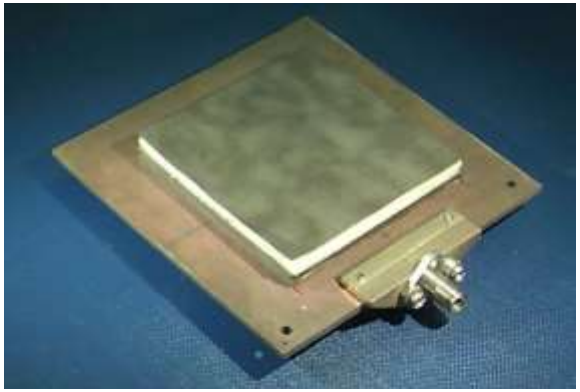
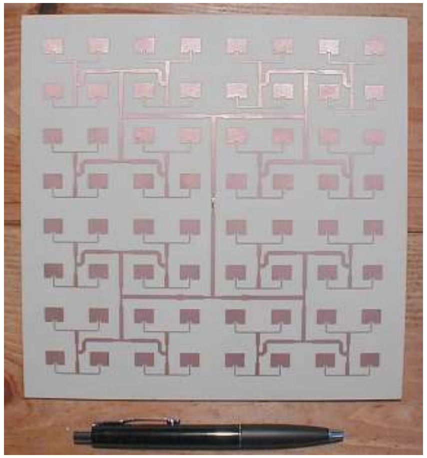
A Presentation on Bandwidth Improvement and miniaturization of Microstrip Antennas





Outline

- Overview of microstrip antennas
- Feeding methods
- Basic principles of operation
- General characteristics
- Improving bandwidth
- Miniaturization
- References

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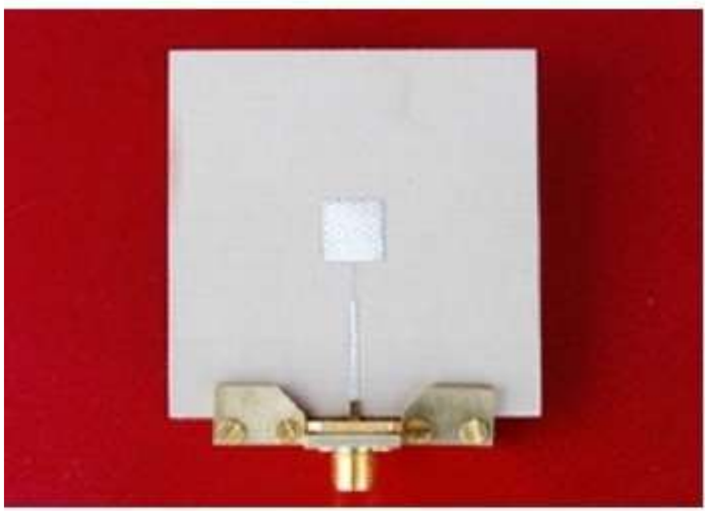
- Overview of microstrip antennas
- Feeding methods
- Basic principles of operation
- General characteristics
- CAD Formulas
- Radiation pattern
- Input Impedance
- Circular polarization
- Circular patch
- Improving bandwidth
- Miniaturization
- Reducing surface waves and lateral radiation

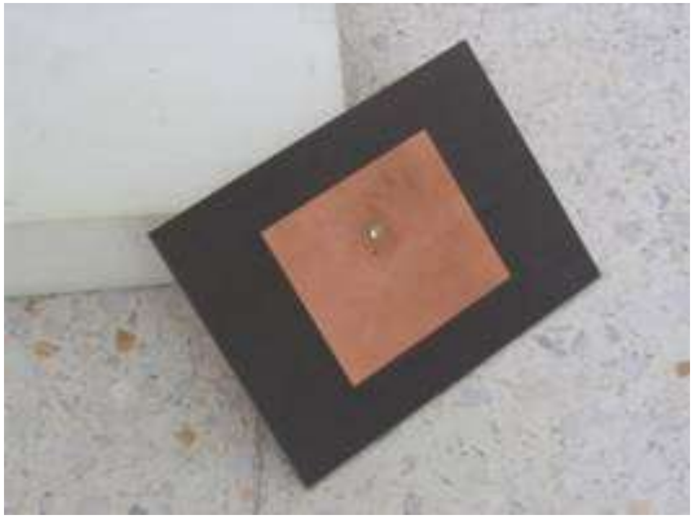
Overview of Microstrip Antennas

Also called "patch antennas"

- One of the most useful antennas at microwave frequencies ($f > 1$ GHz).
- It usually consists of a metal "patch" on top of a grounded dielectric substrate.
- The patch may be in a variety of shapes, but rectangular and circular are the most common.



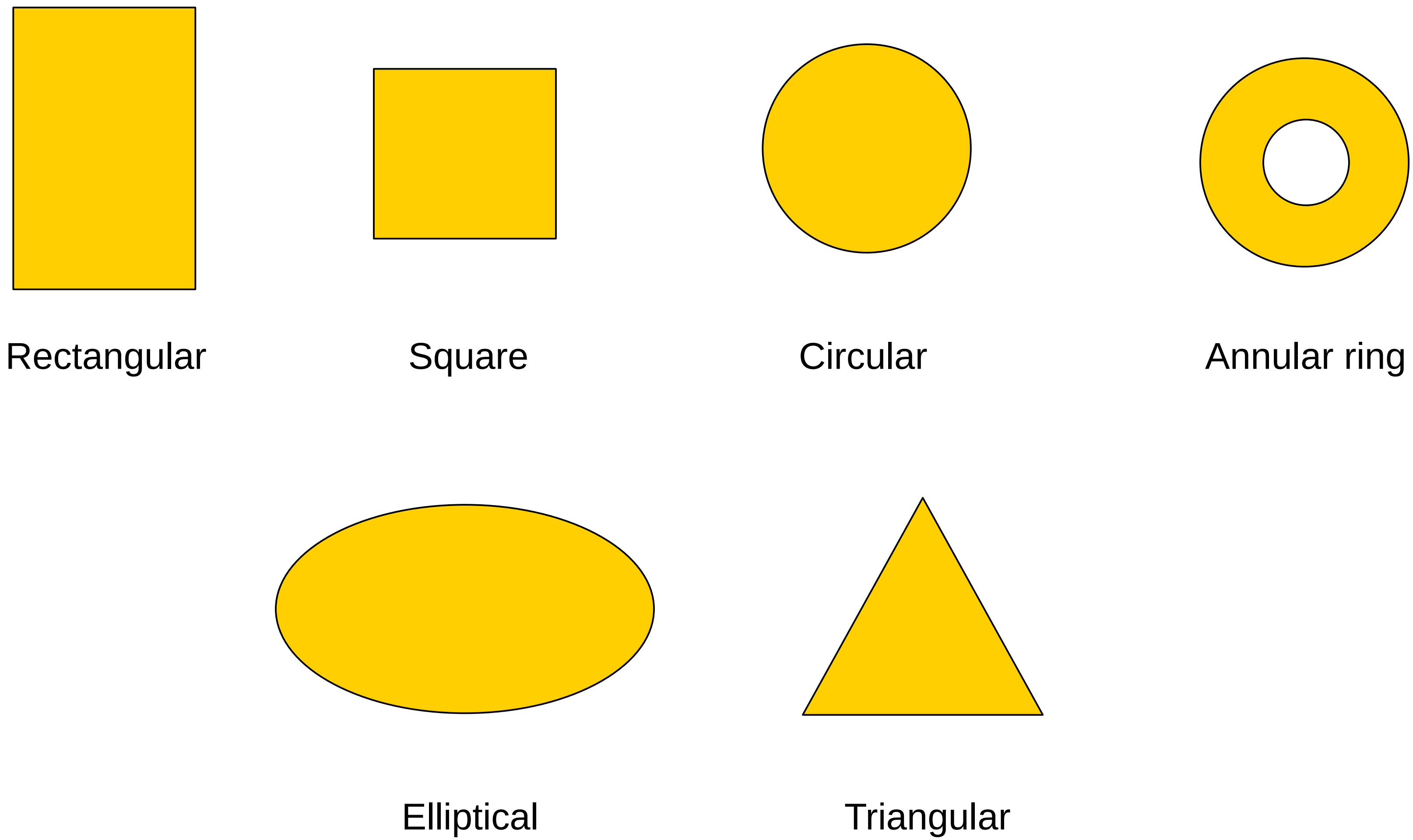
Microstrip line feed



Coax feed

Overview of Microstrip Antennas

Common Shapes



Overview of Microstrip Antennas

History

- Invented by Bob Munson in 1972 (but earlier work by Dechamps goes back to1953).
- Became popular starting in the 1970s.

Overview of Microstrip Antennas

Advantages of Microstrip Antennas

- Low profile (can even be "conformal," i.e. flexible to conform to a surface).
- Easy to fabricate (use etching and photolithography).
- Easy to feed (coaxial cable, microstrip line, etc.).
- Easy to use in an array or incorporate with other microstrip circuit elements.
- Patterns are somewhat hemispherical, with a moderate directivity (about 6-8 dB is typical).

Overview of Microstrip Antennas

Disadvantages of Microstrip Antennas

- Low bandwidth (but can be improved by a variety of techniques). Bandwidths of a few percent are typical. Bandwidth is roughly proportional to the substrate thickness and inversely proportional to the substrate permittivity.

- Efficiency may be lower than with other antennas. Efficiency is limited by conductor and dielectric losses*, and by surface-wave loss**.

- Only used at microwave frequencies and above (the substrate becomes too large at lower frequencies).

- Cannot handle extremely large amounts of power (dielectric breakdown).

* Conductor and dielectric losses become more severe for thinner substrates.

** Surface-wave losses become more severe for thicker substrates (unless air or foam is used).

Overview of Microstrip Antennas

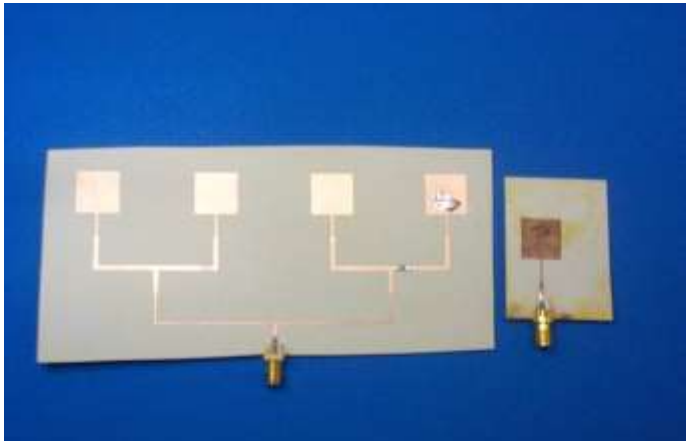
Applications

Applications include:

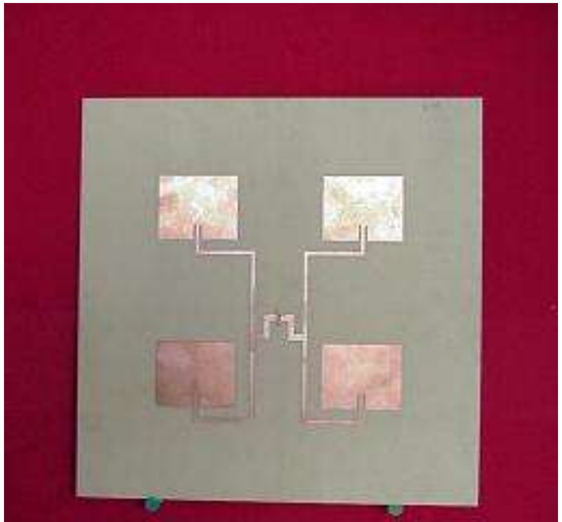
- Satellite communications
- Microwave communications
- Cell phone antennas
- GPS antennas

Overview of Microstrip Antennas

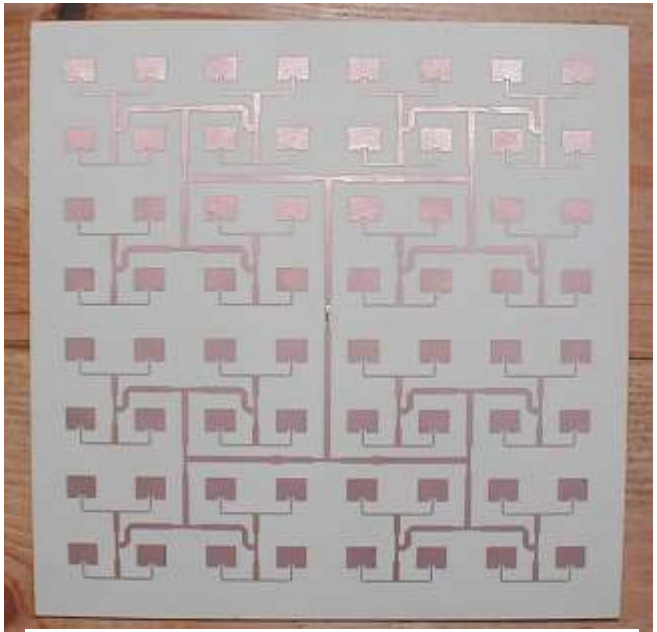
Arrays



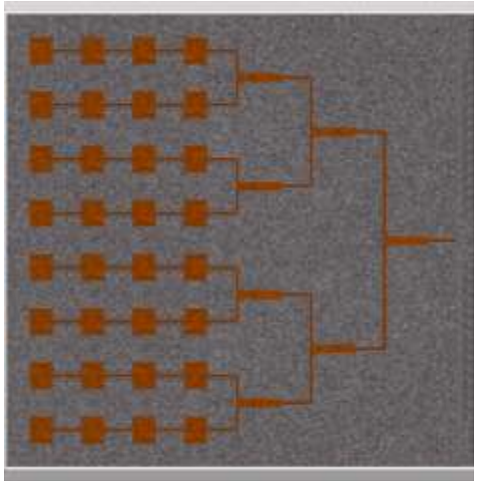
Linear array (1-D corporate feed)



2×2 array



2-D 8X8 corporate-fed array



4 × 8 corporate-fed / series-fed array

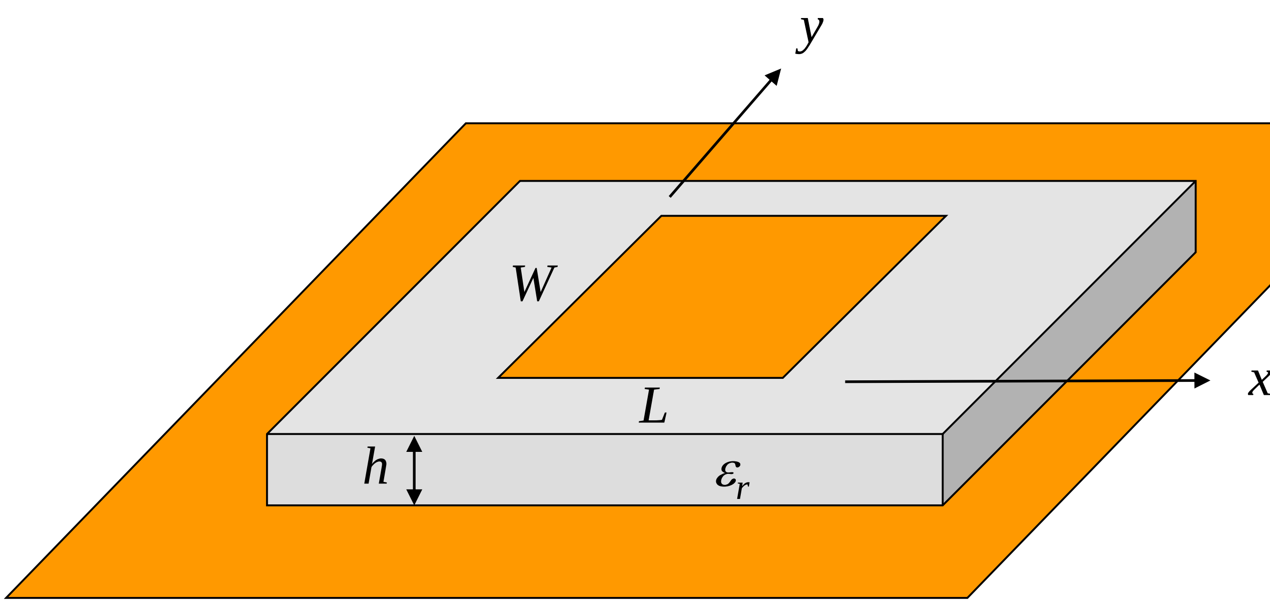
Overview of Microstrip Antennas

Wraparound Array (conformal)

The substrate is so thin that it can be bent to “conform” to the surface.

Overview of Microstrip Antennas

Rectangular patch



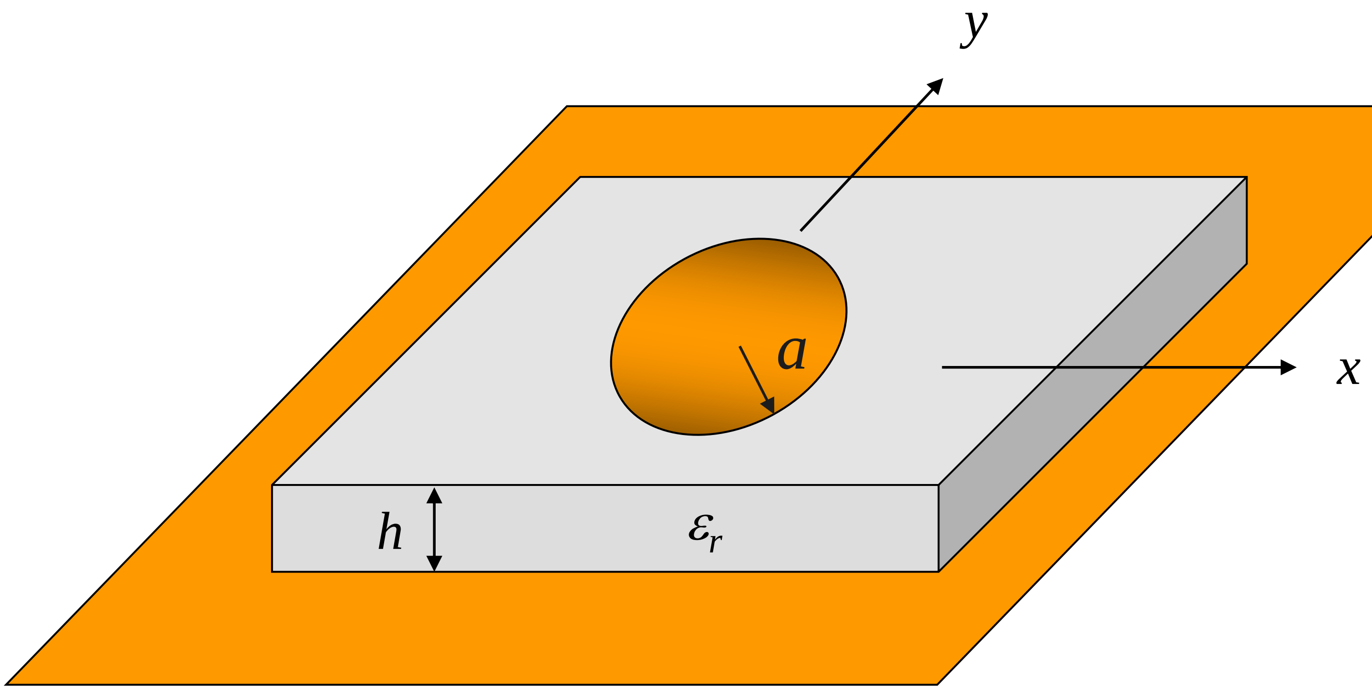
Note: L is the resonant dimension.

The width W is usually chosen to be larger than L (to get higher bandwidth).
However, usually $W < 2L$ (to avoid problems with the $(0,2)$ mode).

$W = 1.5L$ is typical.

Overview of Microstrip Antennas

Circular Patch



The location of the feed determines the direction of current flow and hence the polarization of the radiated field.

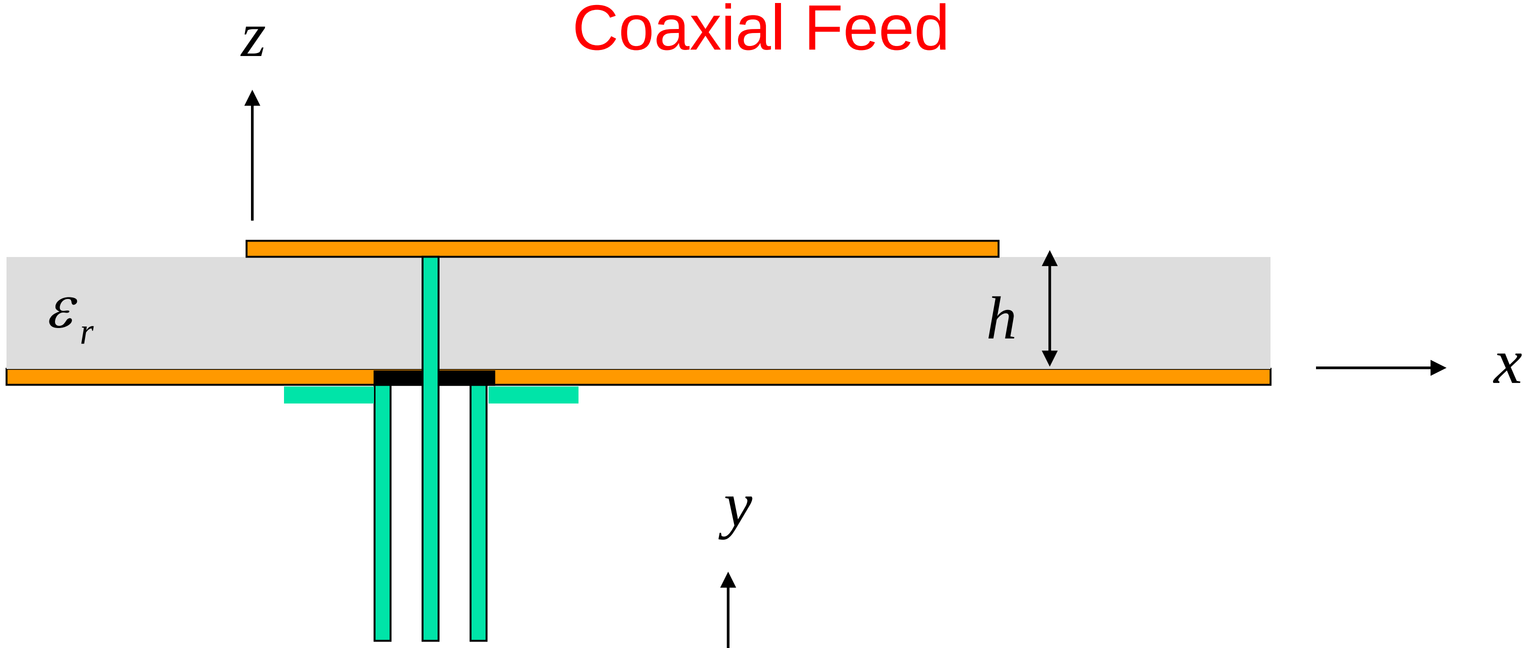
Feeding Methods

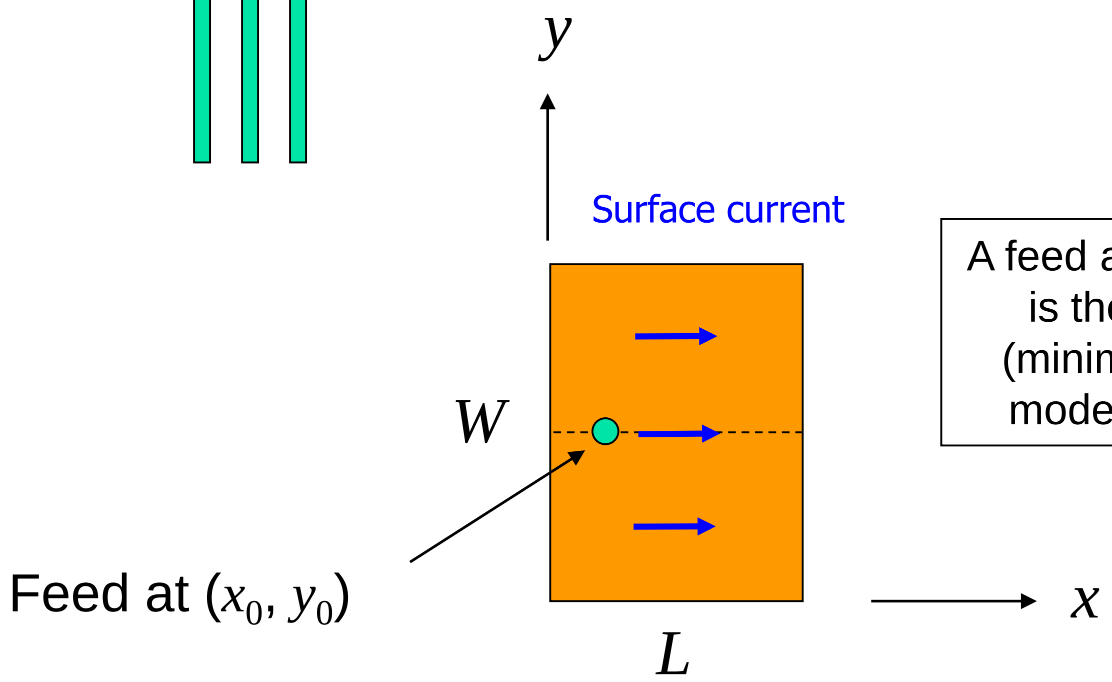
Some of the more common methods for feeding microstrip antennas are shown.

The feeding methods are illustrated for a rectangular patch, but the principles apply for circular and other shapes as well.

Feeding Methods

Coaxial Feed





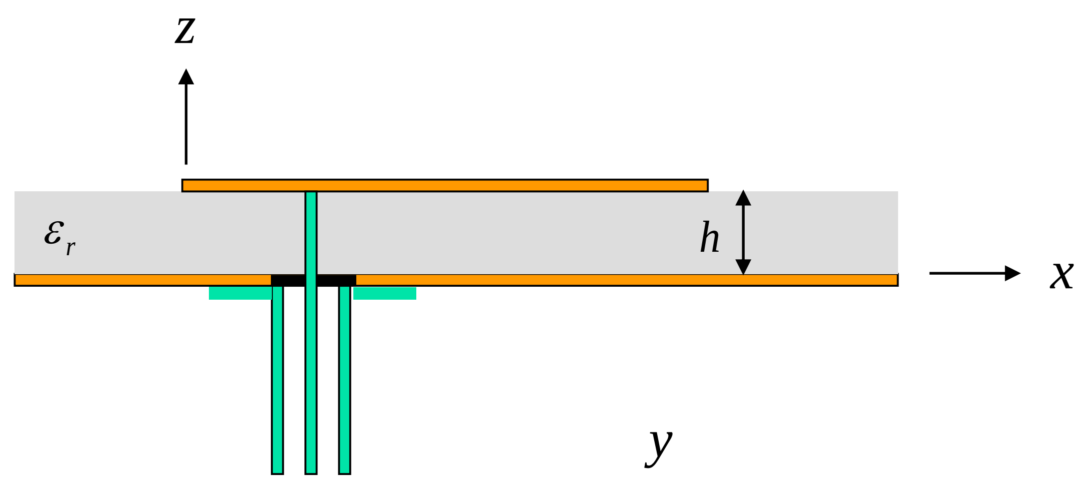
A feed along the centerline is the most common (minimizes higher-order modes and cross-pol).

Feeding Methods

Coaxial Feed

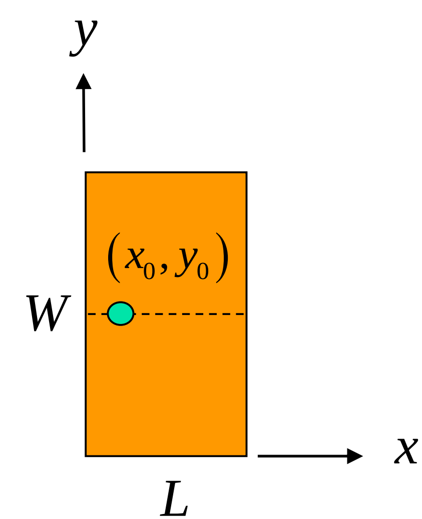
$$R = R_{edge} \cos^2 \left(\frac{\pi x_0}{L} \right)$$

(The resistance varies as the square of the modal field shape.)



Advantages:

- Simple
- Directly compatible with coaxial cables
- Easy to obtain input match by adjusting feed position

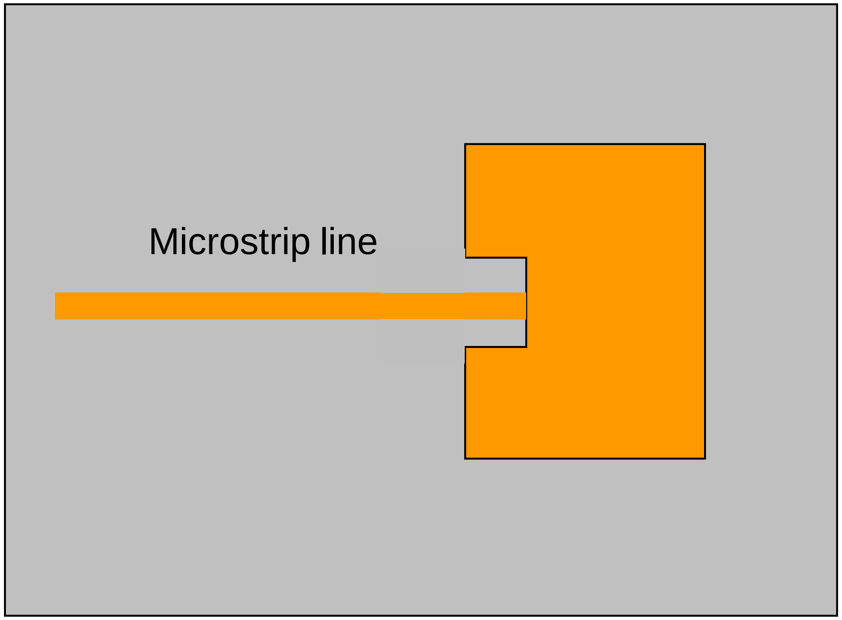


Disadvantages:

- Significant probe (feed) radiation for thicker substrates
- Significant probe inductance for thicker substrates
- Not easily compatible with arrays

Feeding Methods

Inset Feed



Advantages:

- Simple
- Allows for planar feeding
- Easy to use with arrays
- Easy to obtain input match

Disadvantages:

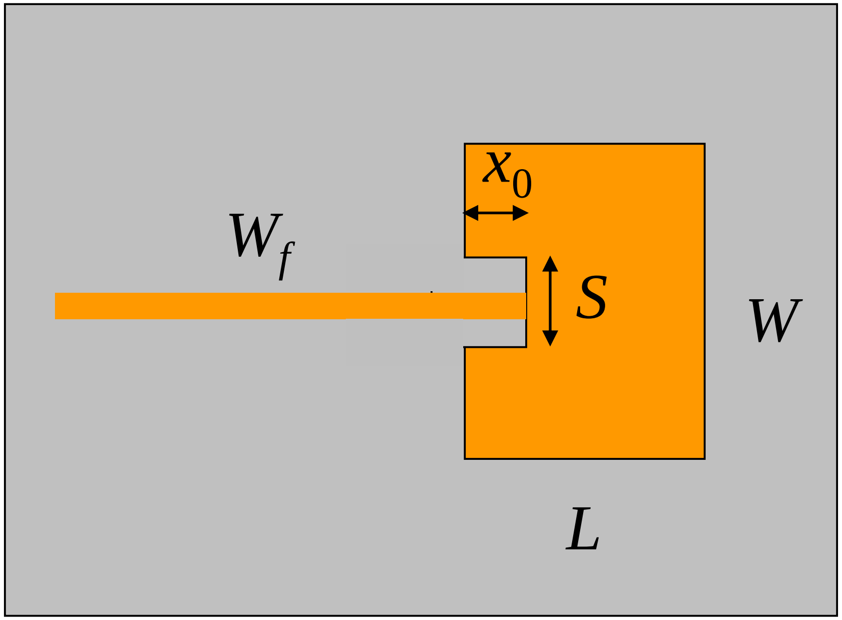
- Significant line radiation for thicker substrates
- For deep notches, patch current and radiation pattern may show distortion

Feeding Methods

Inset Feed

Recent work has shown that the resonant input resistance varies as

$$R_{in} = A\cos^2\left(\frac{\pi}{2}\left(\frac{2x_0}{L} - B\right)\right)$$



The coefficients A and B depend on the notch width S but (to a good approximation) not on the line width W_f.

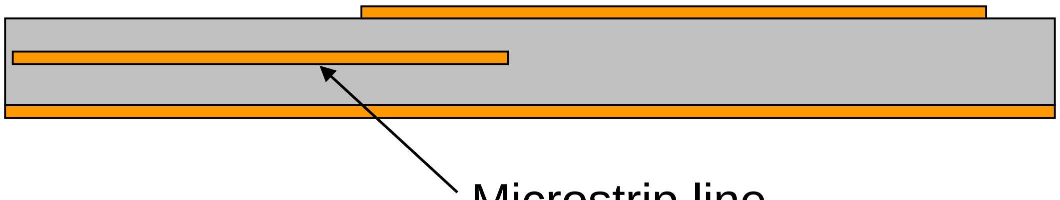
Y. Hu, D. R. Jackson, J. T. Williams, and S. A. Long, "Characterization of the Input Impedance of the Inset-Fed Rectangular Microstrip Antenna," *IEEE Trans. Antennas and Propagation*, Vol. 56, No. 10, pp. 3314-3318, Oct. 2008.

Feeding Methods

Proximity-coupled Feed
(Electromagnetically-coupled Feed)

Advantages:

- Allows for planar feeding
- Less line radiation compared to microstrip feed



Disadvantages:

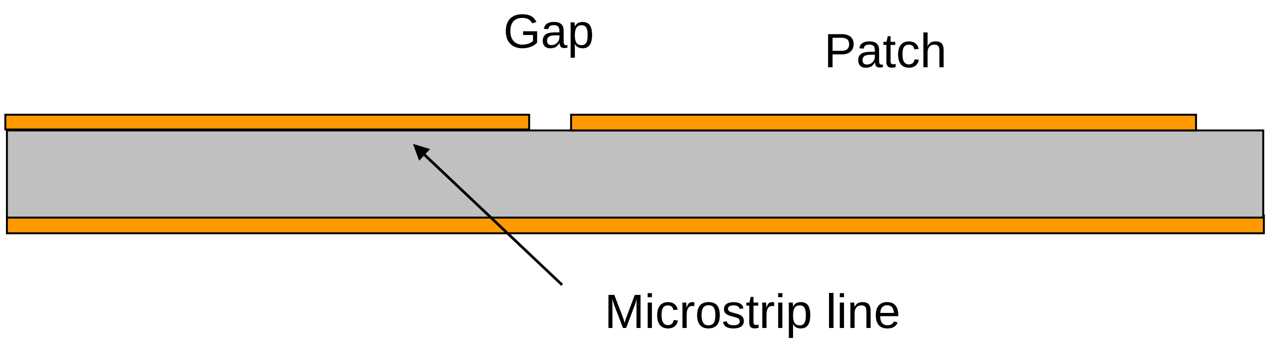
- Requires multilayer fabrication
- Alignment is important for input match

Feeding Methods

Gap-coupled Feed

Advantages:

- Allows for planar feeding
- Can allow for a match even with high edge impedances, where a notch might be too large (e.g., when using high permittivity)



Disadvantages:

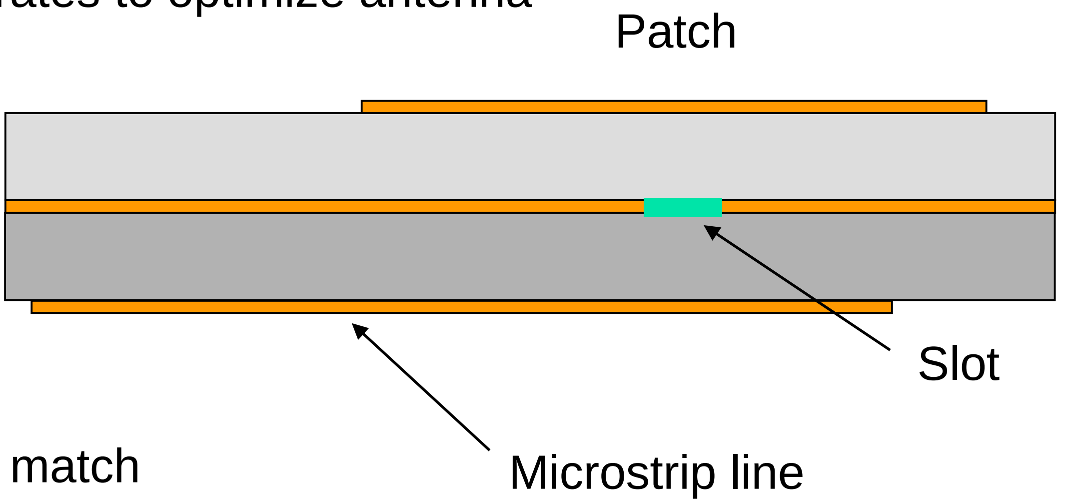
- Requires accurate gap fabrication
- Requires full-wave design

Feeding Methods

Aperture-coupled Patch (ACP)

Advantages:

- Allows for planar feeding
- Feed-line radiation is isolated from patch radiation
- Higher bandwidth is possible since probe inductance is eliminated (allowing for a thick substrate), and also a double-resonance can be created
- Allows for use of different substrates to optimize antenna and feed-circuit performance



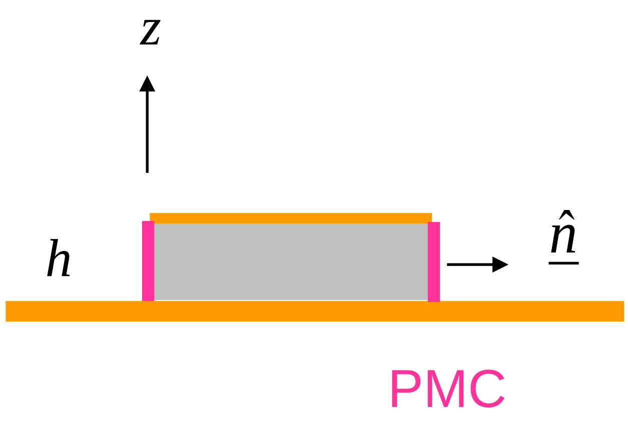
Disadvantages:

- Requires multilayer fabrication
- Alignment is important for input match

Basic Principles of Operation

- The basic principles are illustrated here for a rectangular patch, but the principles apply similarly for other patch shapes.

- We use the cavity model to explain the operation of the patch antenna.



Y. T. Lo, D. Solomon, and W. F. Richards, "Theory and Experiment on Microstrip Antennas," *IEEE Trans. Antennas Propagat.*, vol. AP-27, no. 3 (March 1979): 137–145.

Basic Principles of Operation

Main Ideas:

- The patch acts approximately as a resonant cavity (with short-circuit (PEC) walls on top and bottom, open-circuit (PMC) walls on the edges).
- In a cavity, only certain modes are allowed to exist, at different resonance frequencies.
- If the antenna is excited at a resonance frequency, a strong field is set up inside the cavity, and a strong current on the (bottom) surface of the patch. This produces significant radiation (a good antenna).

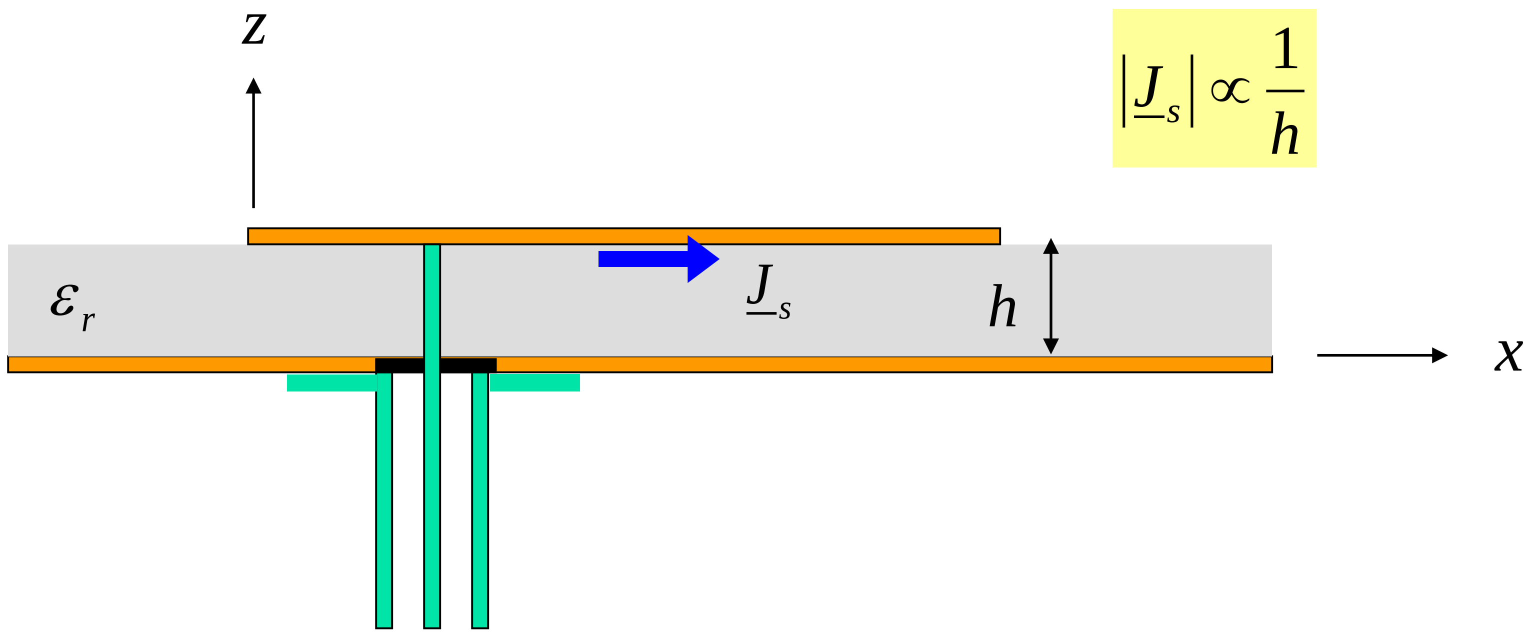
Note: As the substrate thickness gets smaller the patch current radiates less, due to image cancellation. However, the Q of the resonant mode also increases, making the patch currents stronger at resonance. These two effects cancel, allowing the patch to radiate well even for small substrate thicknesses.

Basic Principles of Operation

A microstrip antenna can radiate well, even with a thin substrate.

- As the substrate gets thinner the patch current radiates less, due to image cancellation (current and image are separated by $2h$).
- However, the Q of the resonant cavity mode also increases, making the patch currents stronger at resonance.
- These two effects cancel, allowing the patch to radiate well even for thin substrates.

$$\left|\underline{J}_s\right| \propto \frac{1}{h}$$



General Characteristics

Bandwidth

- The bandwidth is directly proportional to substrate thickness h.
- However, if h is greater than about $0.05\,\lambda_0$, the probe inductance (for a coaxial feed) becomes large enough so that matching is difficult.
- The bandwidth is inversely proportional to ε_r (a foam substrate gives a high bandwidth).
- The bandwidth of a rectangular patch is proportional to the patch width W (but we need to keep $W < 2L$; see the next slide).

General Characteristics

Width Restriction for a Rectangular Patch

$$W < 2L$$

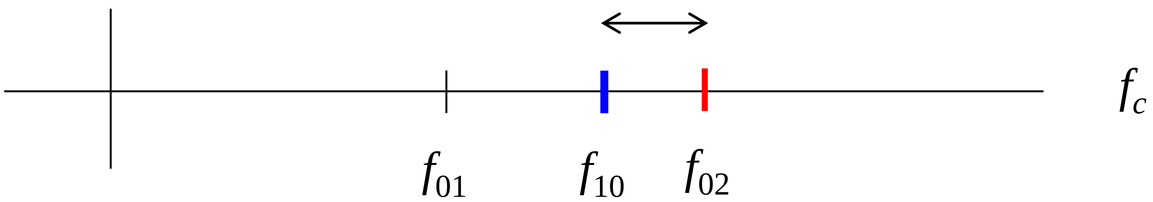
$$f_{mn} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m\pi}{L}\right)^2 + \left(\frac{n\pi}{W}\right)^2}$$

$$f_{01} = \frac{c}{2\sqrt{\varepsilon_r}}\left(\frac{1}{W}\right)$$

$$f_{10} = \frac{c}{2\sqrt{\varepsilon_r}}\left(\frac{1}{L}\right)$$

$$f_{02} = \frac{c}{2\sqrt{\varepsilon_r}}\left(\frac{2}{W}\right)$$

$$f_{02} - f_{01} = \frac{c}{\sqrt{\varepsilon_r}}\left(\frac{1}{W} - \frac{1}{2L}\right)$$



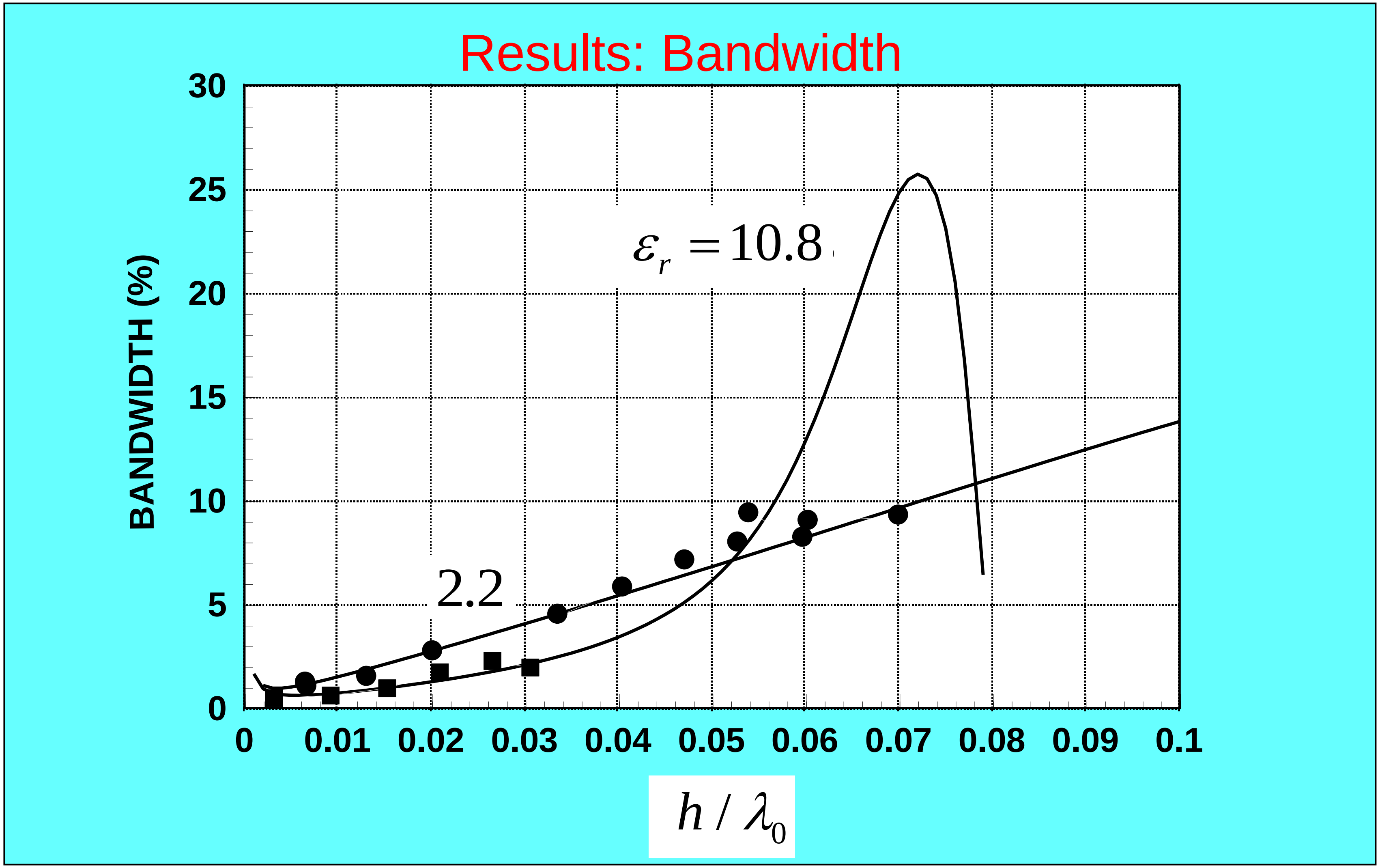
W = 1.5 L is typical.

General Characteristics

Some Bandwidth Observations

- For a typical substrate thickness ($h/\lambda_0 = 0.02$), and a typical substrate permittivity ($\varepsilon_r = 2.2$) the bandwidth is about 3%.
- By using a thick foam substrate, bandwidth of about 10% can be achieved.
- By using special feeding techniques (aperture coupling) and stacked patches, bandwidths of 100% have been achieved.

General Characteristics



The discrete data points are measured values.

The solid curves are from a CAD formula (given later).

ε_r = 2.2 or 10.8 $\qquad W/L = 1.5$

General Characteristics

Radiation Efficiency

- Radiation efficiency is the ratio of power radiated into space, to the total input power.

$$e_r = \frac{P_r}{P_{tot}}$$

- The radiation efficiency is less than 100% due to
  - Conductor loss
  - Dielectric loss
  - Surface-wave excitation

General Characteristics

Radiation Efficiency (cont.)

Some observations:

- Conductor and dielectric loss is more important for thinner substrates (the Q of the cavity is higher, and thus more seriously affected by loss).

- Conductor loss increases with frequency (proportional to $f^{1/2}$) due to the skin effect. It can be very serious at millimeter-wave frequencies.

- Conductor loss is usually more important than dielectric loss for typical substrate thicknesses and loss tangents.

General Characteristics

Radiation Efficiency (cont.)

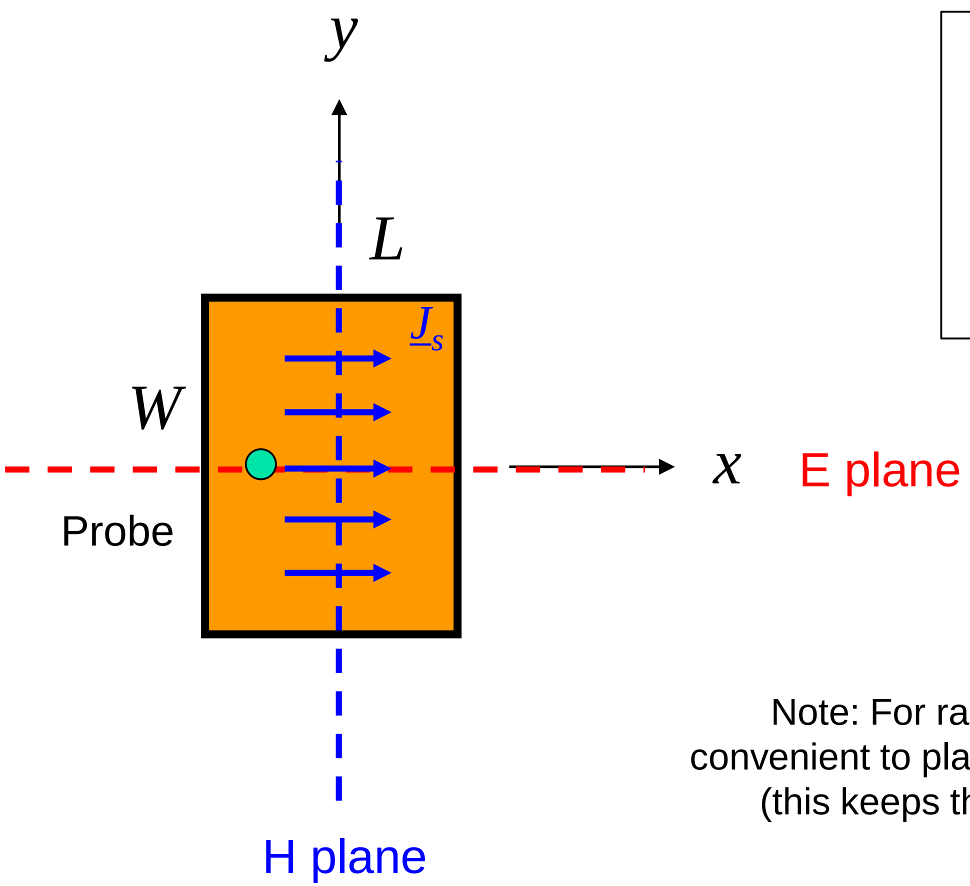
- Surface-wave power is more important for thicker substrates or for higher-substrate permittivities. (The surface-wave power can be minimized by using a thin substrate or a foam substrate.)

  - For a foam substrate, a high radiation efficiency is obtained by making the substrate thicker (increasing the bandwidth). There is no surface-wave power to worry about.

  - For a typical substrate such as $\varepsilon_r = 2.2$, the radiation efficiency is maximum for $h / \lambda_0 \approx 0.02$.

General Characteristics

Radiation Pattern



E-plane: co-pol is E_θ

H-plane: co-pol is E_ϕ

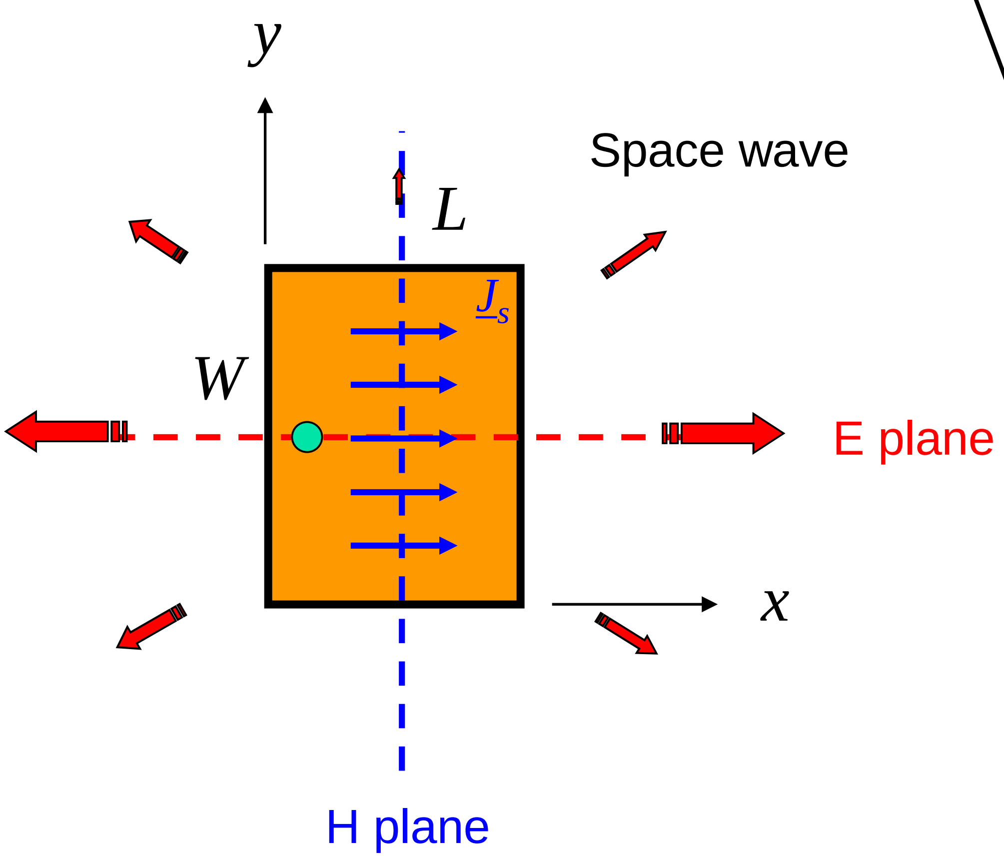
Note: For radiation patterns, it is usually more convenient to place the origin at the middle of the patch (this keeps the formulas as simple as possible).

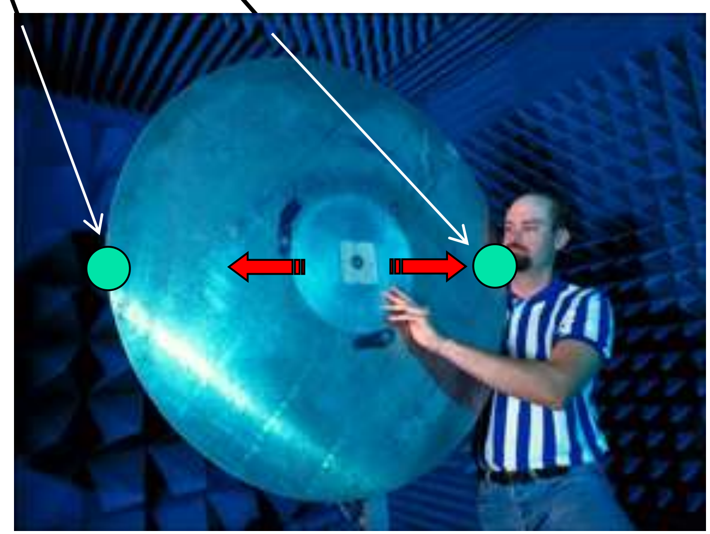
General Characteristics

Radiation Patterns

Edge diffraction is the most serious in the E plane.

E_θ varies as $\cos\phi$





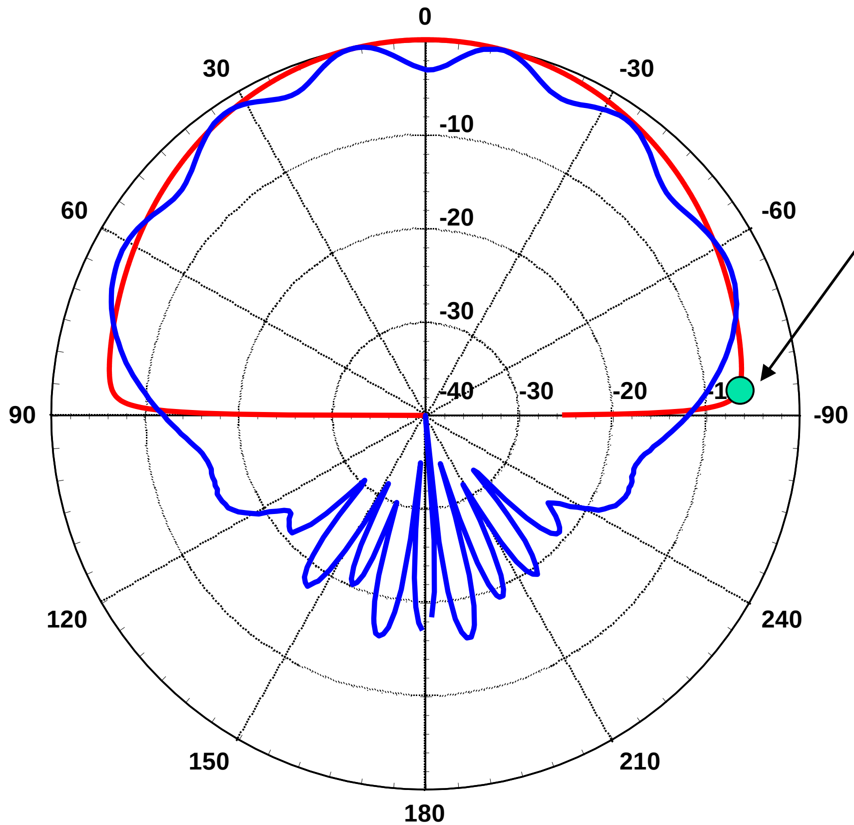
General Characteristics

Radiation Patterns

E-plane pattern

Red: infinite substrate and ground plane

Blue: 1 meter ground plane



Note: The E-plane pattern "tucks in" and tends to zero at the horizon due to the presence of the infinite substrate.

General Characteristics

Directivity

- The directivity is fairly insensitive to the substrate thickness.
- The directivity is higher for lower permittivity, because the patch is larger.

Improving Bandwidth

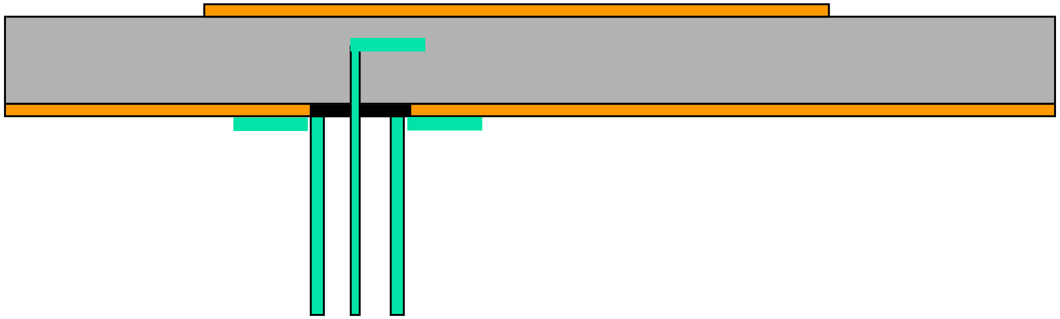
Some of the techniques that have been successfully developed are illustrated here.

The literature may be consulted for additional designs and variations.

Improving Bandwidth

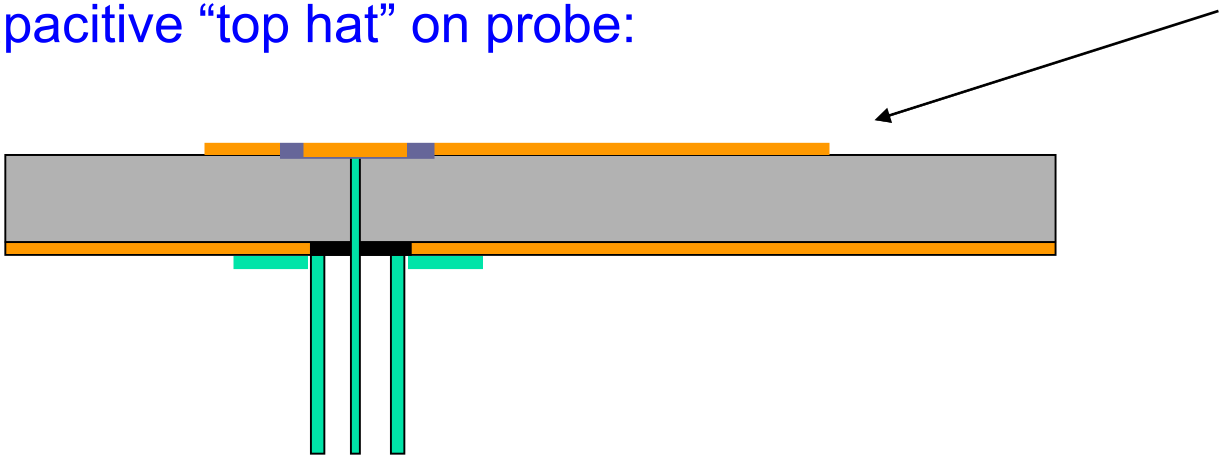
Probe Compensation

L-shaped probe:

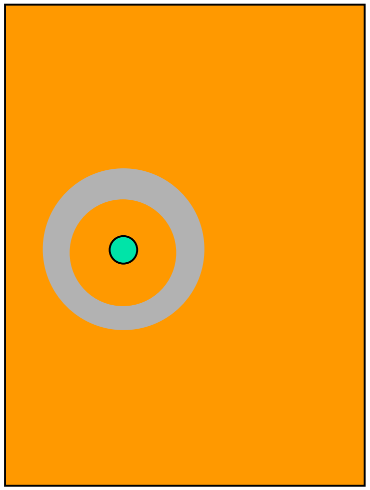


As the substrate thickness increases the probe inductance limits the bandwidth – so we compensate for it.

Capacitive "top hat" on probe:



Top view

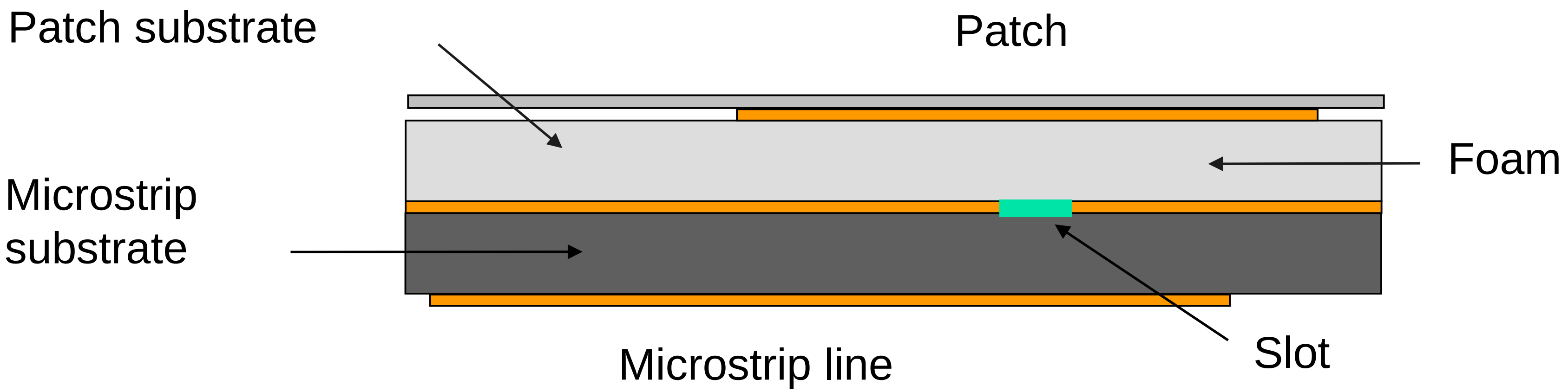


Improving Bandwidth

SSFIP: Strip Slot Foam Inverted Patch (a version of the ACP).

- Bandwidths greater than 25% have been achieved.
- Increased bandwidth is due to the thick foam substrate and also a dual-tuned resonance (patch+slot).

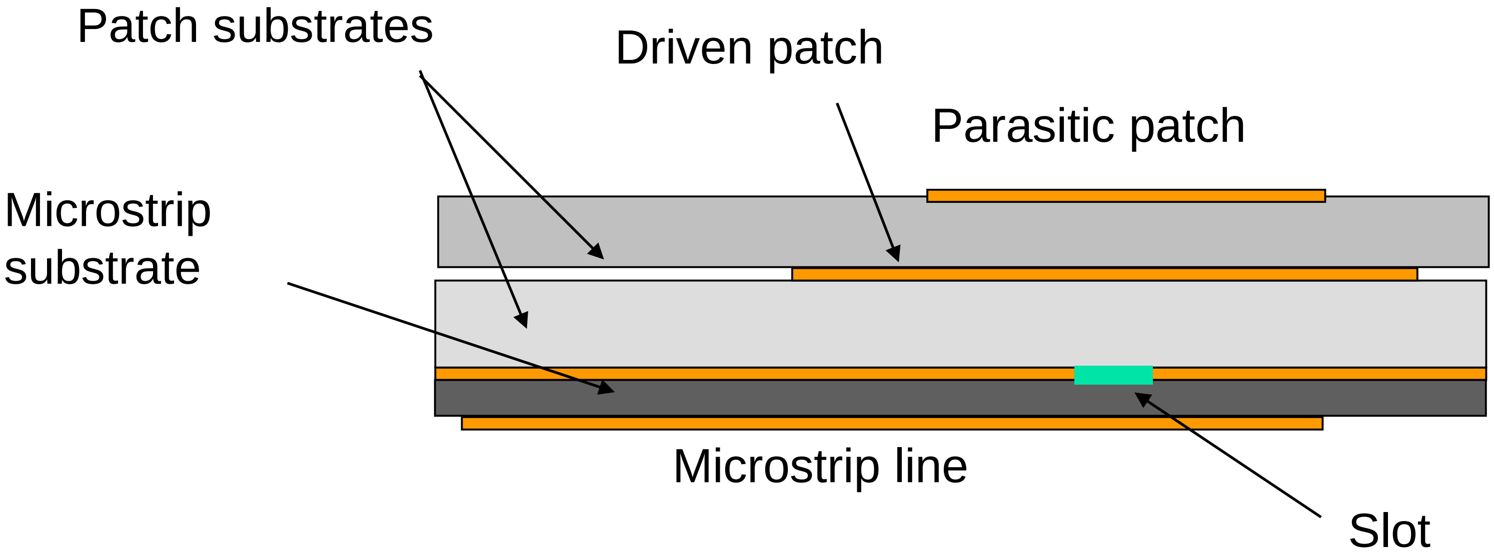
Note: There is no probe inductance to worry about here.



Improving Bandwidth

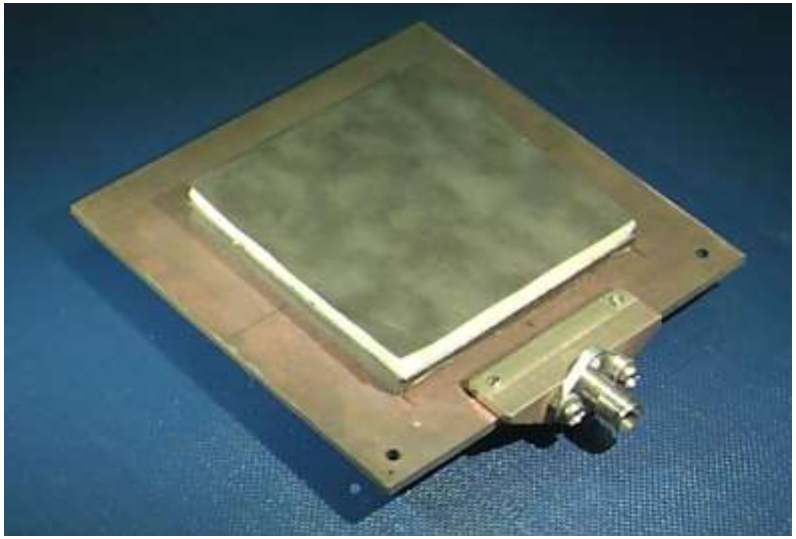
Stacked Patches

- Bandwidth increase is due to thick low-permittivity antenna substrates and a dual or triple-tuned resonance.
- Bandwidths of 25% have been achieved using a probe feed.
- Bandwidths of 100% have been achieved using an ACP feed.

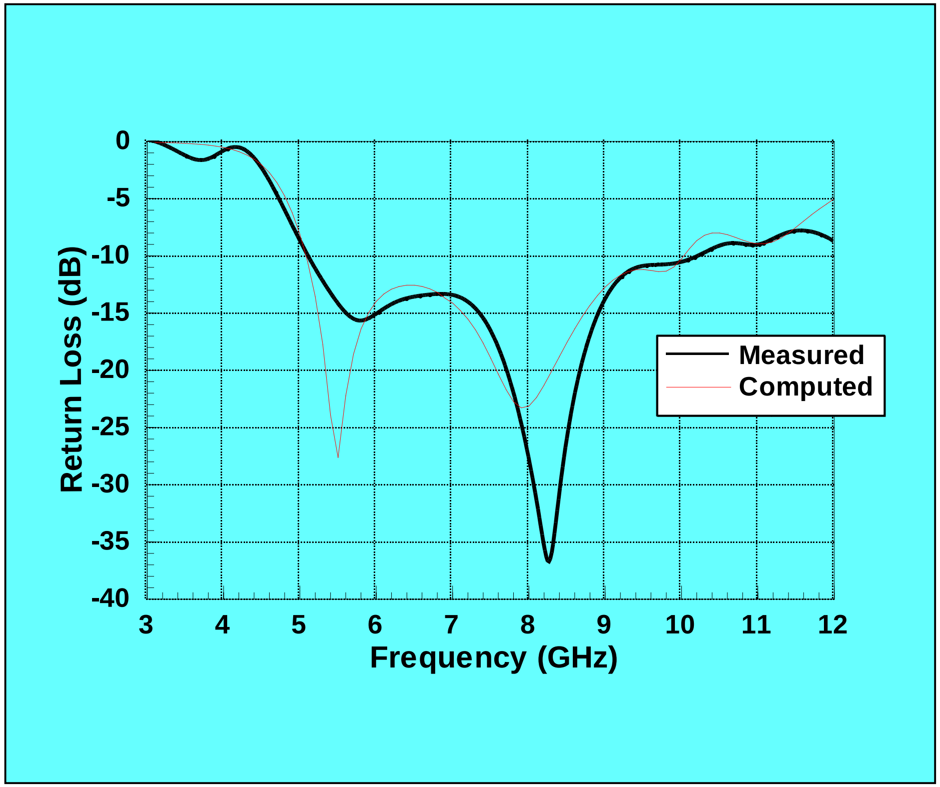


Improving Bandwidth

Stacked Patches



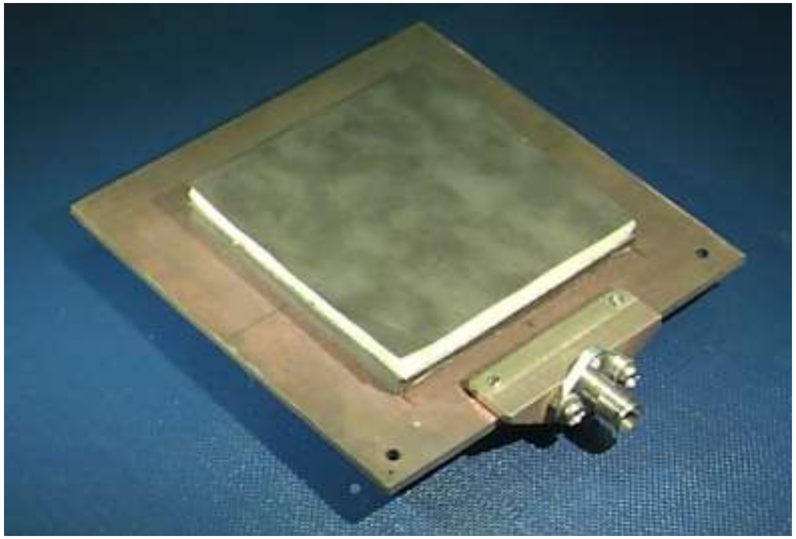
Stacked patch with ACP feed



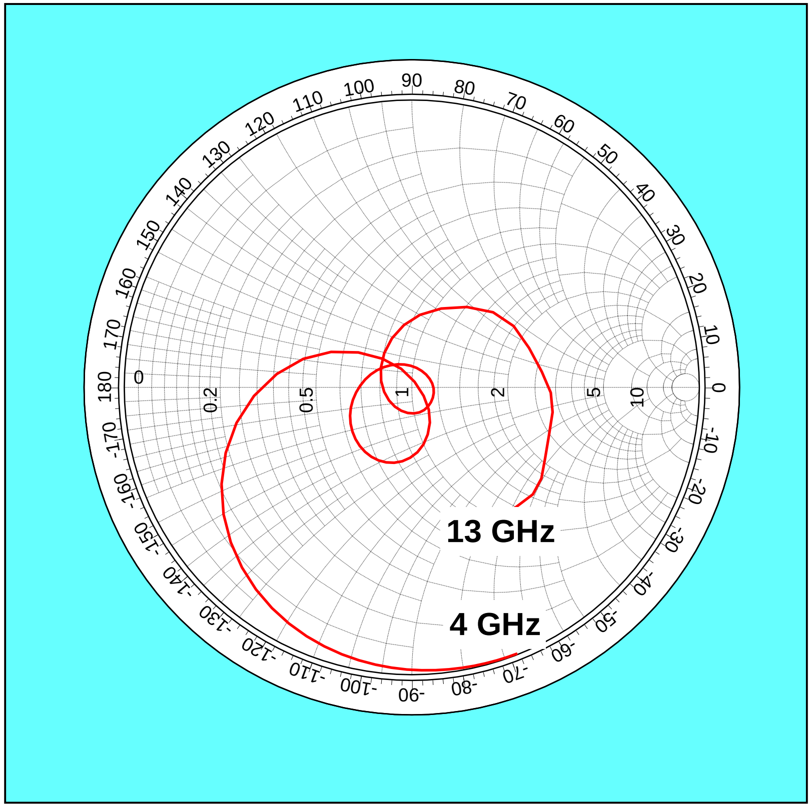
Bandwidth (S_{11} = -10 dB) is about 100%

Improving Bandwidth

Stacked Patches



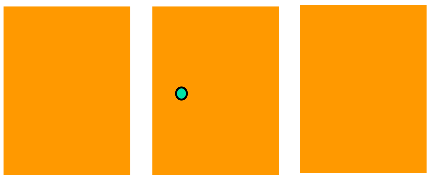
Stacked patch with ACP feed



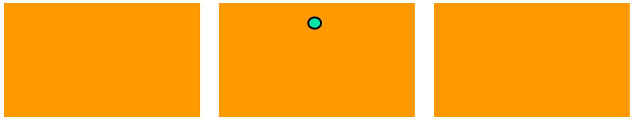
Two extra loops are observed on the Smith chart.

Improving Bandwidth

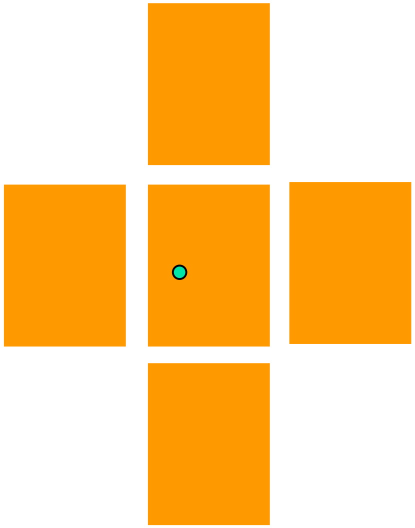
Parasitic Patches



Radiating Edges Gap Coupled Microstrip Antennas (REGCOMA).



Non-Radiating Edges Gap Coupled Microstrip Antennas (NEGCOMA)

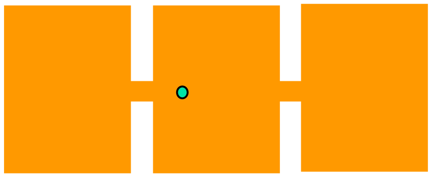


Four-Edges Gap Coupled Microstrip Antennas (FEGCOMA)

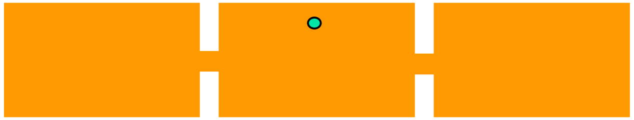
Bandwidth improvement factor:
REGCOMA: 3.0, NEGCOMA: 3.0, FEGCOMA: 5.0?

Improving Bandwidth

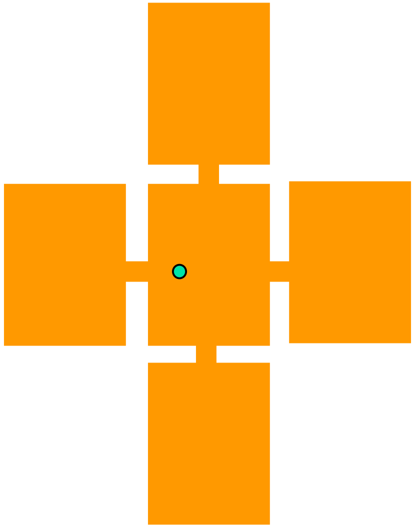
Direct-Coupled Patches



Radiating Edges Direct
Coupled Microstrip Antennas
(REDCOMA).



Non-Radiating Edges Direct
Coupled Microstrip Antennas
(NEDCOMA)

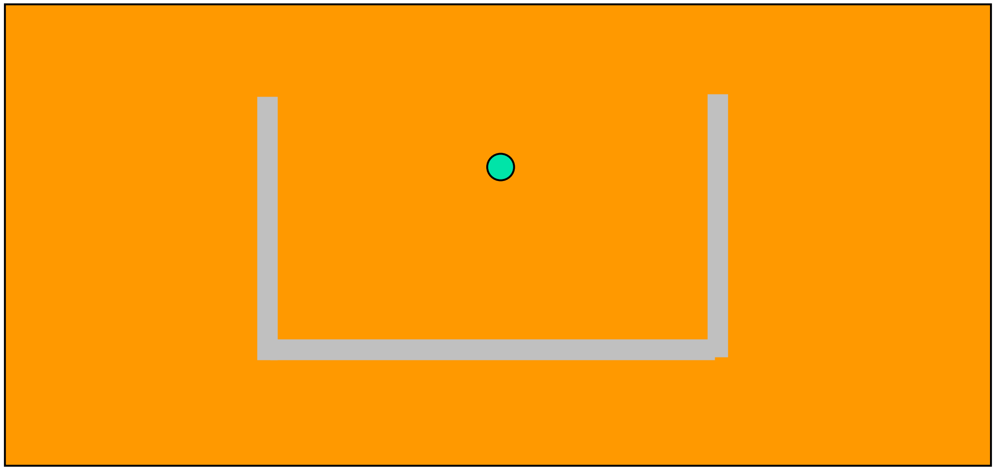


Four-Edges Direct Coupled
Microstrip Antennas
(FEDCOMA)

Bandwidth improvement factor:
REDCOMA: 5.0, NEDCOMA: 5.0, FEDCOMA: 7.0

Improving Bandwidth

U-Shaped Slot

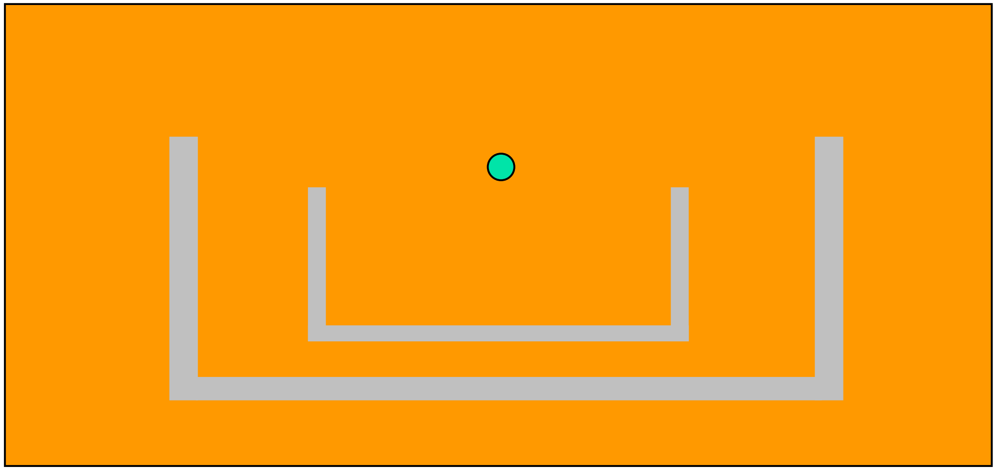


The introduction of a U-shaped slot can give a significant bandwidth (10%-40%).

(This is due to a double resonance effect, with two different modes.)

Improving Bandwidth

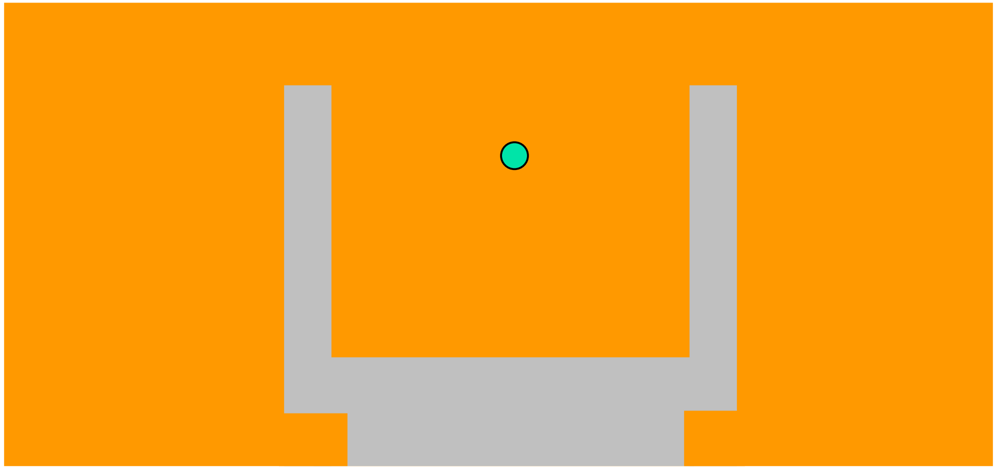
Double U-Slot



A 44% bandwidth was achieved.

Improving Bandwidth

E Patch



A modification of the U-slot patch.

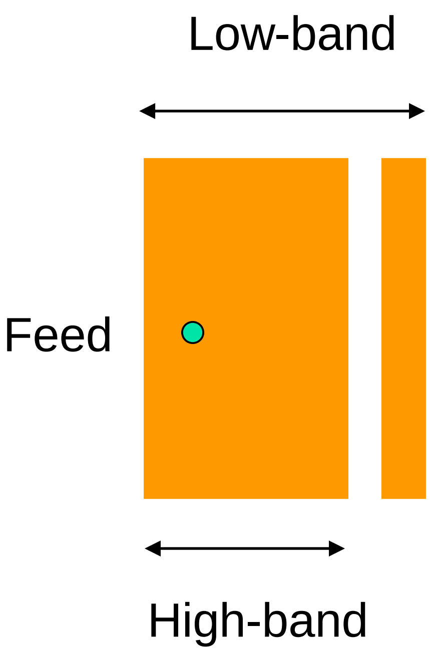
A bandwidth of 34% was achieved (40% using a capacitive “washer” to compensate for the probe inductance).

Multi-Band Antennas

A multi-band antenna is sometimes more desirable than a broadband antenna, if multiple narrow-band channels are to be covered.

Multi-Band Antennas

Dual-band E patch



Dual-band patch with parasitic strip

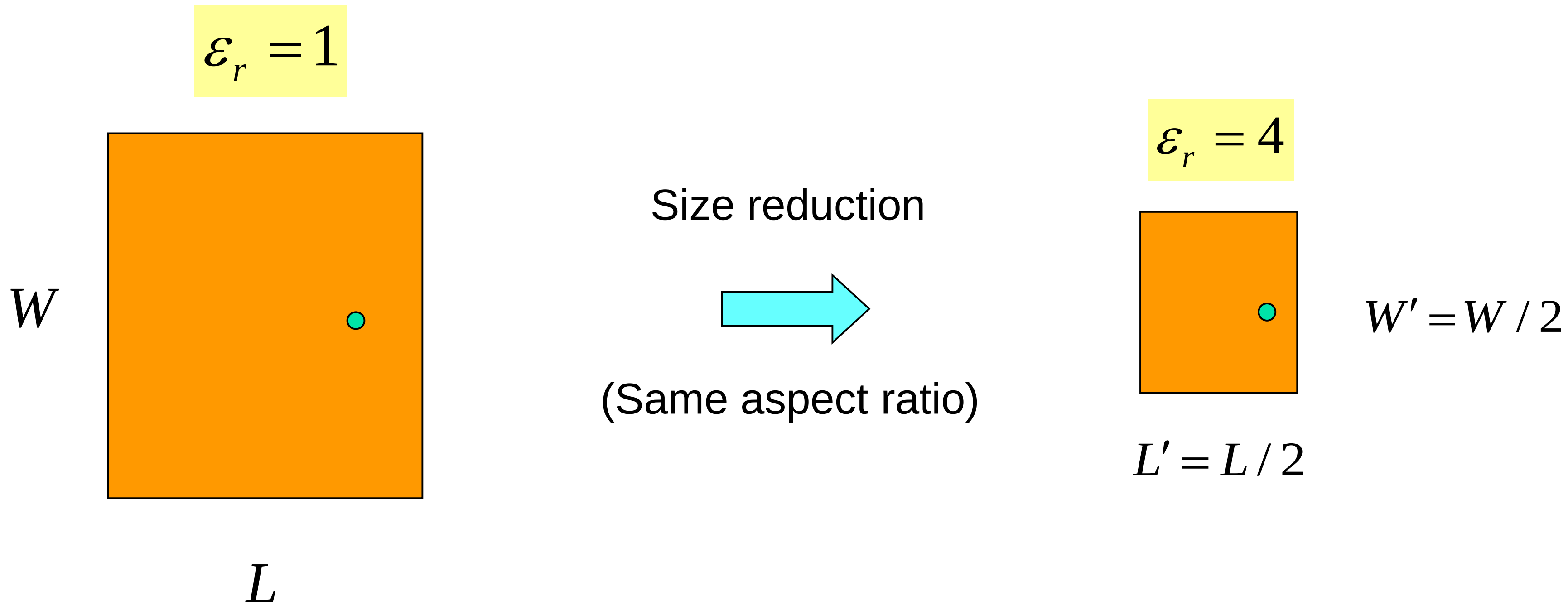
Miniaturization

- High Permittivity
- Quarter-Wave Patch
- PIFA
- Capacitive Loading
- Slots
- Meandering

Note: Miniaturization usually comes at a price of reduced bandwidth!

Miniaturization

High Permittivity

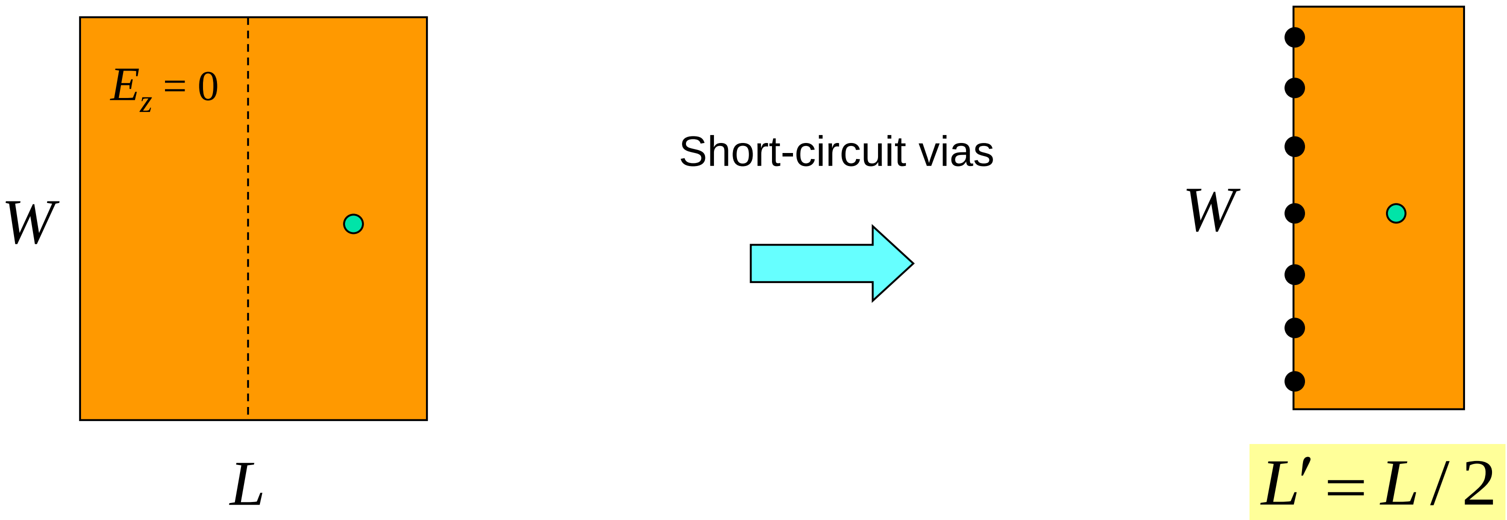


The smaller patch has about one-fourth the bandwidth of the original patch.

(Bandwidth is inversely proportional to the permittivity.)

Miniaturization

Quarter-Wave patch



The new patch has about one-half the bandwidth of the original patch.

Neglecting losses:

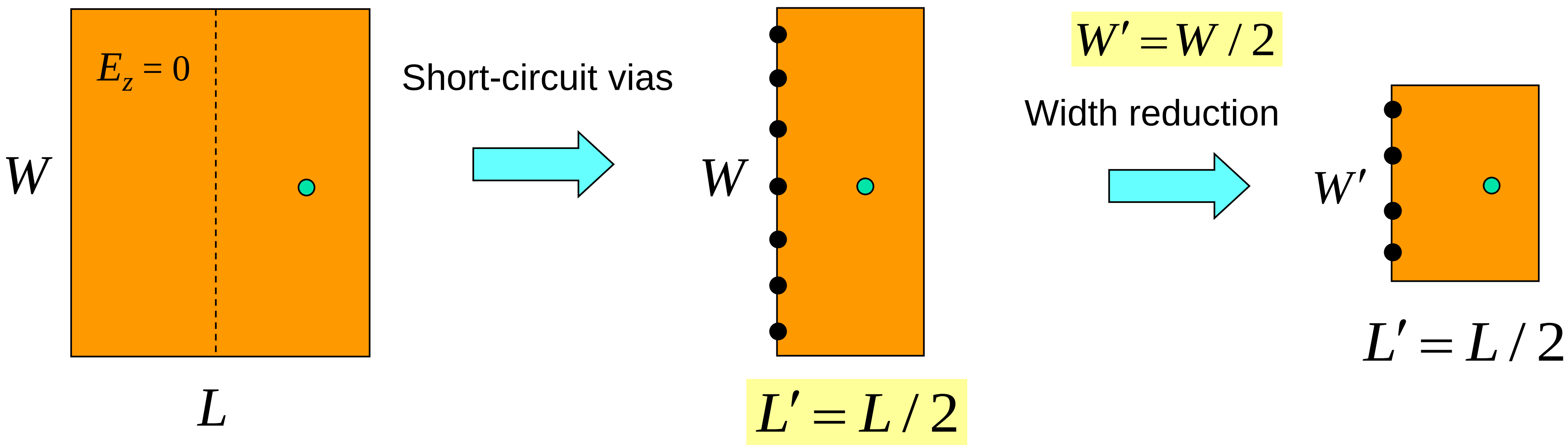
$$Q = \omega_0 \frac{U_s}{P_r} \qquad \left. \begin{array}{l} U_s' = U_s / 2 \\ P_r' = P_r / 4 \end{array} \right\} \Rightarrow Q' = 2Q$$

Note: 1/2 of the radiating magnetic current

Miniaturization

Smaller Quarter-Wave patch

A quarter-wave patch with the *same aspect ratio* W/L as the original patch

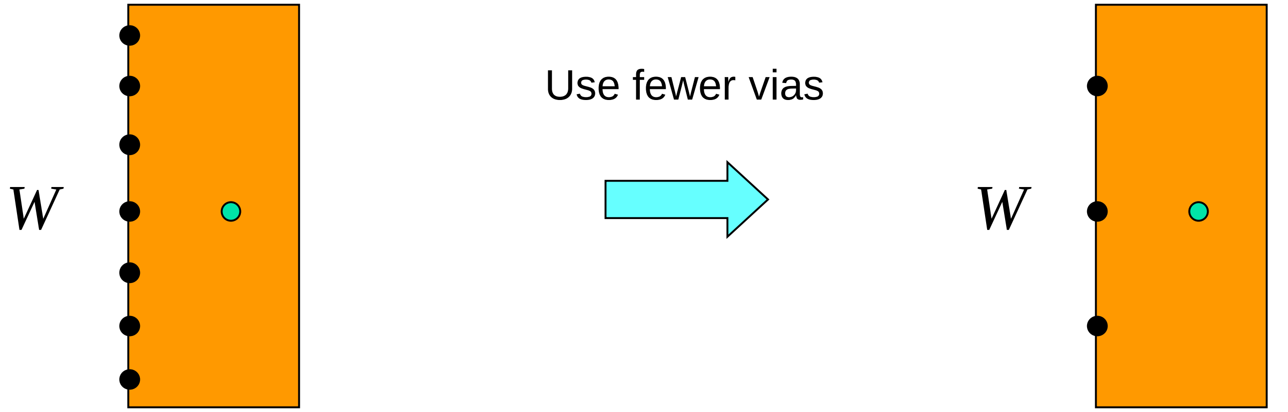


The new patch has about one-half the bandwidth of the original quarter-wave patch, and hence one-fourth the bandwidth of the regular patch.

(Bandwidth is proportional to the patch width.)

Miniaturization

Quarter-Wave Patch with Fewer Vias



$L' = L/2$

L''

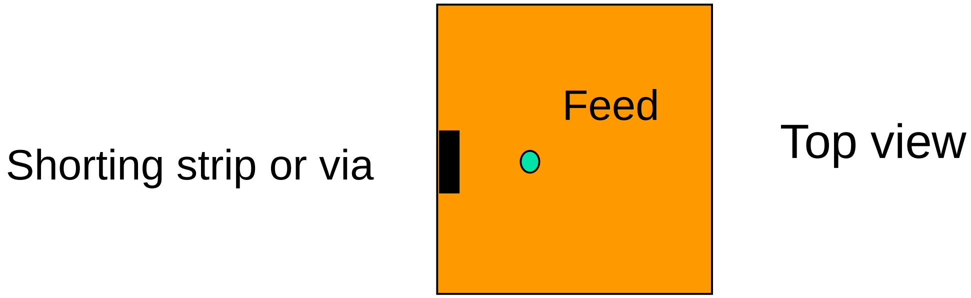
$$L'' < L'$$

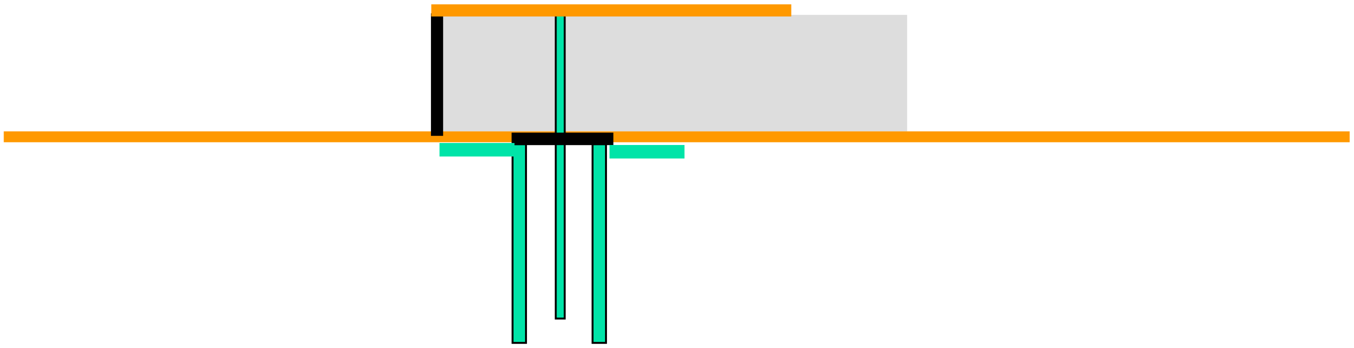
Fewer vias actually gives more miniaturization!

(The edge has a larger inductive impedance: explained on the next slide.)

Miniaturization

Planar Inverted F (PIFA)



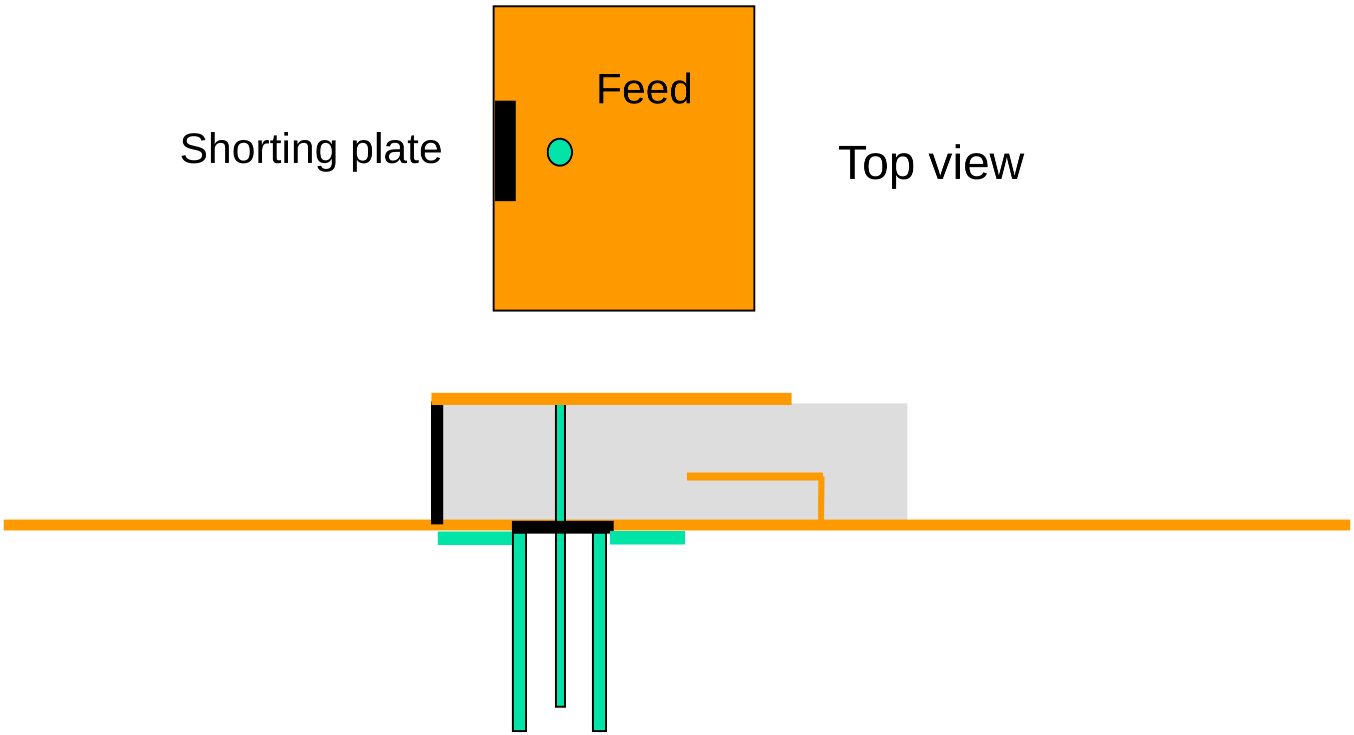


A single shorting strip or via is used.

This antenna can be viewed as a limiting case of the via-loaded patch, or as an LC resonator.

Miniaturization

PIFA with Capacitive Loading

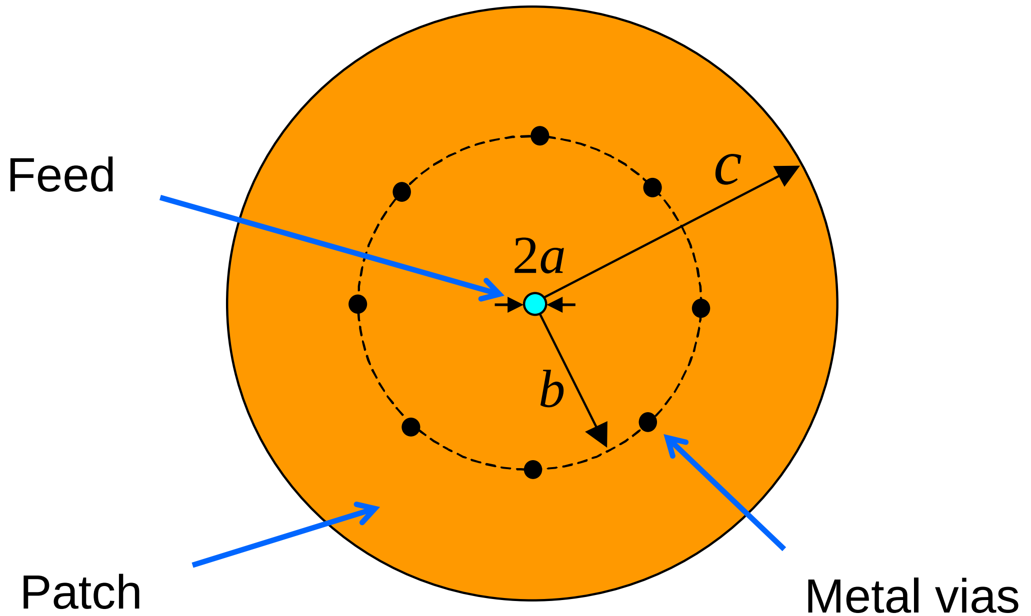


The capacitive loading allows for the length of the PIFA to be reduced.

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Miniaturization

Circular Patch Loaded with Vias

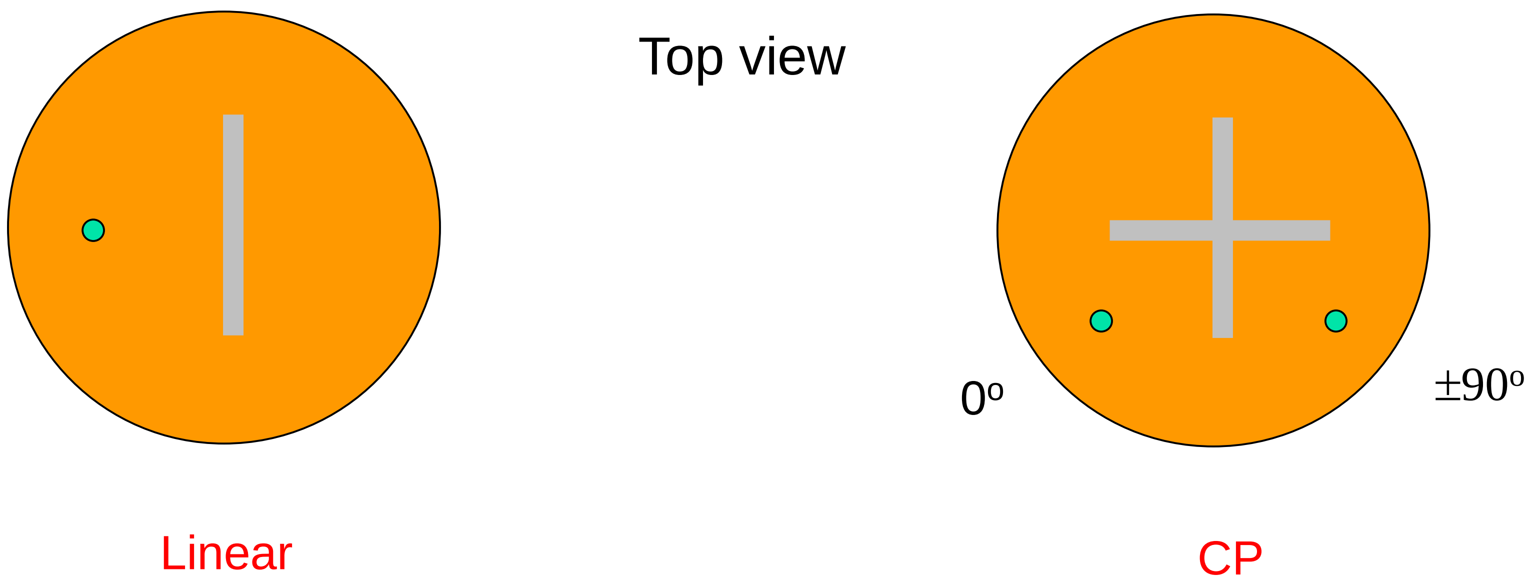


The patch has a monopole-like pattern

The patch operates in the $(0,0)$ mode, as an LC resonator

Miniaturization

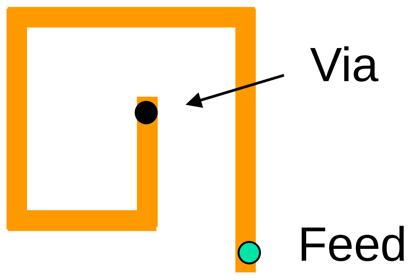
Slotted Patch



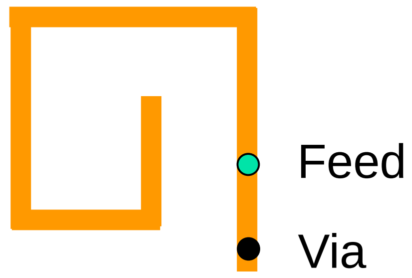
The slot forces the current to flow through a longer path, increasing the effective dimensions of the patch.

Miniaturization

Meandering



Meandered quarter-wave patch



Meandered PIFA

Meandering forces the current to flow through a longer path, increasing the effective dimensions of the patch.

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General references about microstrip antennas:

Microstrip Patch Antennas, K. F. Fong Lee and K. M. Luk, Imperial College Press, 2011.

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More information about the CAD formulas presented here for the rectangular patch may be found in:

Microstrip Antennas, D. R. Jackson, Ch. 7 of Antenna Engineering Handbook, J. L. Volakis, Editor, McGraw Hill, 2007.

Computer-Aided Design of Rectangular Microstrip Antennas, D. R. Jackson, S. A. Long, J. T. Williams, and V. B. Davis, Ch. 5 of *Advances in Microstrip and Printed Antennas*, K. F. Lee, Editor, John Wiley, 1997.

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