2}=J_t, where H_{t1} and H_{t2} are the tangential magnetic fields as shown in the figure below.
- Since $J_t \neq 0$ ➔ $H_t \neq 0$.
- As h decreases, J_t decreases and the approximation becomes more accurate.



Boundary Condition: $|H_{t1}-H_{t2}|=|J_t|$

Cavity Method

- Representing an antenna with a cavity resonator has some inherent problems:
  - A cavity stores energy in the form of EM fields but an antenna radiates EM energy.
  - The input impedance of a lossless antenna includes a resistive term that represents the loss of energy due to radiation.
  - The input impedance of a lossless cavity resonator does not include any resistive term. i.e., the equivalent circuit only includes lossless inductors and capacitors.
- The solution is to add loss to the cavity by considering the dielectric to be lossy with an effective loss tangent of δ_{eff}.
- The dielectric substrate is considered to be truncated and not extended beyond the patch but in reality the dielectric substrate is much larger than the patch.

Cavity Method

$$\nabla^2 A_x + k^2 A_x = 0$$

$$A_x = \{A_1 \cos(k_x x) + B_1 \sin(k_x x)\} \times \{A_2 \cos(k_y y) + B_2 \sin(k_y y)\}$$
$$\times \{A_1 \cos(k_x x) + B_1 \sin(k_x x)\}$$

$$E_x = \frac{1}{j\omega\omega\mu}\left(\frac{\partial^2}{\partial x^2} + k^2\right)A_x \qquad H_x = 0 \qquad k_x = \frac{m\pi}{h} \quad m = 0,1,2,....$$

$$E_y = \frac{1}{j\omega\omega\mu}\frac{\partial^2 A_x}{\partial x\,\partial y} \qquad H_y = \frac{1}{\mu}\frac{\partial A_x}{\partial z} \qquad k_y = \frac{n\pi}{L} \quad n = 0,1,2,....$$

$$E_z = \frac{1}{j\omega\omega\mu}\frac{\partial^2 A_x}{\partial x\,\partial z} \qquad H_z = -\frac{1}{\mu}\frac{\partial A_x}{\partial y} \qquad k_z = \frac{p\pi}{W} \quad p = 0,1,2,....$$

Boundary Conditions: (E_{tan}=0 at x=0, h), (H_{tan}=0 at z=0, W), (H_{tan}=0 at y=0, L)

POSTECH

Cavity Method

$$k_x^2 + k_y^2 + k_z^2 = k^2 = \omega^2 \mu\varepsilon$$

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\varepsilon}} \sqrt{\left(\frac{m\pi}{h}\right)^2 + \left(\frac{n\pi}{L}\right)^2 + \left(\frac{p\pi}{W}\right)^2}$$

$$E_x = \frac{k^2 - k_x^2}{j\omega\mu\varepsilon} A_{mnp} \cos(k_x x)\cos(k_y y)\cos(k_z z)$$

$$E_y = \frac{k_x k_y}{j\omega\mu\varepsilon} A_{mnp} \sin(k_x x)\sin(k_y y)\cos(k_z z)$$

$$E_z = \frac{k_x k_z}{j\omega\mu\varepsilon} A_{mnp} \sin(k_x x)\cos(k_y y)\sin(k_z z)$$

$$H_x = 0$$

$$H_y = -\frac{k_z}{\mu} A_{mnp} \cos(k_x x)\cos(k_y y)\sin(k_z z)$$

$$H_z = \frac{k_y}{\mu} A_{mnp} \cos(k_x x)\sin(k_y y)\cos(k_z z)$$

If, in a rectangular patch antenna, L > W > h, the dominant resonant mode of the antenna is the TM_{010} mode; this mode has the lowest resonant frequency for the patch.

Cavity Method

- The resonant frequency of the dominant mode (TM_{010}) is:

$$(f_r)_{010} = \frac{1}{2L\sqrt{\mu\varepsilon}} = \frac{c}{2L\sqrt{\varepsilon_r}}$$

- The resonant frequency of the second mode (TM_{001}) is:

$$(f_r)_{001} = \frac{1}{2W\sqrt{\mu\varepsilon}} = \frac{c}{2W\sqrt{\varepsilon_r}}$$

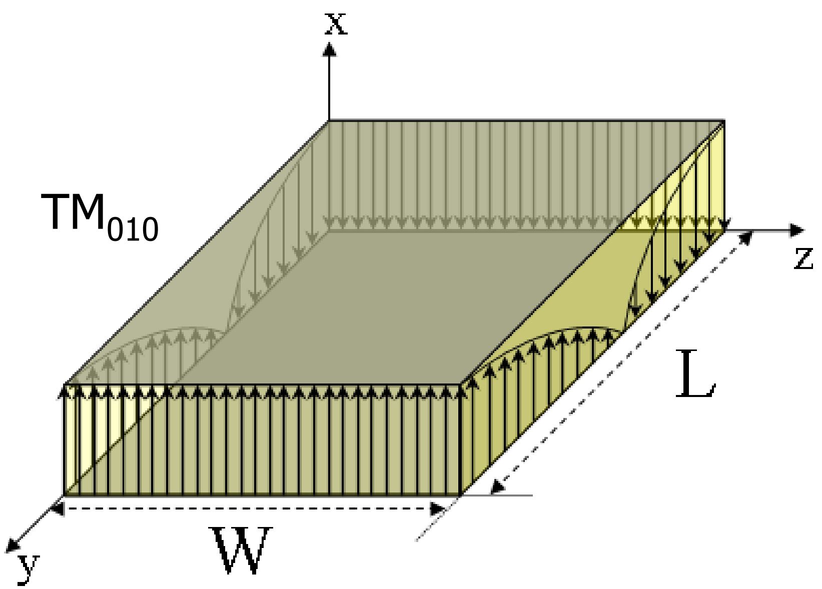
- The resonant frequencies of all higher order modes can also be obtained in a similar fashion. If W > L/2, the next mode is TM_{020} with a resonant frequency of:

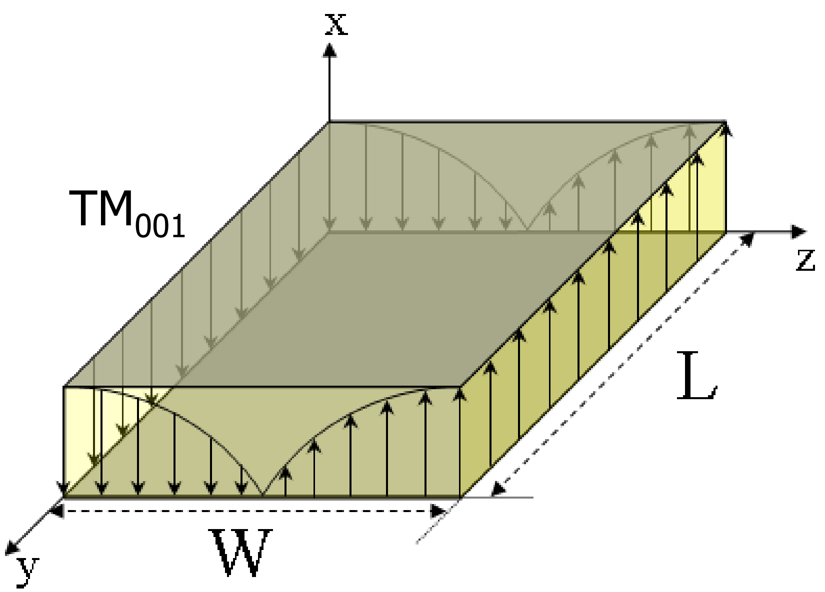
$$(f_r)_{020} = \frac{1}{L\sqrt{\mu\varepsilon}} = \frac{c}{L\sqrt{\varepsilon_r}}$$

POSTECH

Cavity Method

- The field distributions of the TM_{010} and TM_{001} mode are shown in the figures below.
- The cavity method does not take into account the fringing fields that exist.





Cavity Method

- In cavity model:
  - Two PEC layers and 4 PMC side walls are used to model the patch antenna.
  - The substrate material is truncated and does not extend beyond the patch.
- Four PMC side walls represent four narrow apertures through which radiation takes place.
- Equivalence principle can be used to replace the cavity with a number of equivalent currents radiating in free space.
- A top surface electric current J_t represent the top surface of the patch.
- The side walls are represented by electric current, J_s, and the magnetic current, M_s.

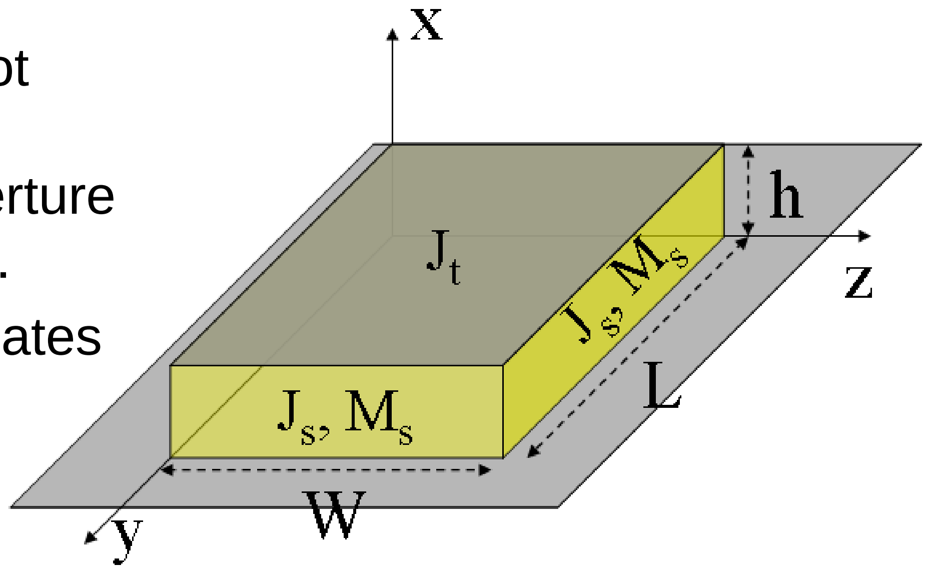
Cavity Method

- The surface electric and magnetic currents are:

$$\vec{J}_s = \hat{n} \times \vec{H}_a \qquad\qquad \vec{M}_s = -\hat{n} \times \vec{E}_a$$

- $\mathbf{E_a}$ and $\mathbf{H_a}$ are the electric and magnetic fields of the slots.
- The current on the top surface of the patch is much smaller than the current on the bottom side of the patch ($\mathbf{J_t} << \mathbf{J_b}$) ➔ $\mathbf{J_t} \approx 0$.

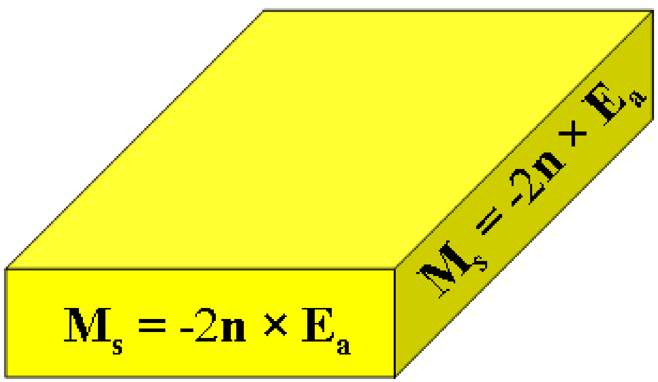
- In the cavity method, fringing is not considered. i.e., the tangential component of **H** field over the aperture is considered to be zero ➔ $\mathbf{J_s} \approx 0$.
- Therefore, only $\mathbf{M_s}$ exists that radiates over an infinite ground plane.

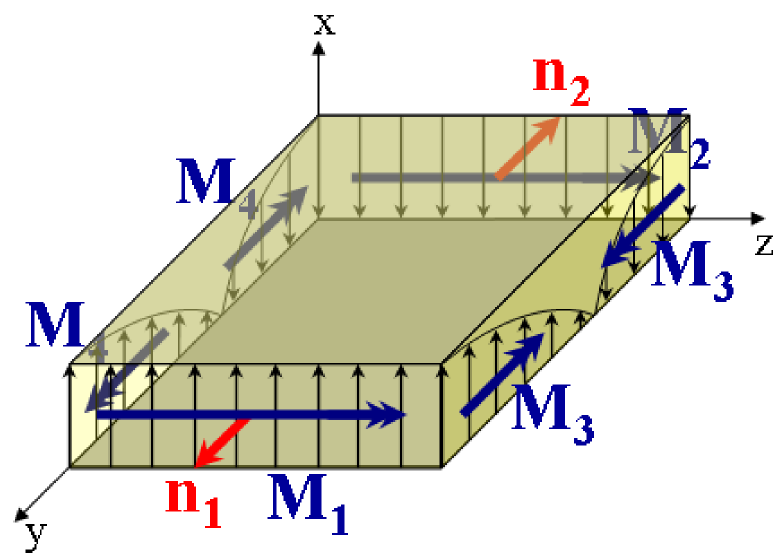


POSTECH

Cavity Method

- Image theory can be used to eliminate the ground plane. Therefore, the ground plane can be removed and the magnetic current doubled.
- The magnetic currents are shown in the figure below; the magnetic currents in the radiation slots are in phase.
- The magnetic currents in the non radiating slots are 180° out of phase with one another (M_3 and M_4).
- In each non-radiating slots, half of the magnetic current cancels the other half as shown in the figure below.





POSTECH

Cavity Method

- In the dominant mode (TM_{010}) the electric and magnetic field expressions are as follows:

$$E_x = E_0 \cos(\frac{\pi y}{L}) \qquad H_z = H_0 \sin(\frac{\pi y}{L})$$

- Magnetic currents, M_1 and M_2 have the same magnitude and phase and are separated by the distance of $\lambda_d/2$, where λ_d is the wavelength in the dielectric substrate. Therefore, they act as a two-element array.
- This results in an antenna with broadside radiation. i.e., the radiation from the two slots add in phase in the broadside direction.
- This is not the case for non-radiating slots. Because of the 180° phase difference, the radiation from these two slots cancel in the H-plane.
- In each non-radiating slot, the anti-symmetric field distribution also results in a null at broadside.
- The non-radiating slots radiate in non-principal planes but their radiation is small compared to the radiation from radiating slots.

Radiated Fields

- The radiated fields of the antenna are obtained by calculating the radiated fields of one slot and using the array theory to find the radiated fields of the two-element array (patch antenna).
- The far field radiated fields of the slots can be obtained using the equivalent currents as follows:

$$E_\varphi = j\frac{k_0 h W E_0\, e^{-jk_0 r}}{2\pi r}\left\{\sin(\theta)\frac{\sin\left(\dfrac{k_0 h}{2}\sin(\theta)\cos(\varphi)\right)}{\dfrac{k_0 h}{2}\sin(\theta)\cos(\varphi)}\,\frac{\sin\left(\dfrac{k_0 W}{2}\cos(\theta)\right)}{\dfrac{k_0 W}{2}\cos(\theta)}\right\}$$

$$\text{For} \quad k_0 h << 1 \Rightarrow E_\varphi = j\frac{h E_0\, e^{-jk_0 r}}{\pi r}\left\{\sin(\theta)\frac{\sin\left(\dfrac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)}\right\}$$

$$\text{The array factor is:} \quad AF = 2\cos\left(\frac{k_0 L_e}{2}\sin(\theta)\sin(\varphi)\right)$$

Radiated Fields

- The total electric field is then:

$$E_\varphi = j\frac{k_0 hWE_0\, e^{-jk_0 r}}{\pi r}\left\{\sin(\theta)\frac{\sin\left(\frac{k_0 h}{2}\sin(\theta)\cos(\varphi)\right)}{\frac{k_0 h}{2}\sin(\theta)\cos(\varphi)}\frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\frac{k_0 W}{2}\cos(\theta)}\right\}$$

$$\times\cos\left(\frac{k_0 L_e}{2}\sin(\theta)\sin(\varphi)\right)$$

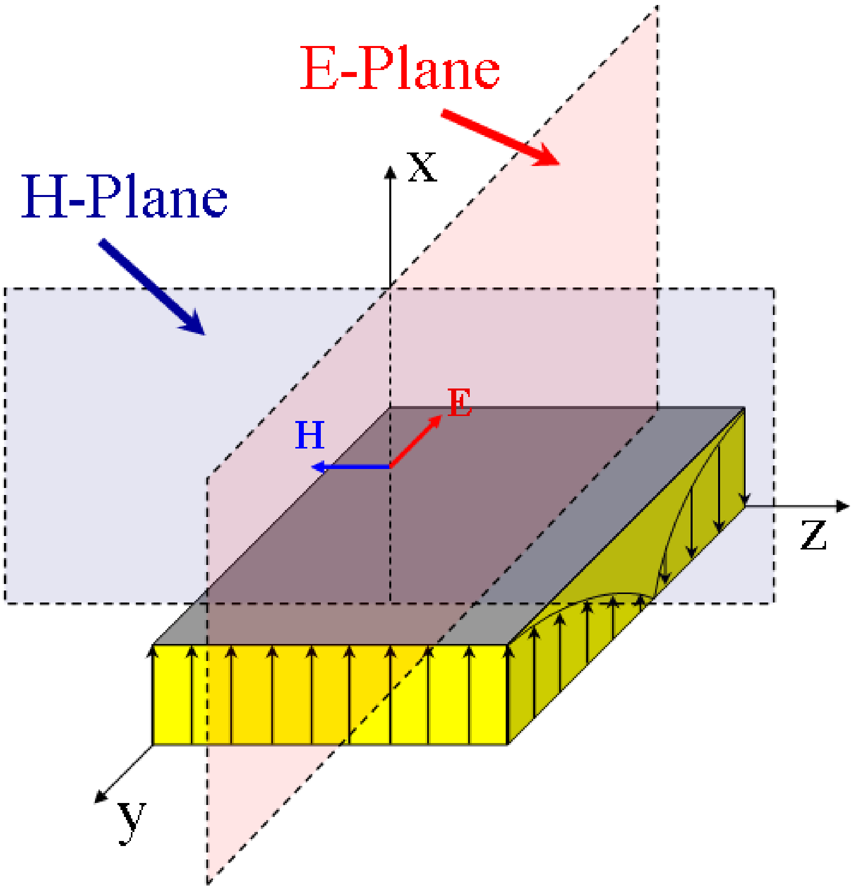
$$\text{For } k_0 h << 1 \Rightarrow E_\varphi = j\frac{2hE_0\, e^{-jk_0 r}}{\pi r}\left\{\sin(\theta)\frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)}\right\}$$

$$\times\cos\left(\frac{k_0 L_e}{2}\sin(\theta)\sin(\varphi)\right)$$

POSTECH

Radiation Patterns

- The principal planes of radiation are the E-Plane and H-Plane as shown in the figure.
- E-Plane: $\theta = 90°$, $0° \leq \varphi \leq 90°$ and $270° \leq \varphi \leq 360°$. E-Plane: X-Y Plane according to the figure.
- H-Plane: $\varphi = 0°$, $0° \leq \theta \leq 180°$. H-Plane: X-Z plane according to the figure.
- The expression for the radiated fields is simplified for the E- and H-Planes.



Radiation Patterns

- E-Plane expression:

$$E_\varphi = j\frac{k_0 hWE_0\, e^{-jk_0 r}}{\pi r}\left\{\frac{\sin\left(\dfrac{k_0 h}{2}\cos(\varphi)\right)}{\dfrac{k_0 h}{2}\cos(\varphi)}\right\}\times\cos\left(\frac{k_0 L_e}{2}\sin(\varphi)\right)$$

- H-Plane expression:

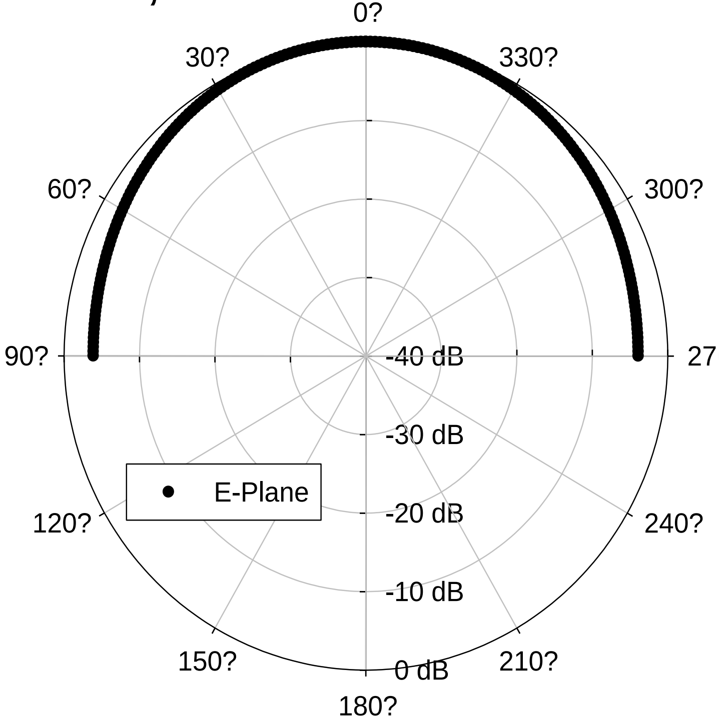
$$E_\varphi = j\frac{k_0 hWE_0\, e^{-jk_0 r}}{\pi r}\left\{\sin(\theta)\frac{\sin\left(\dfrac{k_0 h}{2}\sin(\theta)\right)}{\dfrac{k_0 h}{2}\sin(\theta)}\,\frac{\sin\left(\dfrac{k_0 W}{2}\cos(\theta)\right)}{\dfrac{k_0 W}{2}\cos(\theta)}\right\}$$

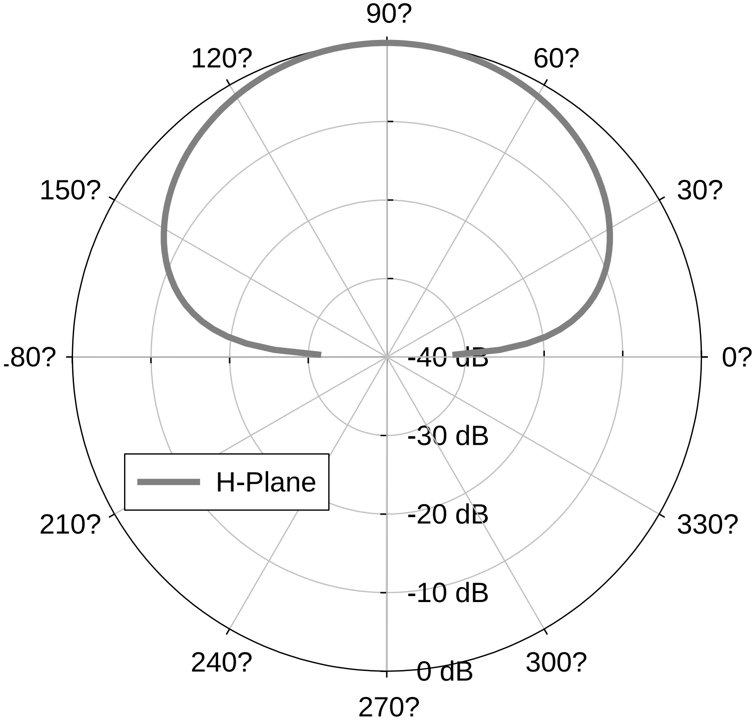
In reality, unlike what is predicted by the cavity technique, the E-plane radiation pattern at grazing angles has a null. This is not predicted by the cavity technique because we assume that the dielectric substrate is finite.

POSTECH

Radiation Patterns

- The radiation patterns of the 2.4 GHz patch antenna example of slide 31-32.
- The antenna parameters are: L=33.5 mm, ΔL=0.72 mm, ε_r=3.4, h=1.5 mm, W=42 mm.





Directivity

- First let's study the directivity of a single slot for which $k_0 h << 1$

$$D_0 = \left(\frac{2\pi W}{\lambda_0}\right)^2 \frac{1}{I_1}$$

$$I_1 = \int_0^{\pi} \left\{ \frac{\sin\left(\frac{k_0 W}{2}\cos(\theta)\right)}{\cos(\theta)} \right\}^2 \sin^3(\theta)\, d\theta = -2 + \cos(k_0 W) + k_0 W\, \mathrm{S_i}(k_0 W) + \frac{\sin(k_0 W)}{k_0 W}$$

$$\mathrm{S_i}(\mathrm{x}) = \int_0^{x} \frac{\sin(\tau)}{\tau} d\tau$$

- Directivity of the patch antenna (two slots) can be obtained using the formula obtained for the total electric field radiated by the patch (two slots).

POSTECH

Directivity

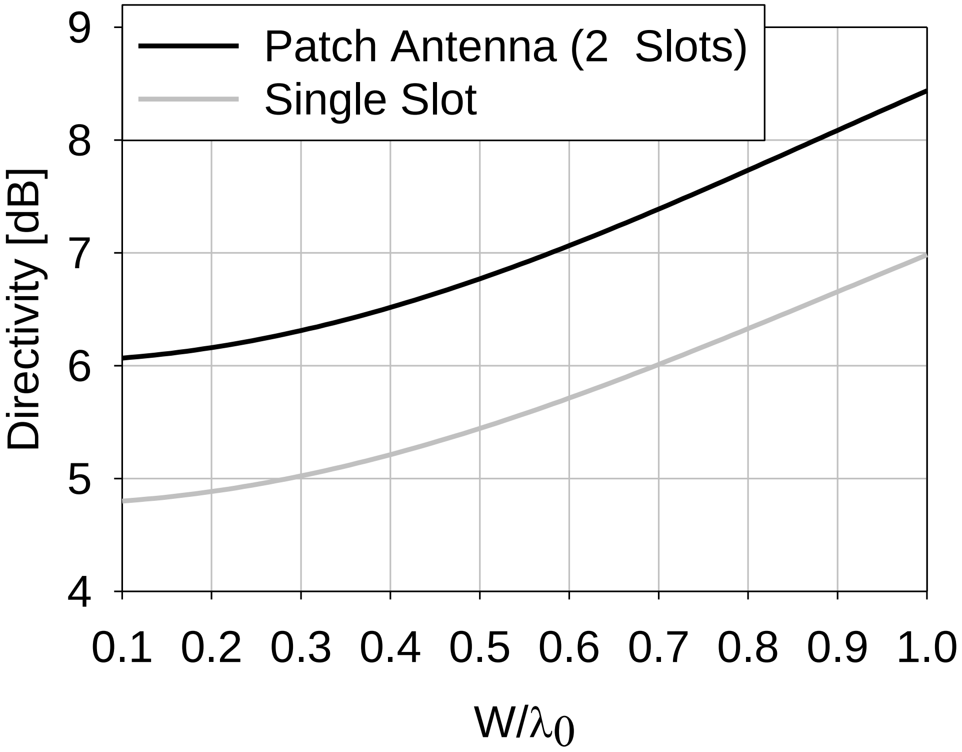
- The directivity of the patch antenna is:

$$D_2 = \left(\frac{2\pi W}{\lambda_0}\right)^2 \frac{\pi}{I_2} = \frac{2}{15G_{rad}}\left(\frac{W}{\lambda_0}\right)^2$$

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

Directivity

- Calculated directivity of the 2.4 GHz patch antenna example of slide 31-32 is plotted in the figure below.
- The antenna parameters:
  - L=33.5 mm
  - ΔL=0.72 mm
  - ε_r=3.4
  - h=1.5 mm
  - W=variable
- For W=42.1 mm
  - D ≈ 6.4 dB
- For W=$0.1\lambda_0$
  - D ≈ 6.0 dB



POSTECH

Bandwidth and Efficiency

- Main mechanisms of radiation in microstrip antennas are:
  - Magnetic currents in the periphery of the patch.
  - Surface waves induced in the dielectric slab as they reach the edges of the substrate.
- TM_0 mode is the lowest surface mode and has no cut off frequency (cut off frequency is the frequency below which a wave cannot propagate in the wave guiding medium).
- The TM_0 mode can easily be excited by the fringing fields from the patch to the ground plane.
- The energy coupled to surface waves increase as h and ε_r increase.
- Surface waves can be controlled by using Photonic Band Gap materials or reducing the substrate area.

Bandwidth and Efficiency

- If no dielectric substrate is present or substrate with very low ε_r are used (such as foam), surface waves can drastically be reduced or eliminated all together.
- Surface waves decay as $1/r^{1/2}$ in the direction of propagation and exponentially in the direction normal to the surface.
- The ratio of space wave radiation to surface wave radiation can be found for an infinitesimal Hertzian dipole mounted on the substrate of the patch antenna.
- The current distribution of the patch antenna can then be approximated as an integral of Hertzian dipoles and the results obtained for the Hertzian dipole, expanded to the patch antenna.

Bandwidth and Efficiency

- Surface wave efficiency of the patch antenna (or an infinitesimal Hertzian dipole) is defined as the ratio of radiated power coupled to the space waves to that of the total power (sum of space and surface waves).

$$\eta_{SW} = \frac{4C}{4C + 3\pi k_0 h \mu_r (1 - 1/n^2)^3}$$

$$C = 1 - \frac{1}{n^2} + \frac{0.4}{n^4}$$

$$n = \sqrt{\mu_r \varepsilon_r}$$

- The 2:1 VSWR of a rectangular patch is related to its Q:

$$Q = \omega_0 \frac{\text{Stored Energy}}{\text{Radiated Power}}$$

$$\text{BW}(\text{SWR} \le 2) = \frac{1}{\sqrt{2}Q}$$

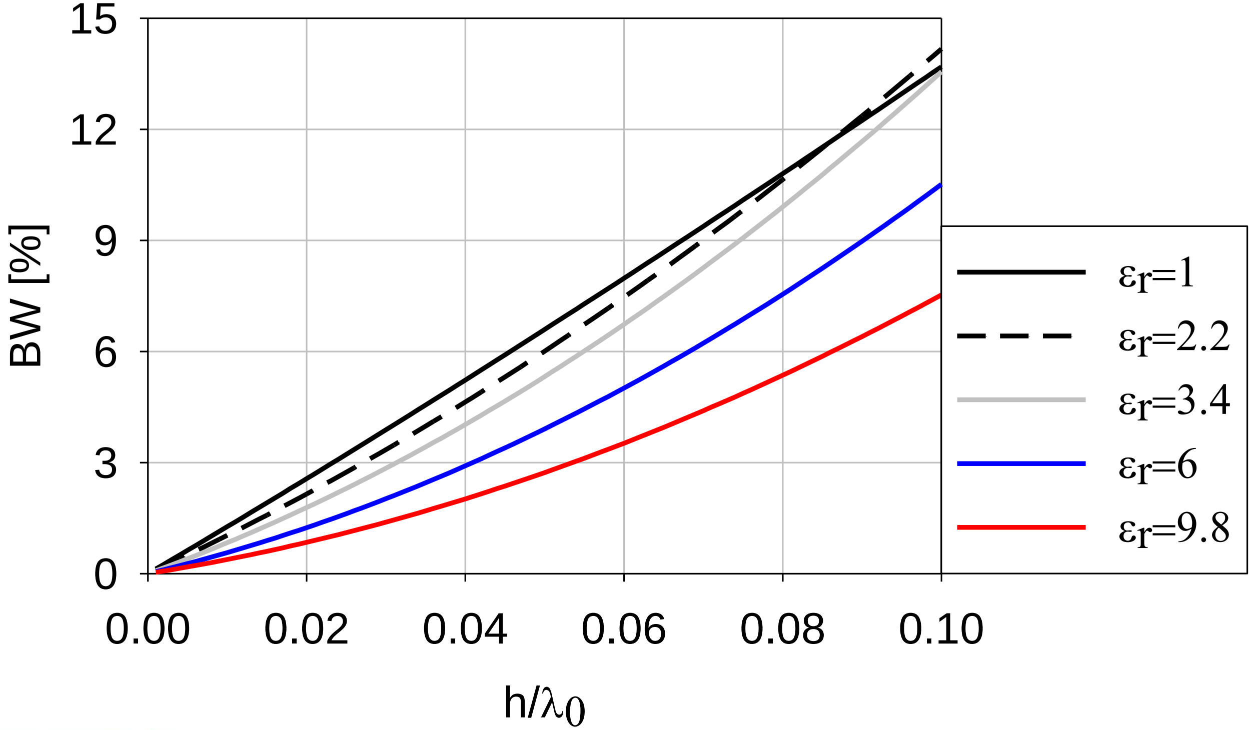
$$\text{BW} = \frac{16C\,p}{3\sqrt{2}\eta_{SW}} \frac{1}{\varepsilon_r} \frac{h}{\lambda_0} \frac{W}{L}$$

$$p = 1 - \frac{0.16605(k_0 W)^2}{20} + \frac{0.02283(k_0 W)^4}{560} - \frac{0.09142(k_0 L)^2}{10}$$

Formulas derived in: D. R. Jackson and N. G. Alexopoulos, "Simple approximate formulas for input resistance, bandwidth, and efficiency of a resonant rectangular patch", IEEE Trans. Antennas and Prop., Vol. 39, pp. 407 – 410, March 1991

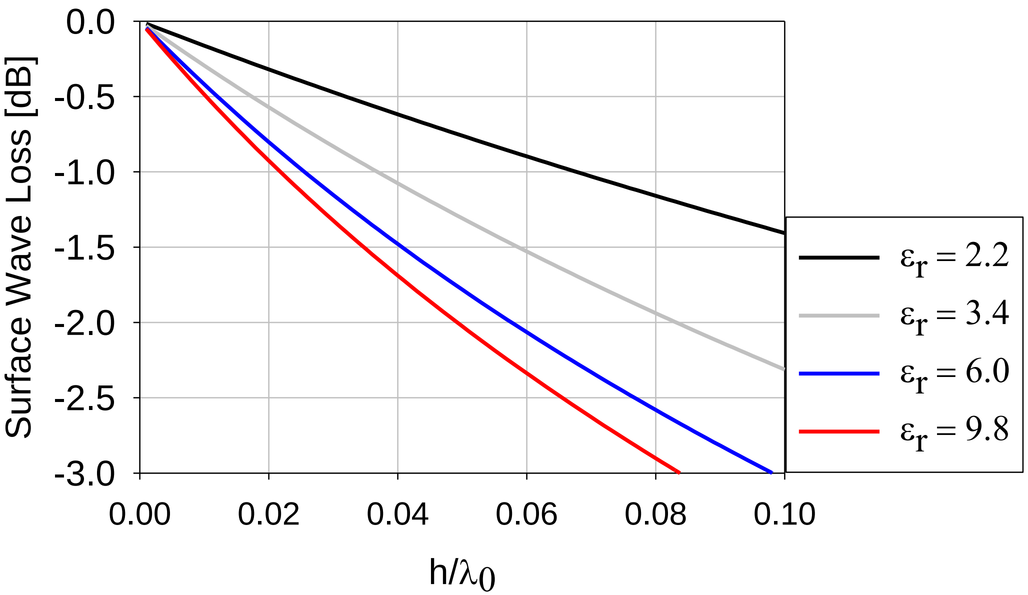
Bandwidth and Efficiency

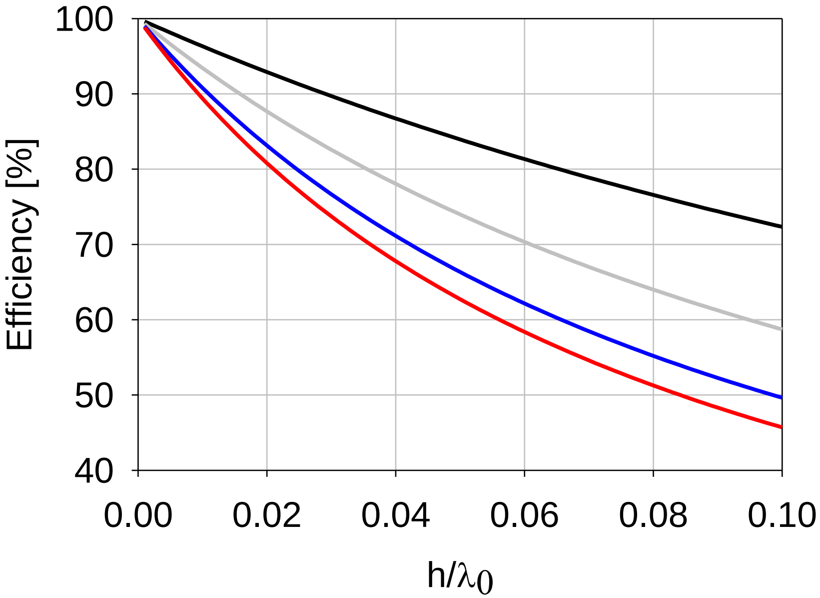
- Approximate BW of a patch antenna with W/L=1 on different substrates is shown in the figure below. In this figure, only the effect of surface waves and space-waves in calculation of Q is considered and dielectric and conductive losses are not.



Bandwidth and Efficiency

- Surface wave efficiency and surface wave loss as functions of the normalized height of the substrate and dielectric constant are plotted in figures below.
- As seen from these figures, as h or ε_r increase, the surface wave efficiency decreases and surface wave loss increases.





POSTECH

Bandwidth and Efficiency

- Bandwidth is related to Q and VSWR as follows:

$$\mathrm{BW} = \frac{\mathrm{VSWR} - 1}{Q\sqrt{\mathrm{VSWR}}}$$

- Q in this equation is a combination of space-wave radiation Q_R and surface-wave radiation Q_{SW}.
- Surface wave is not exactly loss but more like an uncontrolled radiation.
- Dielectric and conductor losses increase the bandwidth of the antenna but reduce its gain.
- Two additional Q values are defined and the total Q of antenna is modified as follows:

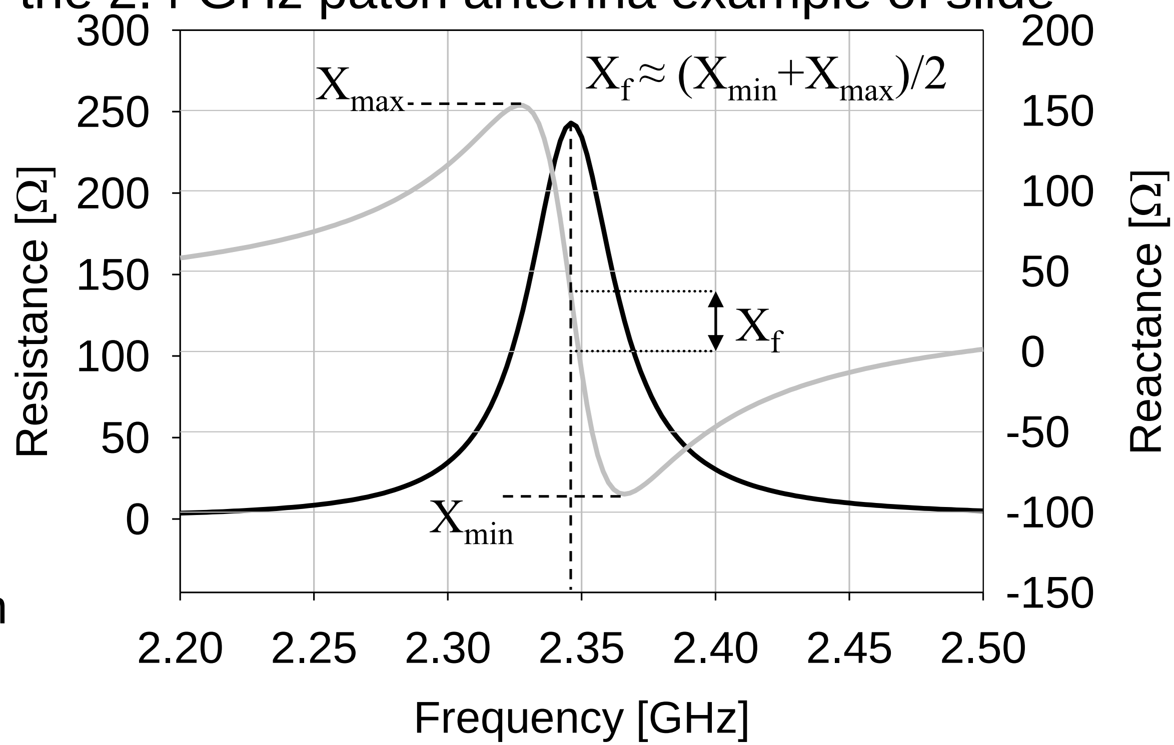
$$Q_d = \frac{1}{\tan\delta}, \quad Q_c = h\sqrt{\pi f \mu_0 \sigma} \qquad \frac{1}{Q_T} = \frac{1}{Q_R} + \frac{1}{Q_{SW}} + \frac{1}{Q_d} + \frac{1}{Q_C}$$

Summary

- Back to the example of slide 31:
- Using the formulas we have so far, let's calculate directivity, gain, efficiency, etc.
  - D=6.4 dB
  - BW=1.26% (Not considering losses)
  - BW=1.52% (tan δ=0.0027, f=2.4 GHz, σ=5.7e7)
  - η_{SW}=92.22%
  - Surface wave loss = 0.35 dB
  - Efficiency = 76.7% (Q_T/Q_{Rad})
  - Input Resistance R_{in}=416.6Ω
  - Input Reactance X_{in}=0 (resonance)

Input Impedance of the Patch Antenna

- For very thin substrates, the feed reactance is negligible at resonance.
- As the height of the substrate increases, the feed reactance becomes important and must be taken into account.
- The input impedance of the 2.4 GHz patch antenna example of slide 31 is shown.
- $Z_{in}=242+j35\ \Omega$
  - Compare with $R_{in}=416.7\ \Omega$ derived using transmission line technique.
  - The results obtained for a center feed location located at one of the radiating edges

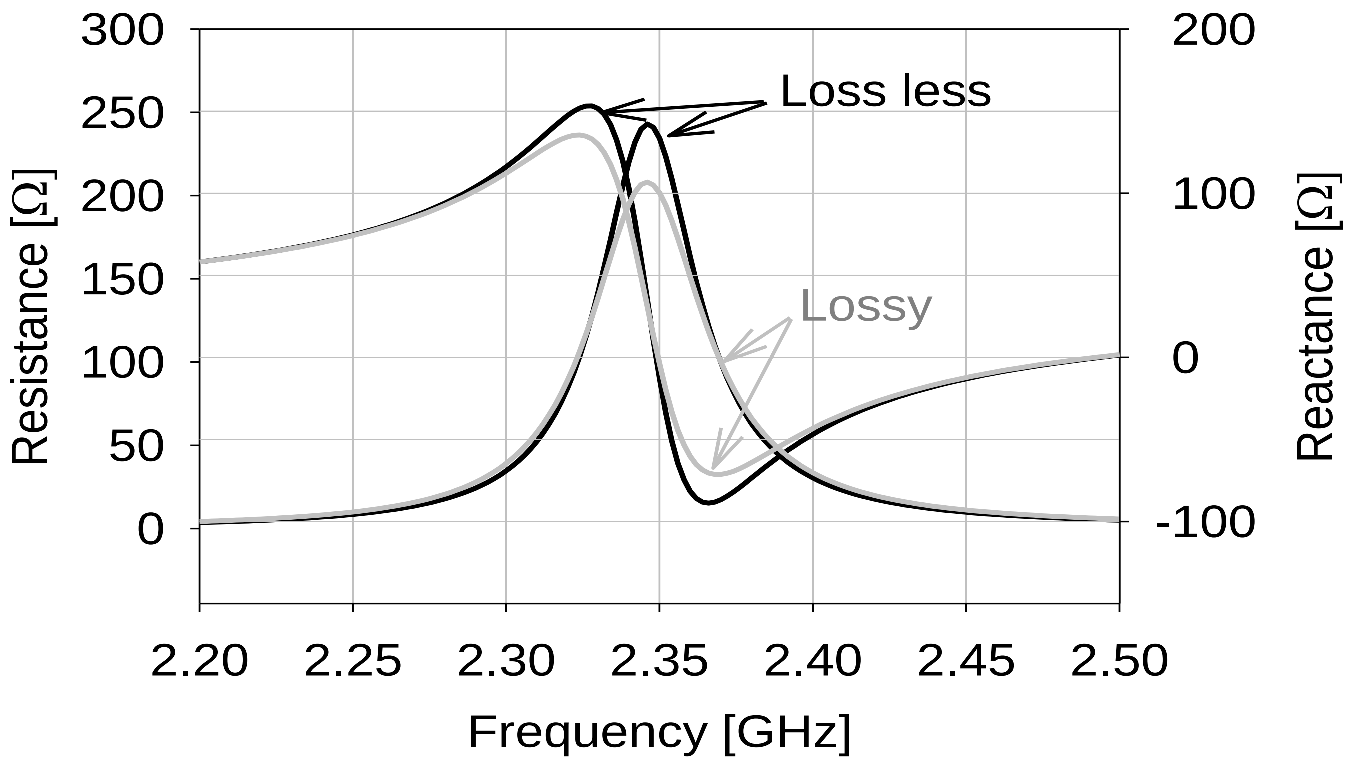


POSTECH

Comparison

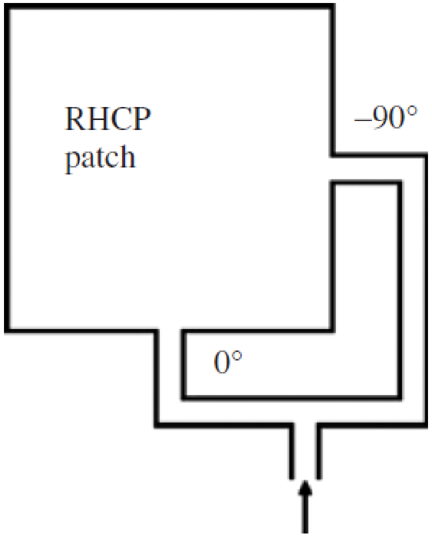
Parameter	Full Wave	Formulas
Directivity	6.88 dBi	6.38 dBi
BW		
Radiation Efficiency	74.8%	76.7%
Input Impedance	242+j35 Ω	417 Ω

Input Impedance of Patch Antennas



Circularly Polarized Patch

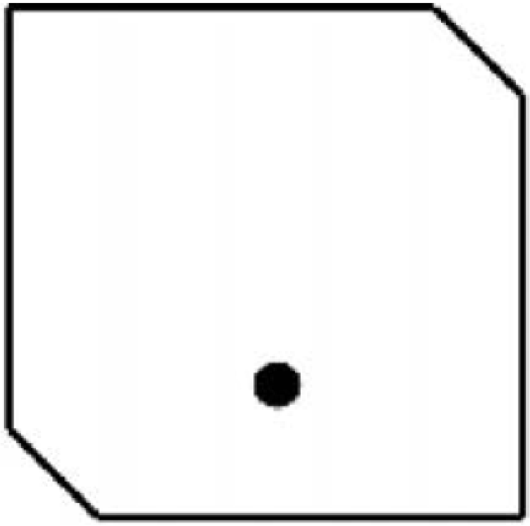
- Circularly polarized patch with two orthogonal feeds.
- Each feed excites a given mode of the antenna.
- The patch is square shaped so the two orthogonal modes will have the same frequency.
- Phase shift can be introduced by using a λ/4 microstrip line.



From Modern Antenna Handbook by Balanis, C. A., © 2008 John Wiley and Sons. This slide include copyrighted materials. Please do not copy or distribute.

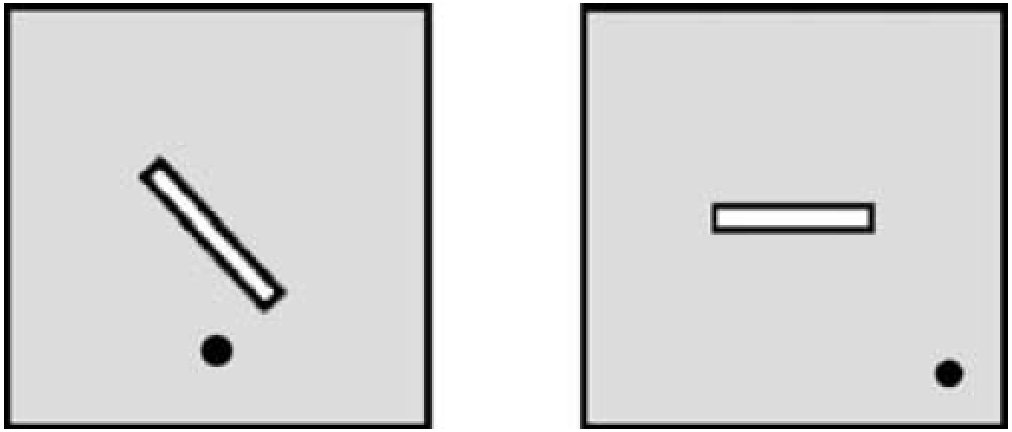
Circularly Polarized Patch Antennas

- Circularly polarized patch antenna with a single feed and truncated corners.
- The goal is to excite both degenerate modes and create a 90° difference of phase between them.
- The truncated corners introduce an asymmetry in the structure.
- This excites the orthogonal mode and by choosing the dimension of the truncation appropriately, it also creates the phase difference.



From Modern Antenna Handbook by Balanis, C. A., © 2008 John Wiley and Sons. This slide include copyrighted materials. Please do not copy or distribute.

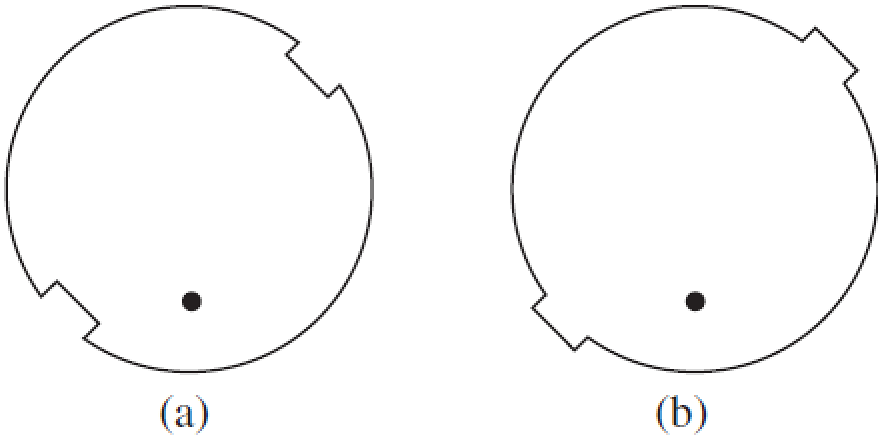
Circularly Polarized Patch Antennas



- Circularly polarized patch with a single feed and a slot.
- Principe of operation is identical to the previous one:
  - Square patch → Two degenerate modes.
  - Excite both of them (using some sort of asymmetry).
  - Create a phase shift of 90° (again using some sort of asymmetry).

From Modern Antenna Handbook by Balanis, C. A., © 2008 John Wiley and Sons. This slide include copyrighted materials. Please do not copy or distribute.

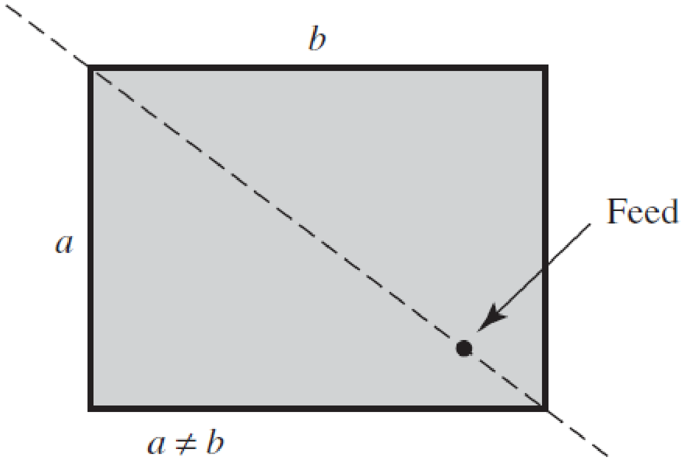
Circularly Polarized Patch Antennas



- Circularly polarized circular patch with a single feed and (a) two indents and (b) two pads.

From Modern Antenna Handbook by Balanis, C. A., © 2008 John Wiley and Sons. This slide include copyrighted materials. Please do not copy or distribute.

Circularly Polarized Patch Antennas



- Circularly polarized patch (slightly rectangular) with a single feed.
- The side lengths are very close. So, we have two very closely-spaced frequencies.
- At the frequency between the resonant frequencies of the two degenerate modes, a phase shift of 90° can be created between them.

From Modern Antenna Handbook by Balanis, C. A., © 2008 John Wiley and Sons. This slide include copyrighted materials. Please do not copy or distribute.

POSTECH

Circularly Polarized Patch Antennas

- Circularly polarized patch antennas that employ a single feed are generally very narrow-band.
- While they may have a few percentage of impedance bandwidths, their axial ratio bandwidths are generally much narrower (less than 1%).