Spring 2019

EECE 588
Lecture 22

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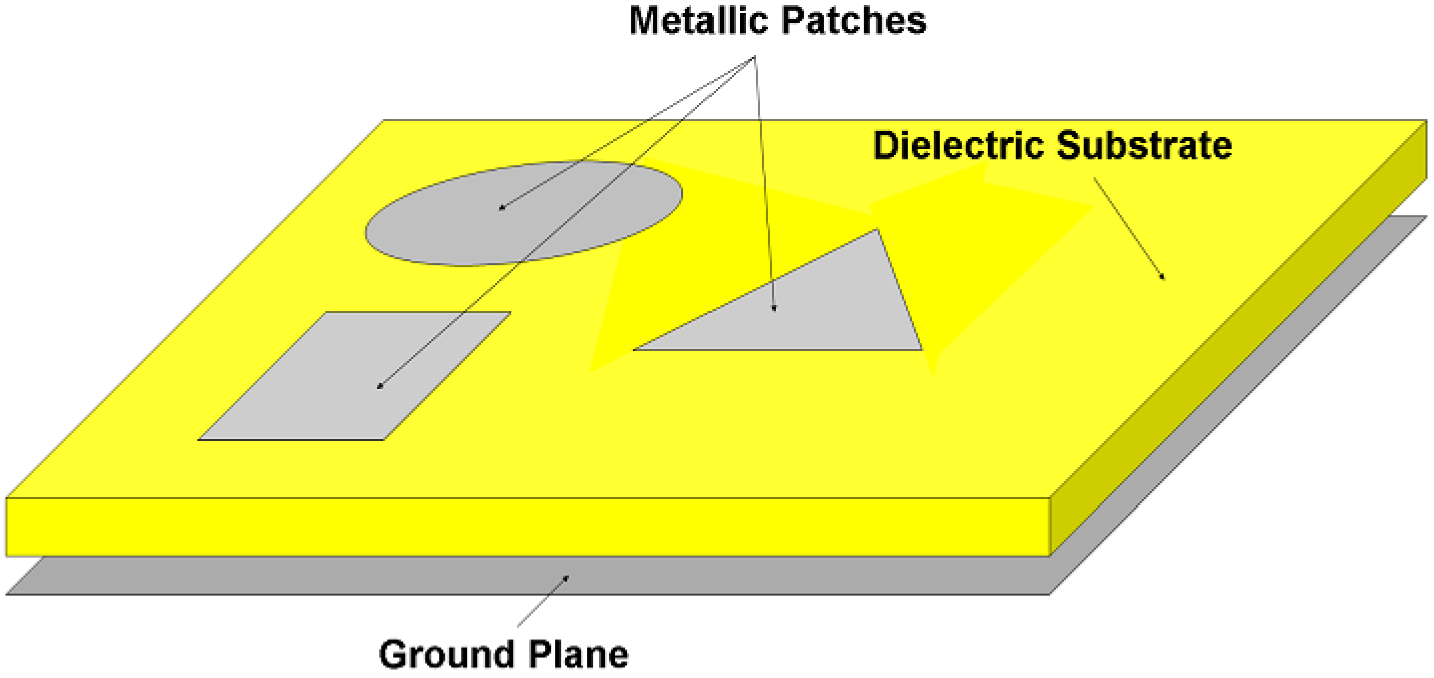
What is a Patch Antenna

- Patch antennas consist of metallic patches (of different shapes and sizes) printed on one side of a dielectric substrate, while the other side of the substrate is entirely covered with ground plane.

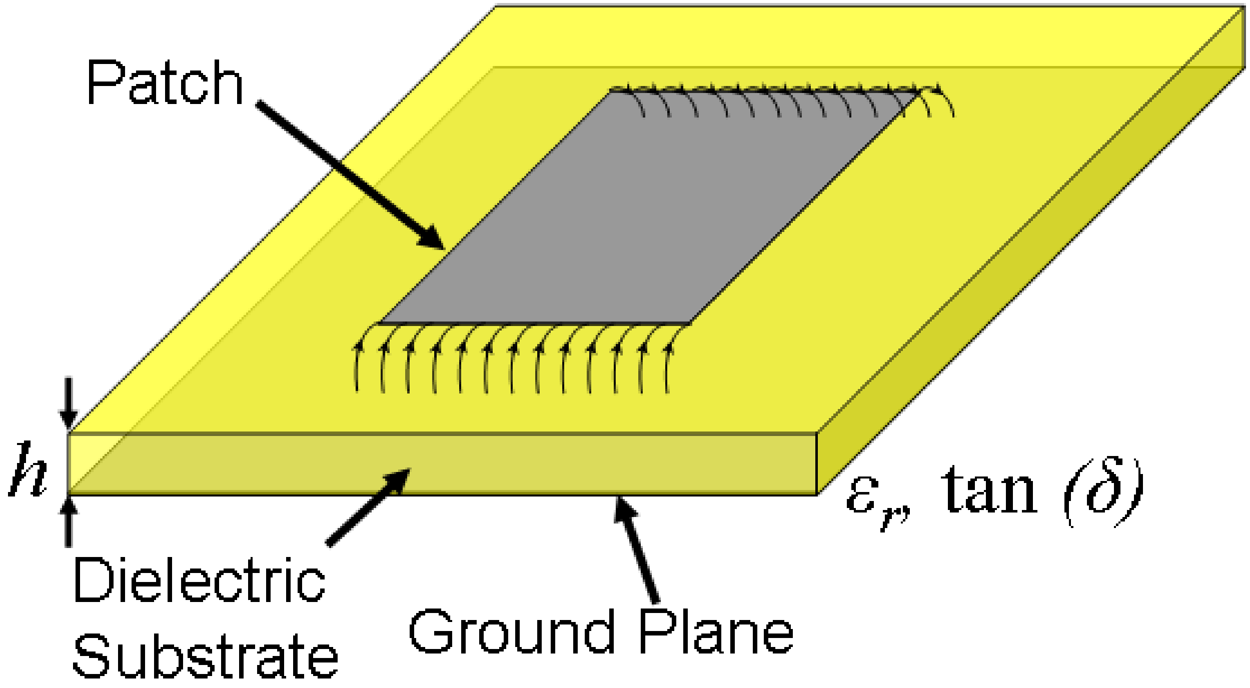


Advantages and Disadvantages of Microstrip Antennas

- Advantages of microstrip antennas include:
  - Low Profile low cost, and easy to manufacture and design.
  - Conformable to planar and non-planar surfaces.
  - Relative ease of integration with active and passive components.
  - Can provide a wide range of antenna responses in terms of radiation pattern, gain, polarization, etc.
- Disadvantages of microstrip antennas:
  - Low efficiency and low power handling.
  - Small fractional bandwidth (at most a few percent).
  - High Q.
  - Poor polarization purity.
  - Poor scan performance.
  - Spurious feed radiation.

Rectangular Patch Antenna

- Here is the topology of a simple rectangular patch antenna.
- The antenna consists of a metallic patch on a dielectric substrate, the other side of which is entirely covered with metal.



Rectangular Patch Antenna

- **The simplest patch antenna consists of a rectangular metallic patch on one side of a dielectric substrate and a ground plane on the other side of the dielectric substrate.**
- **The following parameters determine the response of the rectangular patch:**
  - **The length and width of the patch ($L \times W$).**
  - **Thickness of the dielectric substrate (h).**
  - **Dielectric constant and the loss tangent of the dielectric substrate (ε_r, $\tan(\delta)$).**
  - **Conductivity of the metallic layers constituting the patch.**

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Rectangular Patch Antenna

- The thickness of the metals of the patch and ground plane, t, is very small compared to the wavelength ($t \ll \lambda$).
- However, the metal thickness, t, must be at least a few times larger than the skin depth.
- If the metal thickness is smaller than skin depth, Ohmic losses in the patch and the ground plane drastically reduce the radiation efficiency of the antenna.
- Substrate thickness, h, and its dielectric constant, ε_r, play important roles in the radiation parameters the antenna.
- Substrate thicknesses are usually in the range of $0.002\lambda_0 < h < 0.1\lambda_0$, where λ_0 is the wavelength in free space.
- Substrate dielectric constants usually range from $2.2 < \varepsilon_r < 12$.
- Materials with dielectric constants lower than 2.2 and higher than 12 are also available but usually are not that common in commercial designs

Rectangular Patch Antenna

- Substrates with low dielectric constants and larger thickness, h, values are more desirable for patch antennas.
- Advantages of such substrates are as follows:
  - Larger bandwidth
  - Higher efficiency (loosely bounded waves can be radiated more easily)
  - Note: (h↑ ➔ BW↑) (ε_r↑ ➔ BW↓)
- Disadvantages of such substrates are as follows:
  - Larger element sizes.
  - Larger dimensions of microstrip lines and other microstrip circuits located on the same surface as the patch antenna.
  - For example, a 50Ω microstrip line on a substrate with dielectric constant of 3.4 and thickness of 0.5 mm has a width of 1.1 mm. The same line on the same substrate but with a substrate thickness of 3 mm has a width of about 6.3 mm.

Rectangular Patch Antenna

Disadvantages (Continued):

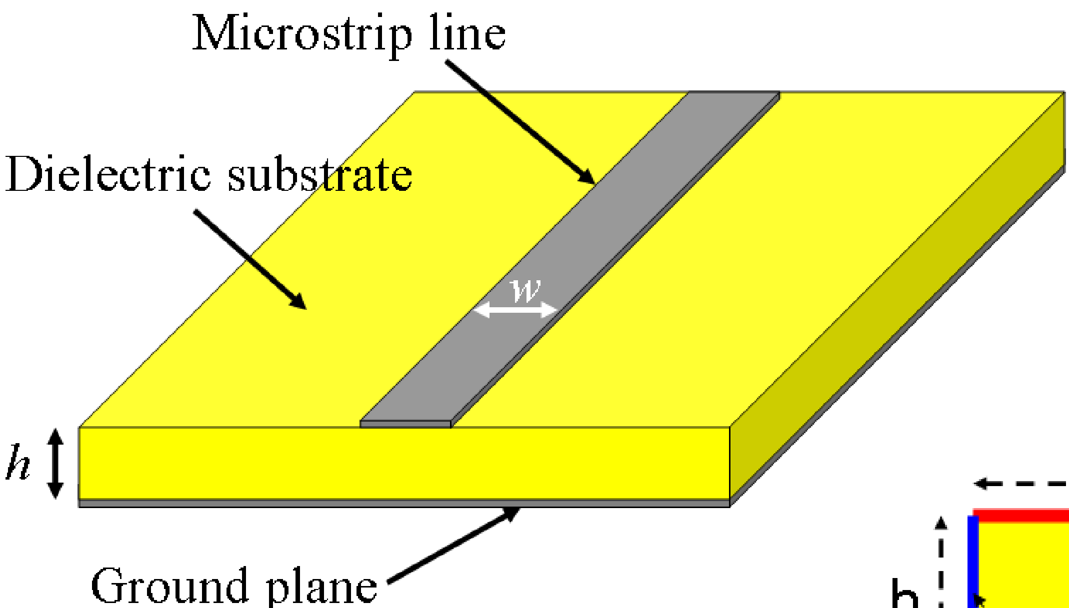
- As the substrate thickness increases and the dielectric constant decreases, the other microstrip circuitry located on the same layer (microstrip lines, microstrip filters, etc.) start to radiate. This reduces the radiation efficiency of the antenna and distorts its radiation pattern.

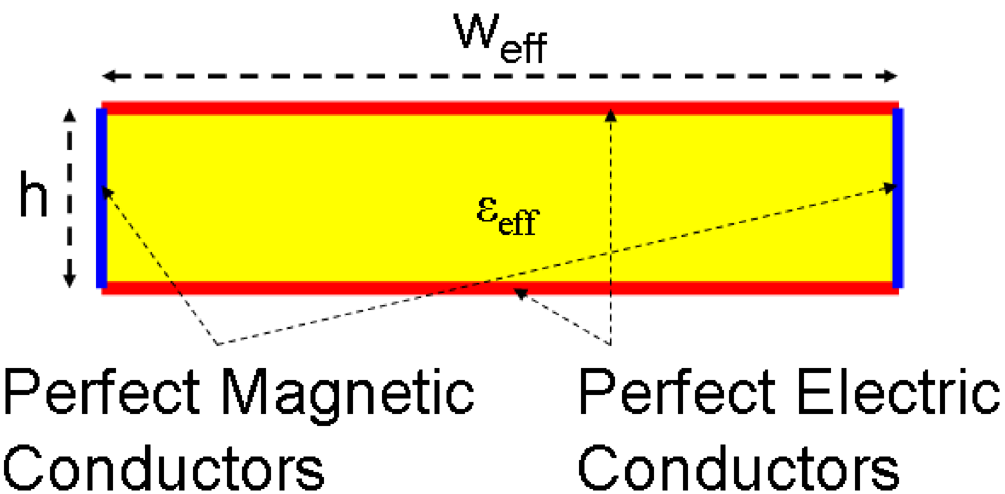
- Overall
  - In microstrip type microwave circuits, we prefer higher dielectric constants and smaller substrate thicknesses (tightly bound waves).
  - In microstrip antennas, we prefer lower dielectric constants and thick substrates.
  - Since most of the time we have both of these structures integrated with each other, we have to compromise.

Feeding Techniques: Microstrip-fed Patch Antennas

- Direct feeding using microstrip lines:
  - Easiest of all to fabricate and easy to match.
  - As substrate thickness increases, the spurious radiations increase. Therefore, for practical purposes, this limits the bandwidth of the antenna to 1%-5%.
  - If you don’t get the design right and fabricate the antenna, it is still possible to change tune the parameters of the antenna after it is fabricated

Microstrip Lines: Empirical Formulas





Microstrip Lines: Empirical Formulas

- Empirical formulas for calculating the impedance of a microstrip line
- More accurate formulas, obtained using conformal mapping, are also available.

$$F = 6 + (2\pi - 6)e^{\left(-\frac{4\pi^2}{3}\right)\left(\frac{h}{w}\right)^{3/4}}$$

$$w_{eff} = \frac{2\pi h}{\ln\left\{\frac{hF}{w} + \sqrt{1 + \left(\frac{2h}{w}\right)^2}\right\}}$$

$$Z = \frac{\eta}{\sqrt{\varepsilon_{eff}}}\frac{h}{w_{eff}}$$

$$\beta = \sqrt{\varepsilon_{eff}}\,k$$

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 10\frac{h}{w}\right]^{-1/2}$$

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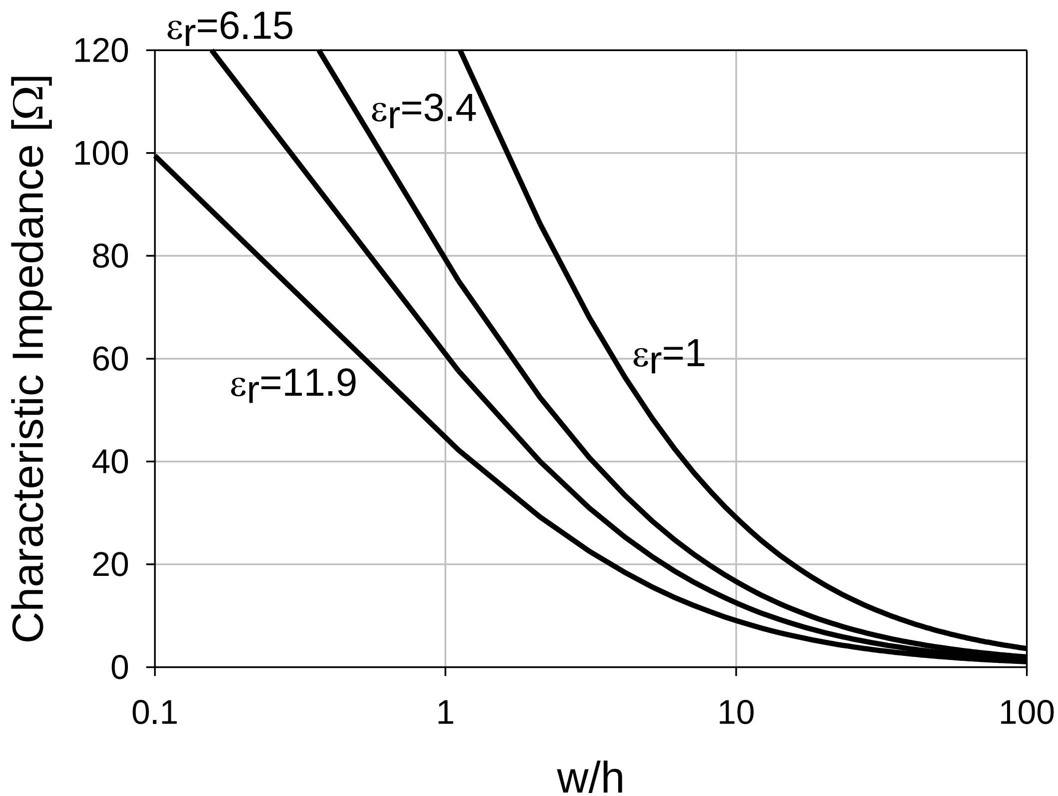
Characteristic Impedance of Microstrip Lines

Note the relationship between the phase velocity and capacitance per unit length of the microstrip line.

$$Z_C = \sqrt{\frac{L}{C}}$$

$$v_p = \frac{1}{\sqrt{LC}}$$

$$Z_C = \frac{1}{v_p C}$$



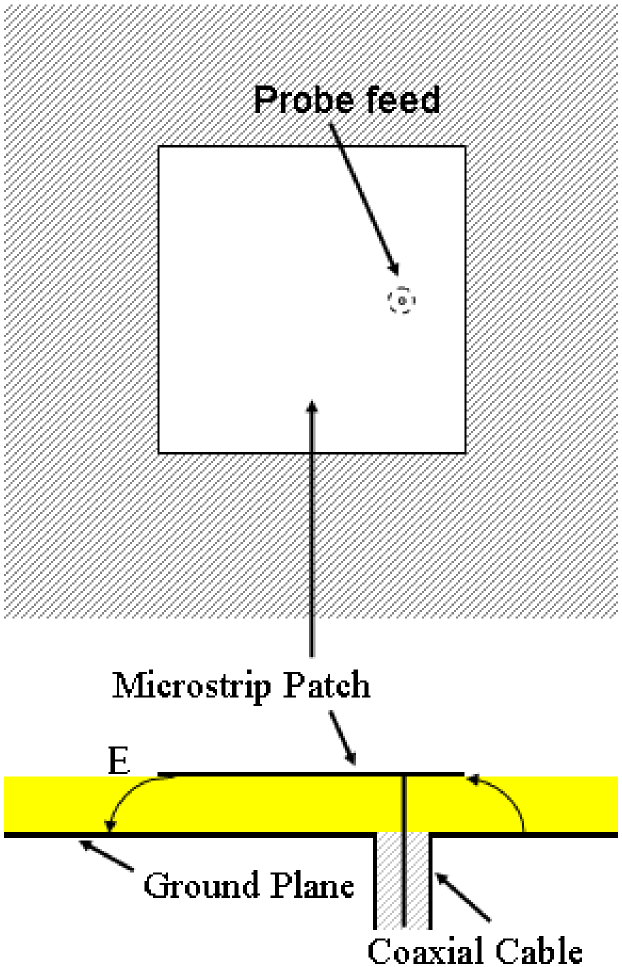
Characteristic impedances of microstrip lines as functions of w/h and ε_r

Probe-Fed Patch Antennas

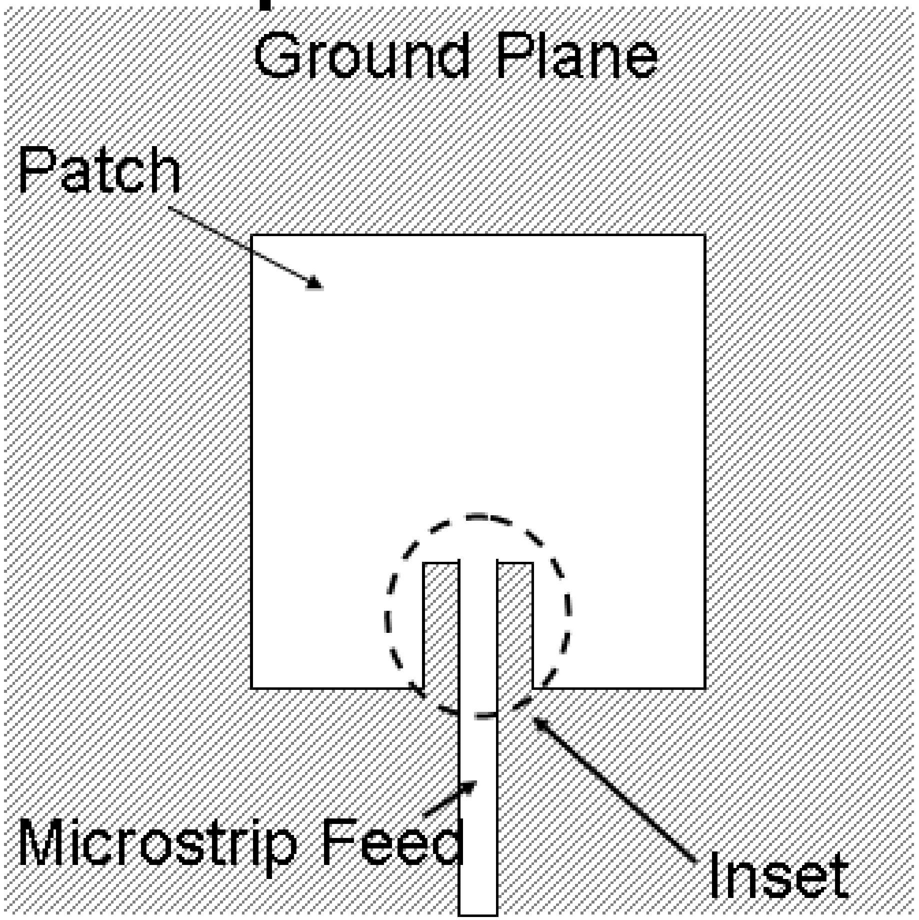
- Feeding using coaxial probes
  - Easy to fabricate (not as easy as the microstrip feed though) and relatively easy to match.
  - Low spurious radiations
  - Narrow bandwidth and not easy to model
  - If you don’t find the feed position correctly, corrections are not easy to make after the antenna is fabricated
  - The outer conductor of the coaxial cable is connected to the ground plane and the inner conductor of the coaxial cable should be connected to the patch at the appropriate location.

Probe- and Microstrip-Fed Patch Antennas

Probe-Fed Patch Antenna



Microstrip-Fed Patch Antenna

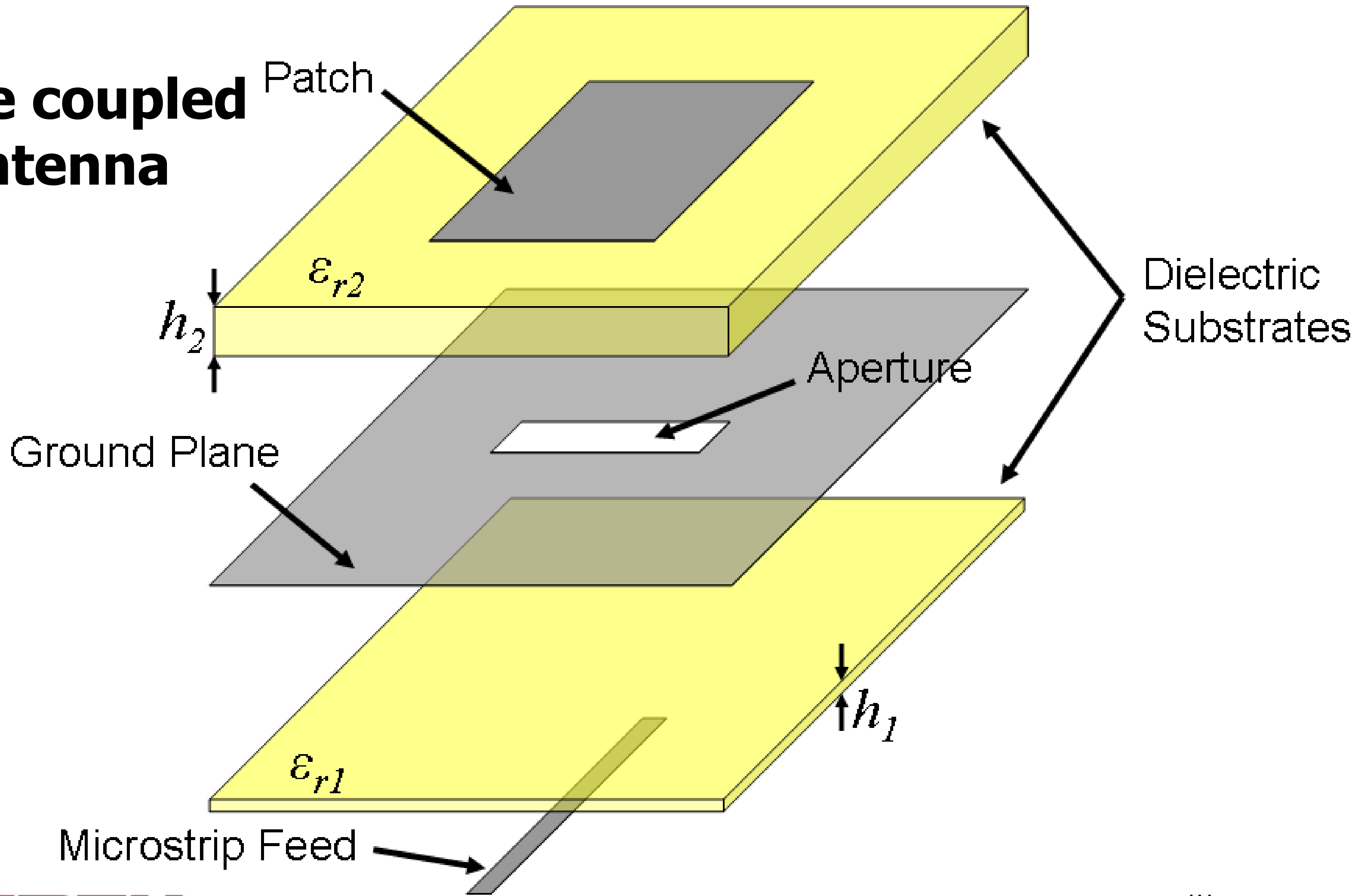


Aperture Coupled Patch Antennas

- Aperture coupled microstrip antennas:
  - The hardest of all to fabricate (etching 3 layers + aligning the layers).
  - Lower spurious radiation than direct feeding using microstrip lines.
  - The microstrip line and the patch antenna are separated by a ground plane and energy is coupled through an aperture in the ground plane.
  - The antenna substrate can be optimized independently from the microstrip line substrate.
  - Usually the bottom substrate is thin with high ε_r and the antenna substrate is thick with low ε_r.
  - <u>Warning: In designing aperture coupled patch antennas, make sure that the aperture (slot) is not resonant. Otherwise it can radiate and ruin everything!!!</u>

Aperture Coupled Patch Antennas

Aperture coupled patch antenna



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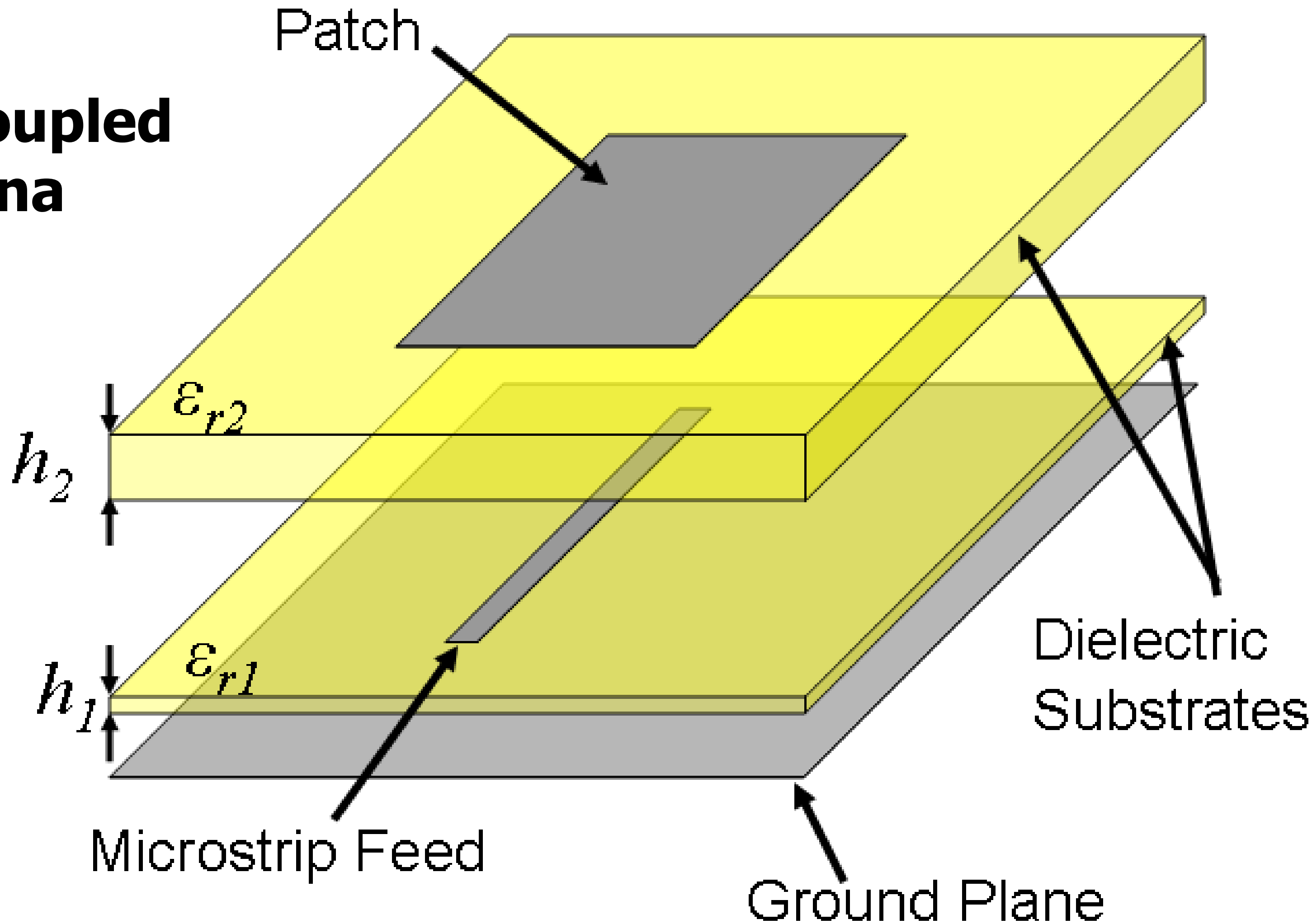
Proximity Coupled Patch Antennas

- Proximity Coupled Patch Antennas:
  - Difficult to fabricate
  - Wide bandwidth
  - Low spurious radiation
- Fabrication Difficulty:
  - Aperture Coupled > Proximity Coupled > Probe-Fed > Microstrip-Fed

Proximity Coupled Patch Antennas

Proximity coupled patch antenna



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Analysis Methods

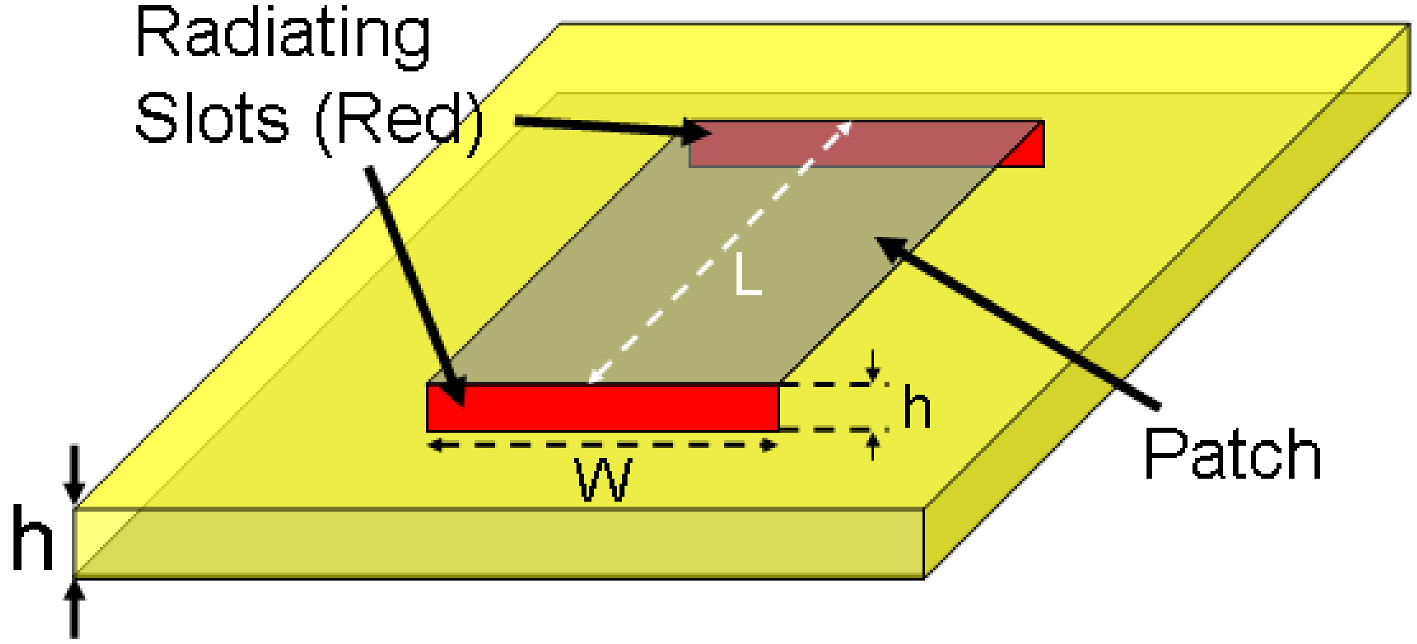
- There are numerous methods for analyzing microstrip antennas. Try IEEEXplore (ieeexplore.ieee.org).
- Most popular methods are as follows:
  - Transmission line method
  - Cavity method
  - Full-wave methods and numerical simulations:
    - Since closed form expressions for Green's functions of layered media exist, integral equations combined with Method of Moments (MoM) are a very popular way of accurately modeling microstrip antennas.
- Other Methods:
  - Numerical simulations using Finite Element Method (FEM), Finite Difference Time Domain (FDTD), Transmission Line Method (TLM), etc.

Analysis Methods

- Transmission Line Method:
  - Provides good physical insight.
  - Not very accurate.
  - Difficult to model coupling .
- Cavity Model:
  - Provides good physical insight.
  - More accurate than the TLM.
  - Difficult to model coupling.
  - More accurate than TLM.
- Full-Wave methods:
  - Very accurate, versatile, and very complex.
  - Can handle single element, multi elements, arrays, couplings, etc as long as you have the computing resources.
  - These methods are implemented in commercial software packages.

Transmission Line Method

- In this method, the microstrip antenna is modeled with two radiating slots (with a width of h and length of W) separated by a low impedance microstrip transmission line with a length of L and width of W (which is the patch itself) as shown in the figure below.



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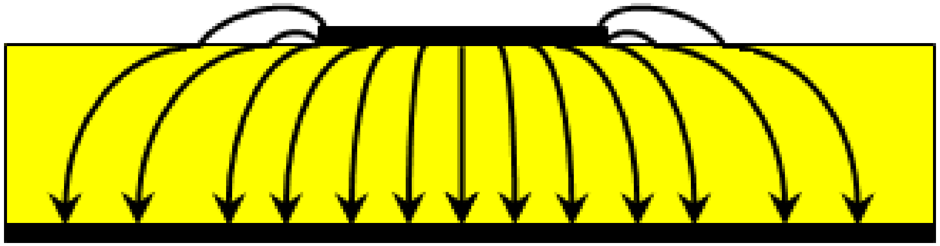
TLM: Fringing

- Since the dimensions of the patch antenna are finite, the fields at the edges of the patch antenna undergo fringing.
- The amount of fringing is a function of the dimensions of the patch, h, and ε_r.
- The electric field lines of a typical microstrip patch are shown in the figure below.
- Notice that there are two dielectrics present: the substrate and air.
- For W/h >> 1 and ε_r >> 1, most of the fields concentrate in the substrate



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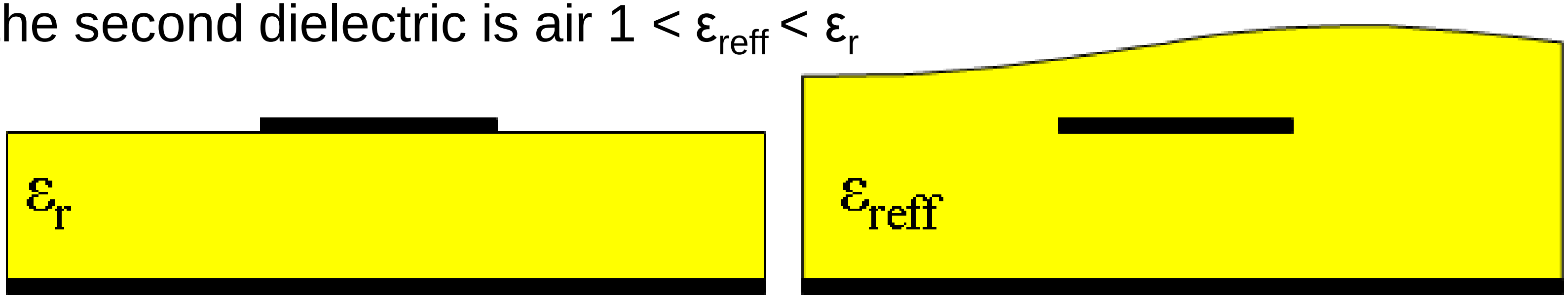
TLM: Effective Dielectric Constant

- As seen in the previous figure, field lines exist in both media.
- This means that the wave propagates both in air and in the dielectric medium.
- Now, assume the same microstrip line (without its dielectric) is immersed in a material with a dielectric constant of ε_{reff}. (See the figure below)
- Effective Dielectric Constant ε_{reff} is the dielectric constant of the new medium, if it is chosen such that the electrical parameters of both lines are identical (propagation constant, impedance, propagation velocity, etc.).
- If the second dielectric is air $1 < \varepsilon_{reff} < \varepsilon_r$



TLM: Effective Dielectric Constant

- Low frequency (quasi-static) approximation for ε_{reff}:

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 10\frac{h}{W}\right]^{-1/2}$$

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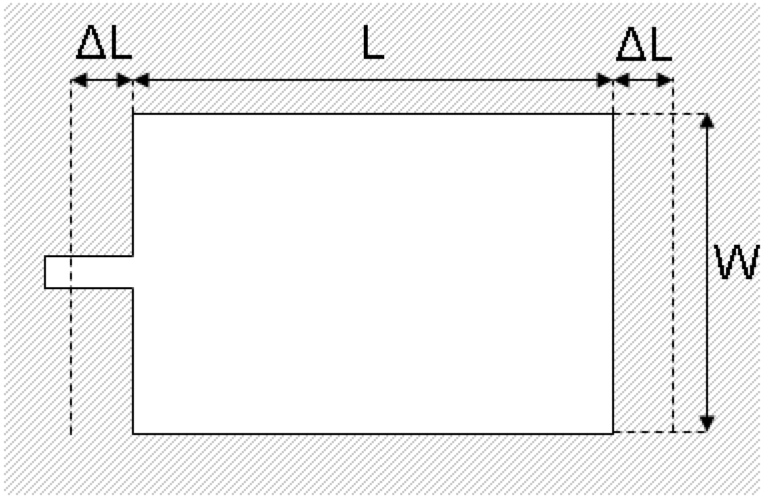
- This formula is a widely used approximation for the effective dielectric constant.

TLM: Effective Dielectric Constant

- Fringing affects the resonant length (effective length), effective width, and the resonant frequency of the antenna.

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



$$L_{eff} = L + 2\Delta L$$

First resonance (L > W) occurs when $L_{eff}=\lambda_g/2$

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Transmission Line Method

- Effective length of the patch is: $L_{eff} = L + 2\Delta L$
- Resonant frequency of the dominant mode (TM_{010}) of the patch antenna can be obtained using its effective length:

$$f_r = \frac{c}{2L_{eff}\sqrt{\varepsilon_{reff}}}$$

- Here, c is the speed of light: $c = 1/\sqrt{\mu_0 \varepsilon_0}$
- Note that this formula essentially states that the first resonance of the patch occurs when $L_{eff}=\lambda_g/2$, where λ_g is the (guided) effective wavelength.

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Designing Rectangular Patch Antennas

- The design procedure of rectangular patch antennas is very simple:
  - Usually, the substrate parameters and the operating frequency are known.
  - L, W, and type of the feed must be chosen.
- L can be chosen from the formula presented in the previous page.
- There is a lot of flexibility in choosing W. You can choose W as provided by this formula. However, this is not absolutely necessary.

$$W = \frac{c}{2 f_r} \sqrt{\frac{2}{\varepsilon_r + 1}}$$

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Designing Rectangular Patch Antennas

1. Large W values result in higher gains and directivity values. Smaller W values result in smaller gain and directivity.
2. If you choose a W > L, the first resonant frequency occurs when $W_{eff}=\lambda/2$, which happens at a lower frequency than $L_{eff}=\lambda/2$. That's not necessarily a bad thing but be aware of it.
3. Do not choose W very close to L because the resonant frequency associated with $W_{eff}=\lambda/2$ will be very close to the main (desired) resonant frequency.
4. In practice, asymmetries in the feed result in excitation of orthogonal modes and if W is close to L, you will have two resonant frequencies very close to one another. This, essentially, will be a useless dual-band antenna!!!
5. In patch antennas with circular polarization, we will use this as an advantage!!!

Rectangular Patch Antennas: Design Procedure

1. The first step is to choose the substrate. Doing this determines the following parameters:
   1. Dielectric constant (ε_r)
   2. Loss tangent tan δ
   3. The substrate thickness, h
   4. Metal thickness
2. The next step is to choose the width of the patch, W.
   1. You have quite a bit of flexibility in choosing W
   2. If W increases ➔ Directivity and Gain increase
   3. For linearly polarized patch antennas, it makes sense to choose 0.6 < W/L < 0.8 or 1.2 < W/L < 1.4 depending on the gain and directivity requirements.
3. The length of the patch, L, must then be determined. This can be done using the equations provided in previous slides.
   1. $L_{eff} = L + 2\Delta L$ ➔ $L = L_{eff} - 2\Delta L$

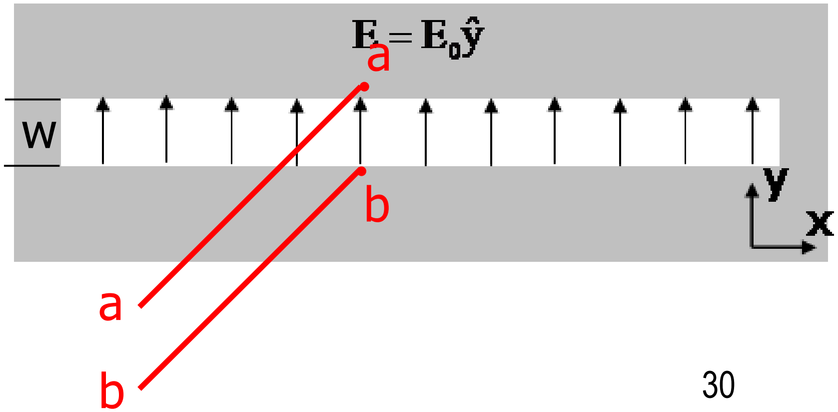
Aperture Admittance and Input Impedance of a Patch Antenna

- Aperture admittance is defined as:

$$Y_a = \frac{2P^*}{|V|^2}$$

- P*= conjugate of complex power transmitted by the aperture.
- V = Aperture reference voltage.

$$V_{ab} = -\int_b^a \vec{E} \cdot d\vec{\ell}$$



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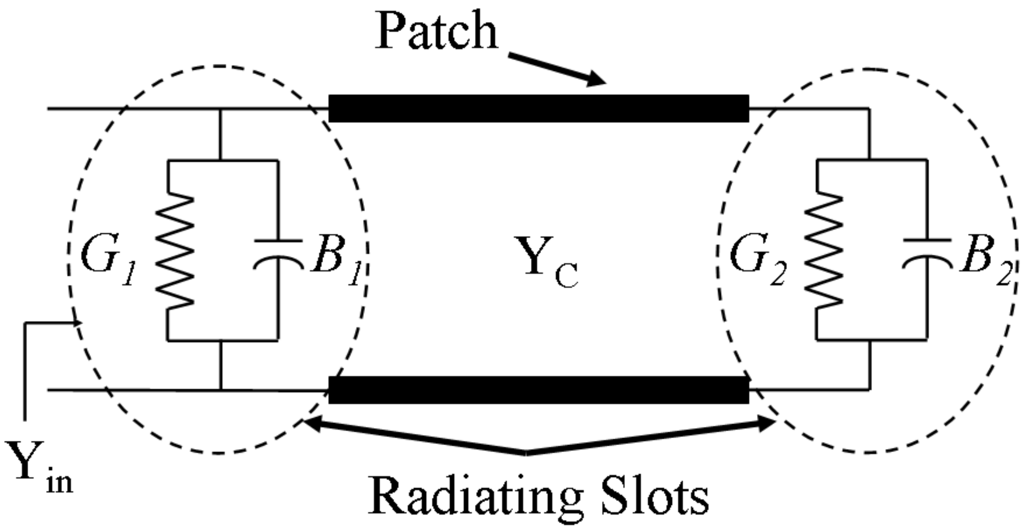
Conductance and Input Impedance of the Patch Antenna

- Each slot is modeled with a parallel conductance G and susceptance B.
- The equivalent admittances G and B can be obtained based on the admittance of an infinitely long uniform slot (for h < 0.1λ)
- $G_1=G_2$, $B_1=B_2$

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

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



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Conductance and Input Impedance of the Patch Antenna

- To calculate the input impedance (admittance), you can use impedance transformation formula of a transmission line:

$$Y_{in} = Y_C \frac{Y_L + jY_C \tan(\beta\ell)}{Y_0 + jY_C \tan(\beta\ell)}$$

- Admittance of Y_2 should first be transformed to the location of Y_1.
- Then the input admittance is simply the sum of Y_1 and Y_2.

$$Y_{in} = G_1 + jB_1 + Y_C \frac{G_2 + j(B_2 + Y_C \tan(\beta\ell))}{Y_C - B_2 \tan(\beta\ell) + jG_2 \tan(\beta\ell)}$$

Conductance and Input Impedance of the Patch Antenna

- Resonance is achieve when the imaginary part of Y_{in} goes to zero. This occurs when the line length is:

$$\tan(\beta\ell) = \frac{2Y_C B}{G^2 + B^2 - Y_C^2}$$

$$B_1 = B_2 = B,$$
$$G_1 = G_2 = G$$

- The input admittance at resonance is:

$$Y_{in} = 2G$$

- The value of G can be calculated using the following formula:

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Conductance of a Single Slot: Side Note

- The conductance of a single slot can also be obtained by calculating the total radiated power

$$G_1 = \frac{2P_{rad}}{|V_0|^2}$$

- The electric and magnetic field expressions are obtained using the cavity technique. The total radiated power is:

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

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Conductance of a Single Slot: Side Note

- The conductance of a single slot can also be obtained by calculating the total radiated power.
- The asymptotic values of the conductance calculated using this technique are given by:

$$G_1 = \begin{cases} \dfrac{1}{90}\left(\dfrac{W}{\lambda_0}\right)^2 & W << \lambda_0 \\ \dfrac{1}{120}\left(\dfrac{W}{\lambda_0}\right) & W >> \lambda_0 \end{cases}$$

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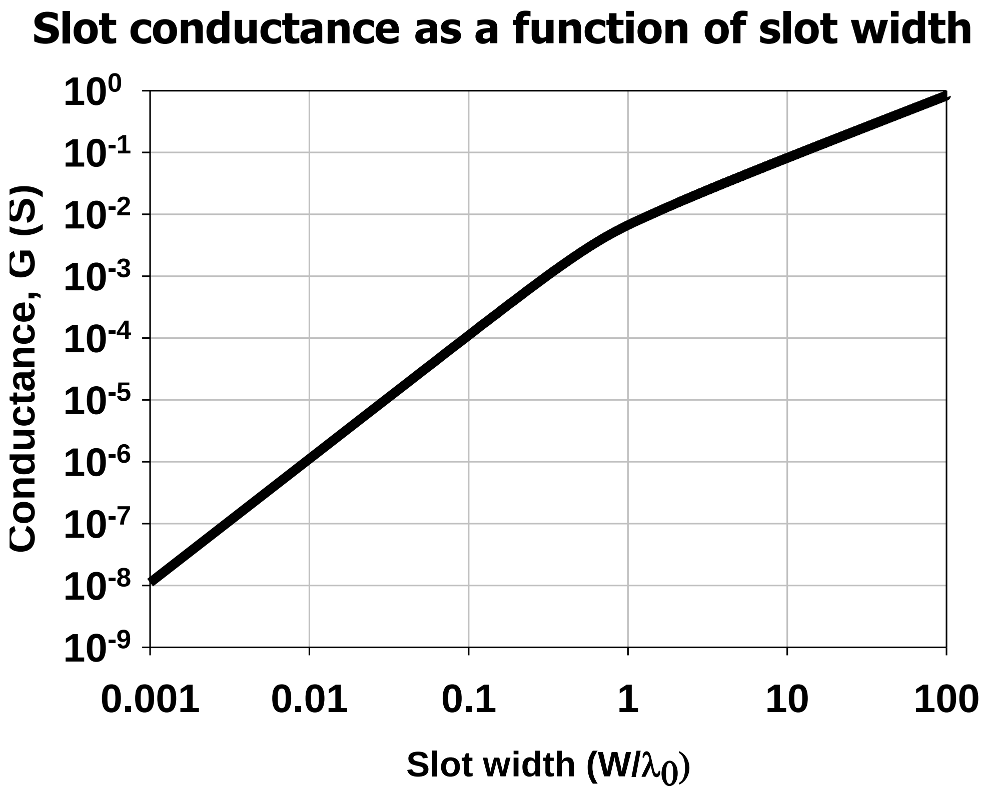
Conductance and Input Impedance of the Patch Antenna

- Input admittance can be calculated using the expressions provided in the previous slide.
- This is the input admittance as seen from the edge of the microstrip antenna (radiating slot 1)



- Using an inset feed, the input impedance can be changed to match it to that of the feeding line.

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Input Impedance of the Rectangular Patch Antenna

- The input impedance of the patch antenna is obtained as:

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

- This formula does not take into account the effect of mutual coupling between the two slots. A more accurate formula is:

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

- + sign for the ODD modes (anti-symmetric resonant voltage distribution beneath the patch between the two slots) and – sign for the EVEN mode.

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Input Impedance of the Rectangular Patch Antenna

- The mutual conductance is defined in terms of the far zone fields as:

$$G_{12} = \frac{1}{|V_0|^2} \mathrm{Re} \iint_S \vec{E}_1 \times \vec{H}_2^{\,*} \cdot d\vec{S}$$

- E_1 is the electric field radiated by Slot #1 and H_2 is the magnetic field radiated by Slot #2, V_0 is the voltage across the slot and S is a sphere of large radius.

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

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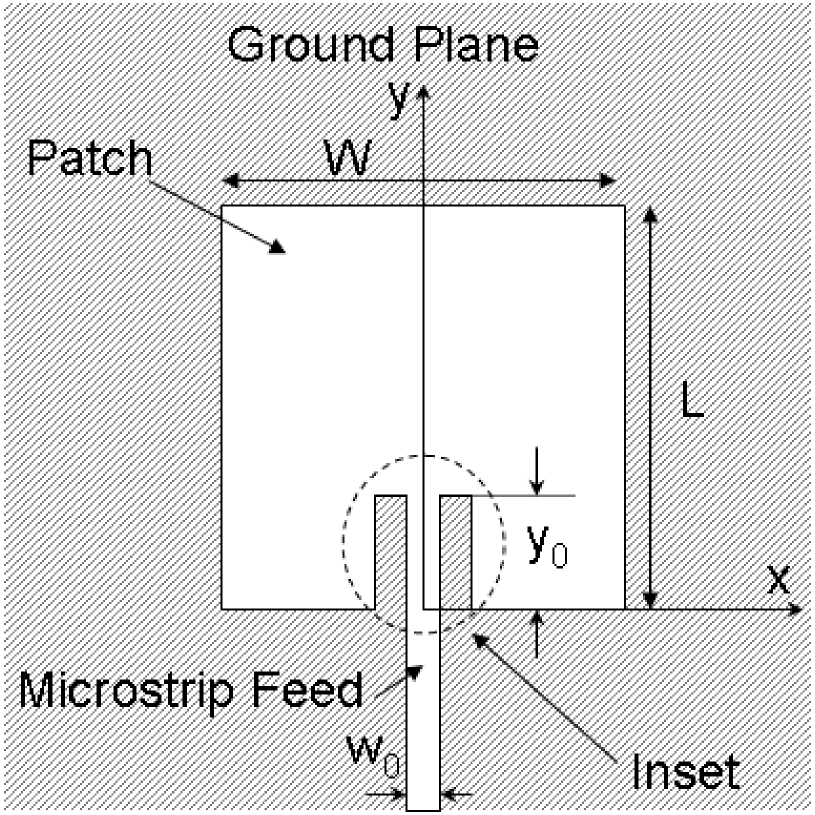
Input Impedance of the Rectangular Patch Antenna

- The input resistance of the microstrip line can be changed by using an inset microstrip-line feed as shown in the Figure.
- The input resistance of the patch antenna is approimately:

$$R_{in}(y = y_0) =$$

$$\frac{1}{2(G_1 \pm G_{12})} \cos^2\left(\frac{\pi}{L} y_0\right)$$

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



A microstrip-fed patch antenna can be matched using an inset feed.

Input Impedance of the Rectangular Patch Antenna

- The normalized input resistance of the patch antenna is shown in this figure.
- The inset feed introduces a capacitance at the feed location, which shifts the resonant frequency of the antenna.
- Normally, this frequency shift is about 1%.

Variation of the normalized input resistance of the patch antenna as a function of the feed location