



Antenna Design for the Laptop Radar Project*

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Introduction

- **Purpose of presentation**
 - **Describe some of the fundamental characteristics of antennas to successfully complete this project**

Gain radiation patterns, power density, beamwidth, reflection coefficient, transmission coefficient, antenna arrays, measurements
 - **Describe the design, fabrication, and testing of an antenna that can be used as the transducer for the laptop radar system**

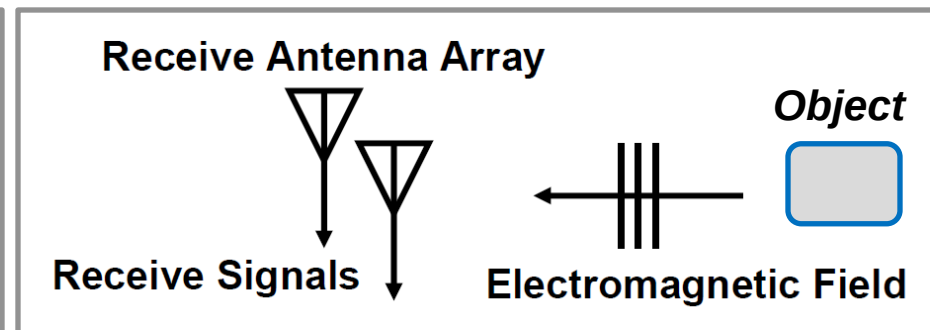
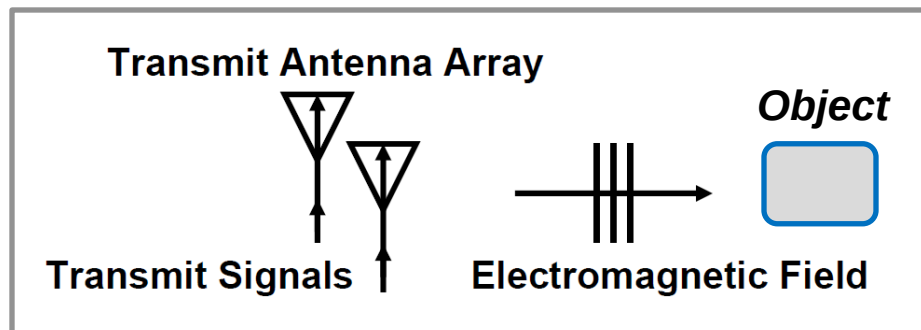
Simple circular waveguide antenna (fabricated from a coffee can) with coaxial connector and wire probe feed

Two identical antennas, one for transmit, one for receive



Antennas for Transmitting and Receiving Electromagnetic Signals

- An antenna can be either single or multiple *transducers* that can convert a signal voltage on a transmission line to a transmitted electromagnetic (EM) wave (also receives EM waves)
 - Radar transmitter induces a time-varying microwave signal that travels along coaxial cable to the transmit antenna
 - Time-varying signal applied to the transmit antenna induces an electrical current on the antenna which produces electromagnetic radiation (microwave photons)
 - Electromagnetic energy flows away (at the speed of light) from the transmit antenna and reflects off an object
 - The reflected energy illuminates the receive antenna and induces an electrical current on the antenna which induces a signal in coaxial cable that guides the signal to the radar receiver

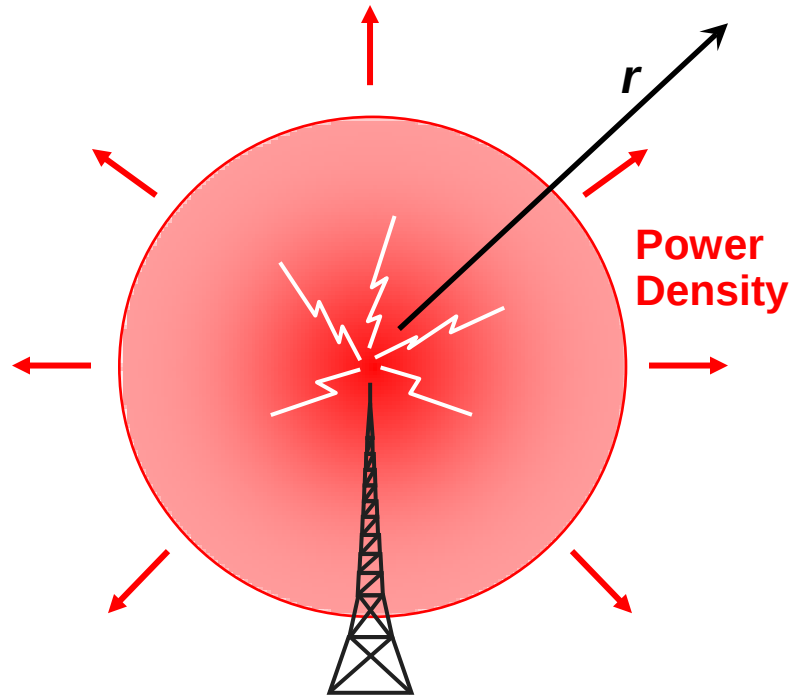




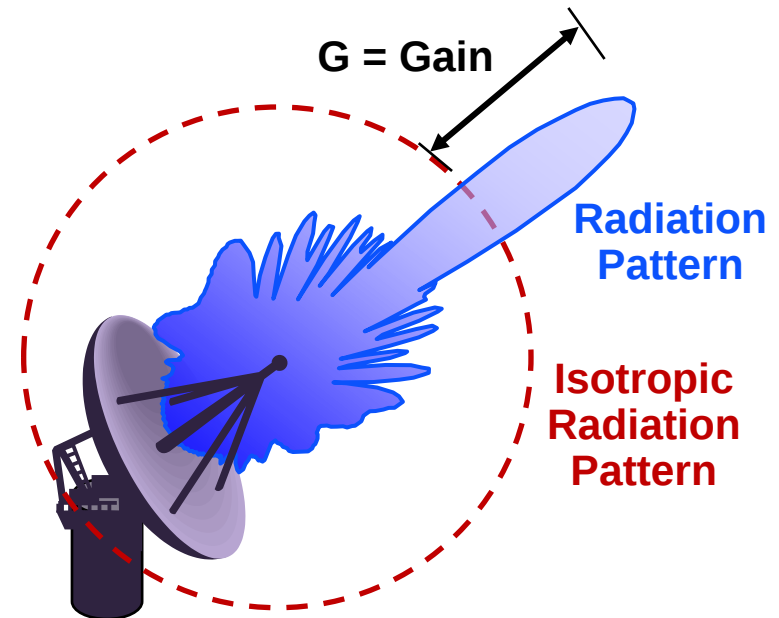
Antenna Power Density and Gain

Isotropic and Directional Antennas

Isotropic Antenna



Directional Antenna

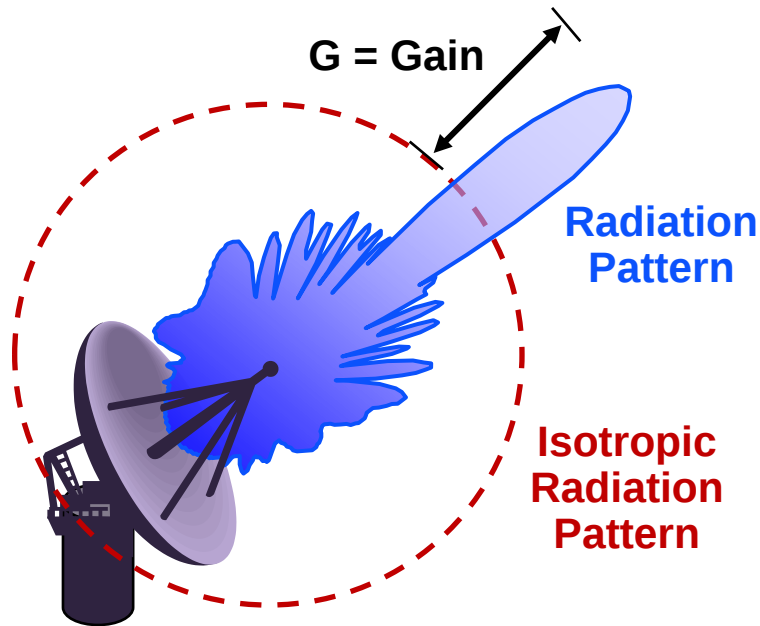


Source: R.M. O'Donnell, <http://ocw.mit.edu/resources/res-II-001-introduction-to-radar-systems-spring-2007/>

- Power density (W/m^2) decreases as range r increases, Gain is relative to isotropic antenna
- Directional antenna produces a gain radiation pattern that depends on the aspect angle
- Peak gain and peak power density increase for a directional antenna compared to an isotropic antenna

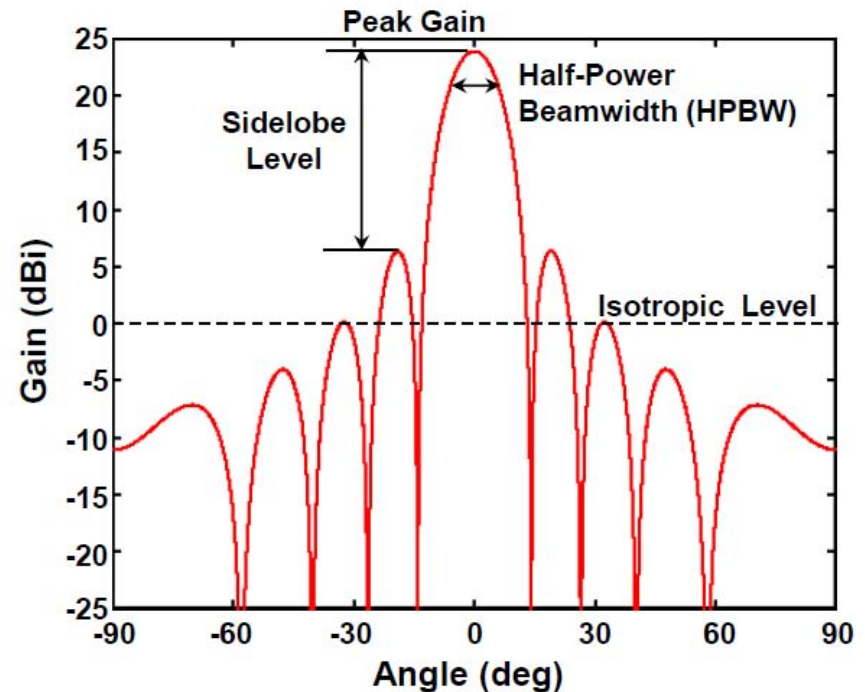


Antenna Gain Radiation Pattern Characteristics



Source: R.M. O'Donnell,
<http://ocw.mit.edu/resources/res-ll-001-introduction-to-radar-systems-spring-2007/>

Gain Pattern for Circular Aperture, 5 Wavelengths Diameter

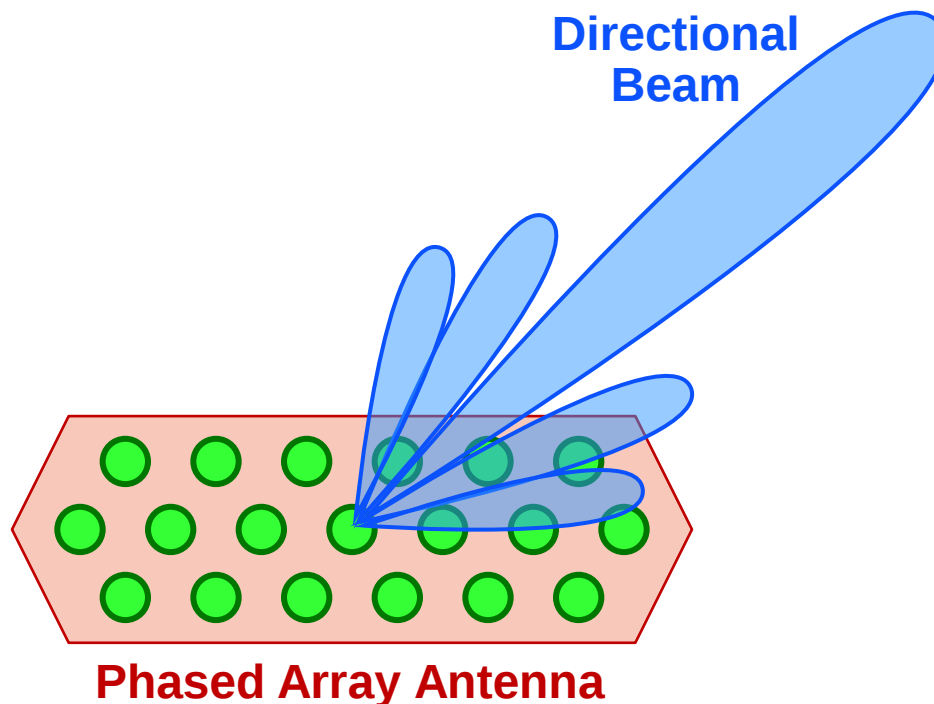


- A directional antenna has a main beam pointed in a particular direction and has sidelobes away from the main beam
- As the antenna diameter increases, the main beam gain increases and the beamwidth becomes narrower



Phased Array Antenna Aperture

A phased array consists of two or more transmitting or receiving antenna elements that can be used together to form a directional radiation pattern

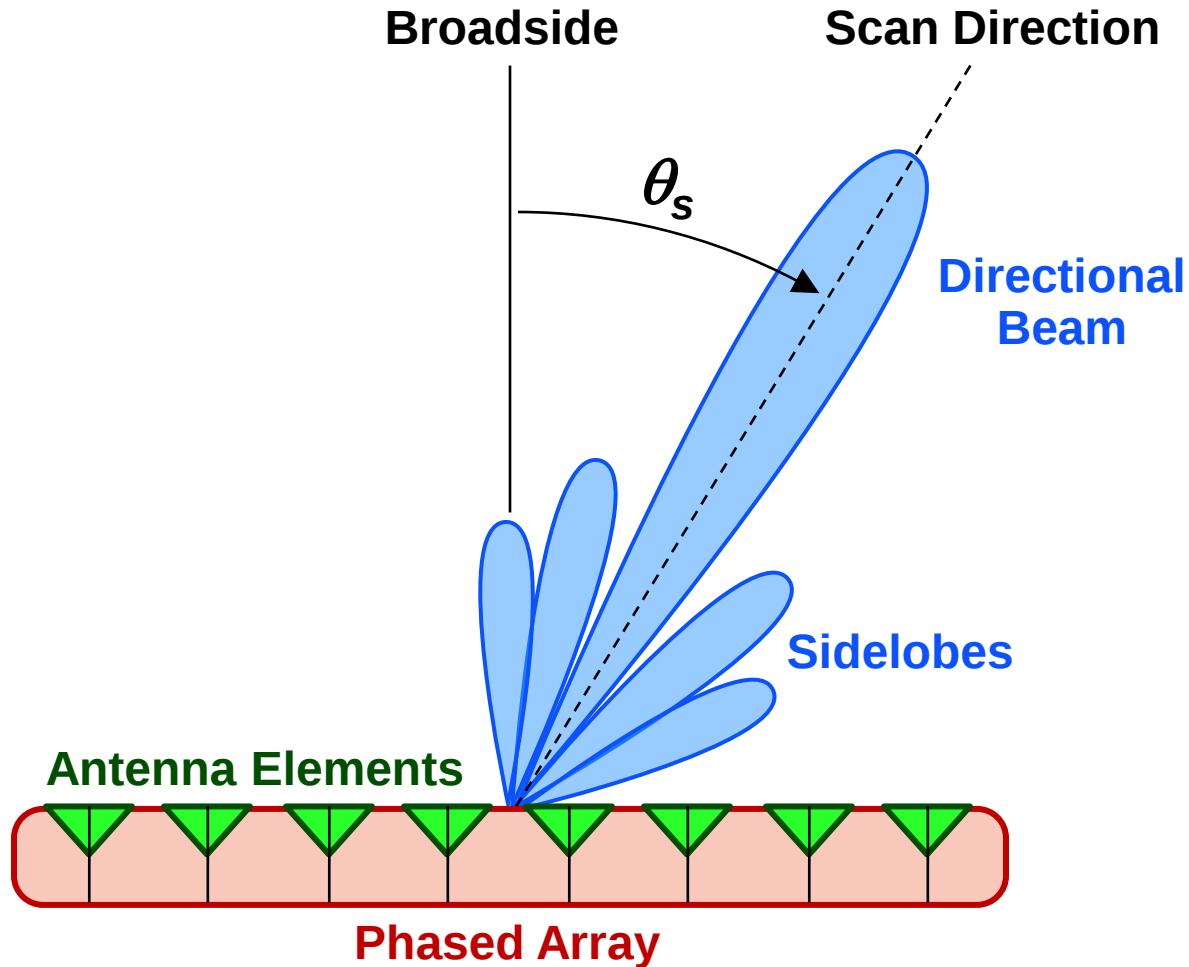


Ref: Online Course, MIT OpenCourseWare: A.J. Fenn, *Adaptive Antennas and Phased Arrays*,
<http://ocw.mit.edu/resources/res-6-007-adaptive-antennas-and-phased-arrays-spring-2010/>

Ref: Book: A.J. Fenn, *Adaptive Antennas and Phased Array for Radar and Communications*,
Artech, Norwood, MA, 2008, Chapter 8 (this slide and next 5 slides).

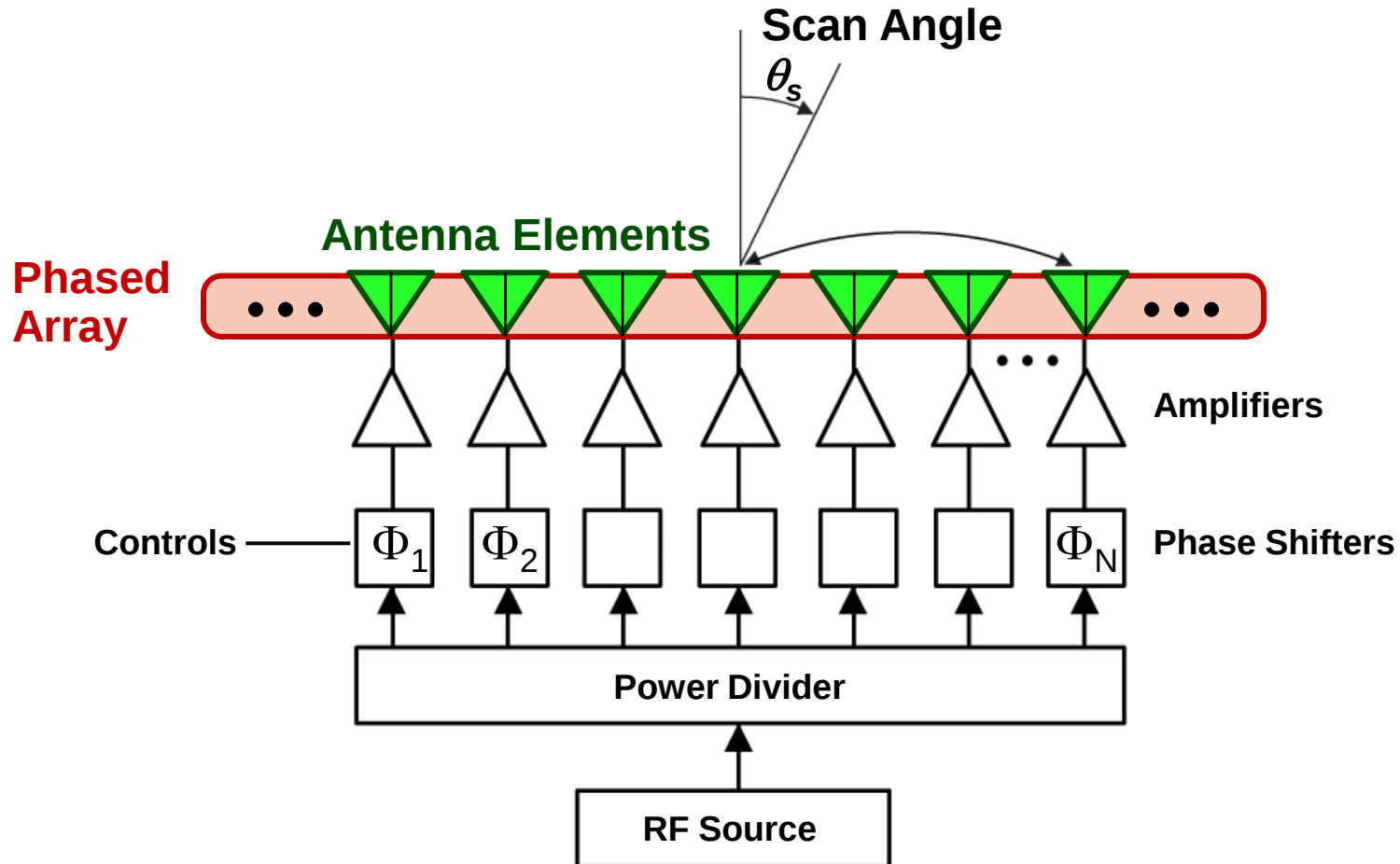


Linear Array with Main Beam Steered from Broadside





Transmit Phased Array Antenna Block Diagram

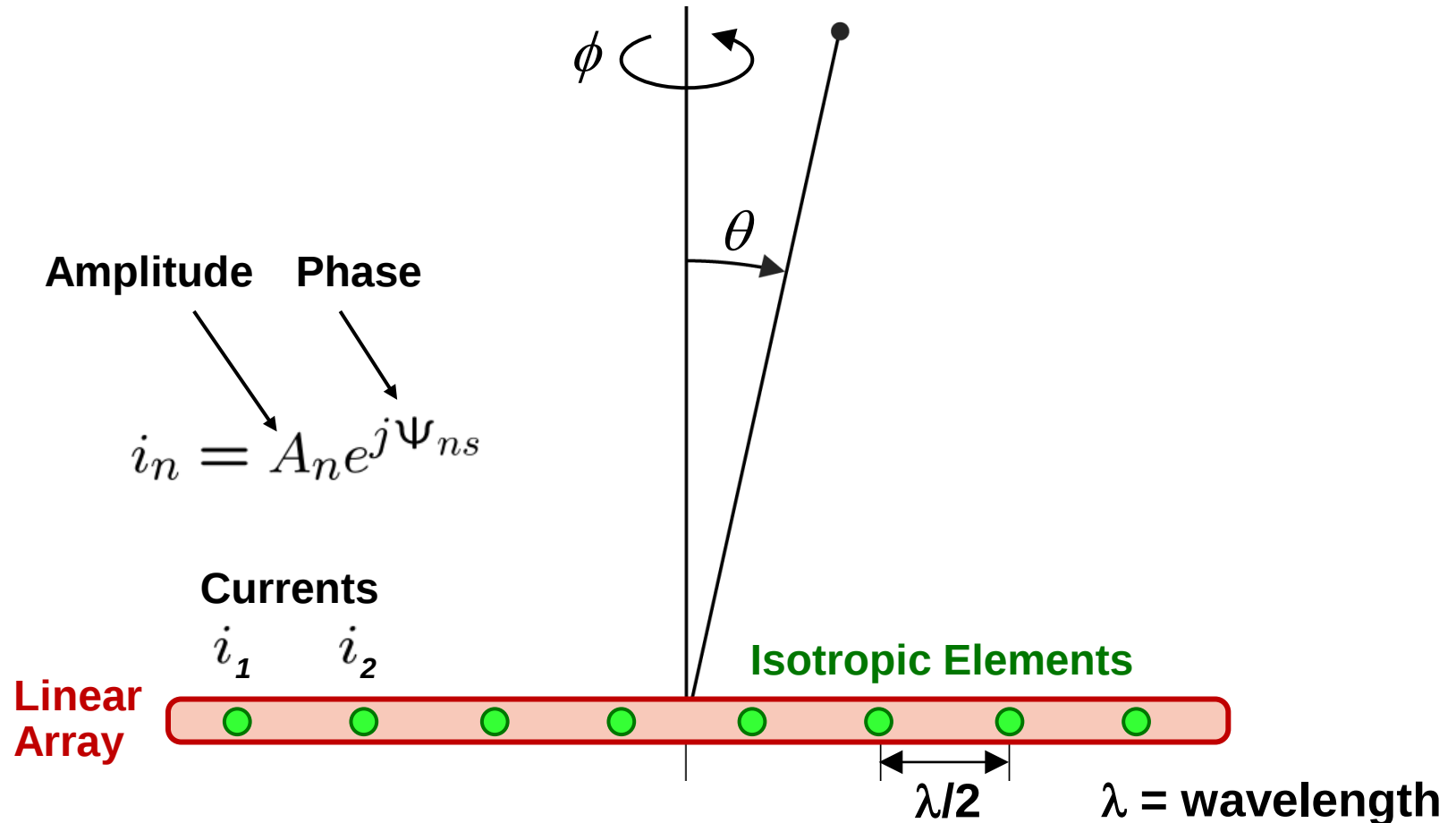


Phase shifters are used to electronically scan the array directional beam



Example 8-Element Linear Array of Isotropic Elements

Isotropic array elements have an element radiation pattern that is independent of observation angles in spherical coordinates as $p_e(\theta, \phi) = 1$



Calculated Radiation Patterns for an 8-Element Linear Array of Isotropic Elements (uniform illumination)

Array Factor →

$$AF(\theta, \phi) = \sum_{n=1}^N i_n e^{j\psi_n}$$

$$i_n = A_n e^{j\psi_{ns}}$$

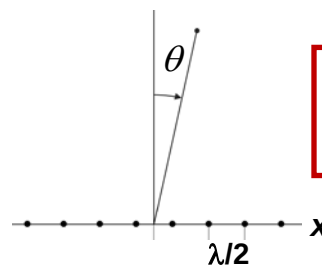
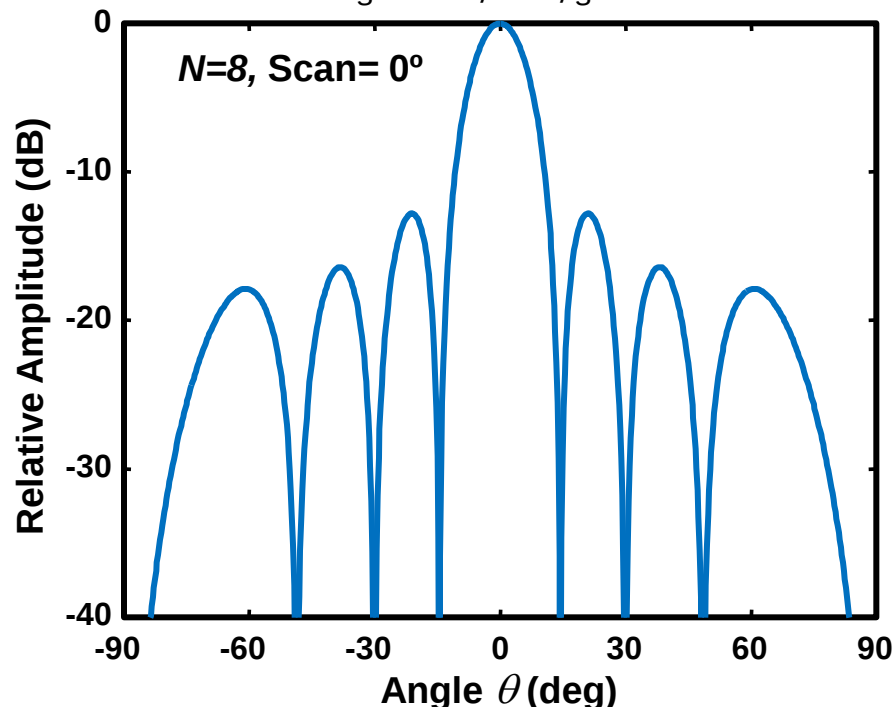
$$AF(\theta, \phi) = \sum_{n=1}^N A_n e^{j(\psi_n + \psi_{ns})}$$

$$\psi_n = \beta \sin \theta (x_n \cos \phi + y_n \sin \phi)$$

$$\psi_{ns} = -\beta \sin \theta_s (x_n \cos \phi_s + y_n \sin \phi_s)$$

$\beta = 2\pi/\lambda$ (is the phase constant)

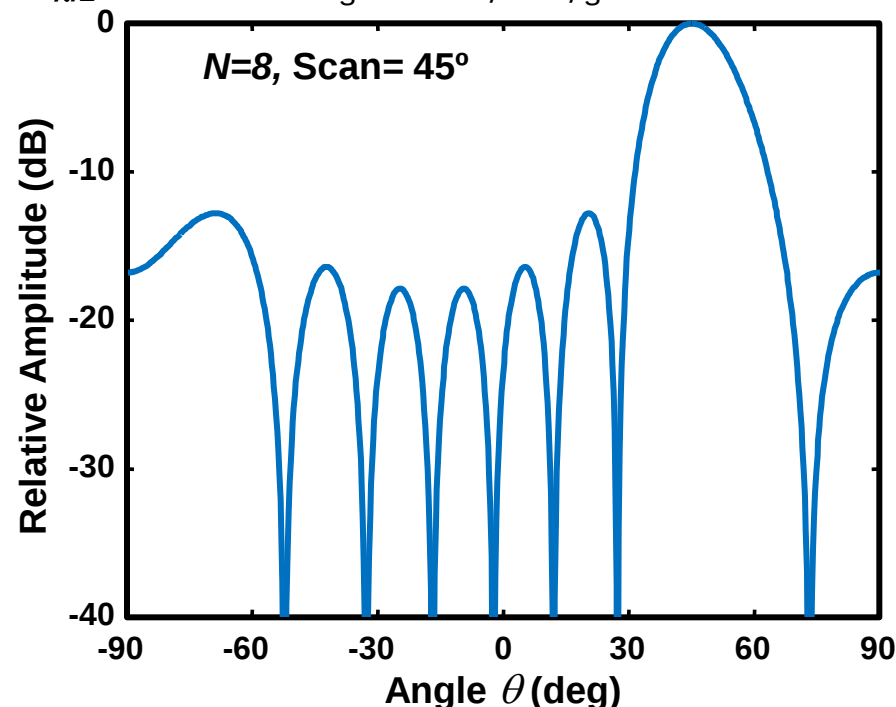
$$\theta_s = 0^\circ, \phi = \phi_s = 0^\circ$$



Radiation Pattern

$$AF(\theta) = \sum_{n=1}^N A_n e^{j\beta x_n (\sin \theta - \sin \theta_s)}$$

$$\theta_s = 45^\circ, \phi = \phi_s = 0^\circ$$

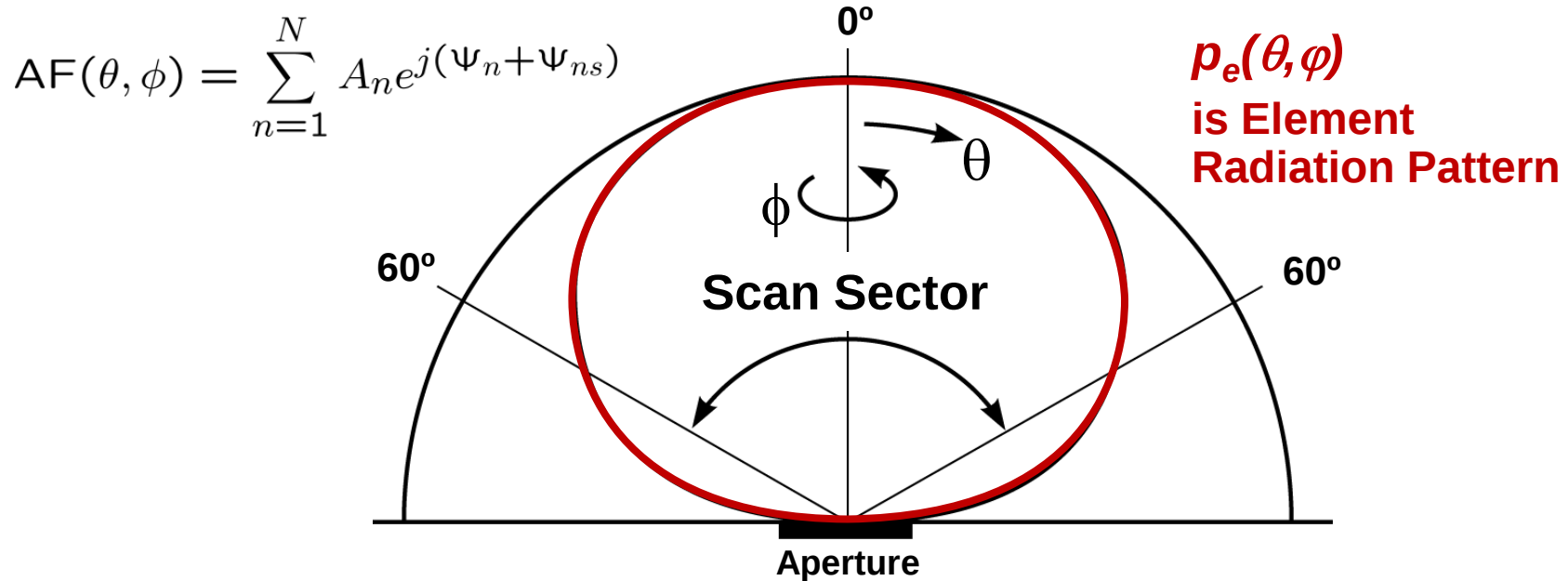




Example Element Radiation Pattern

Array Pattern, Radiation Intensity, Directivity

Most array elements have an element radiation pattern that favors broadside scan and depends on observation angle, that is, $p_e(\theta, \phi)$ has a peak at broadside ($\theta=0$) and a taper over the scan sector

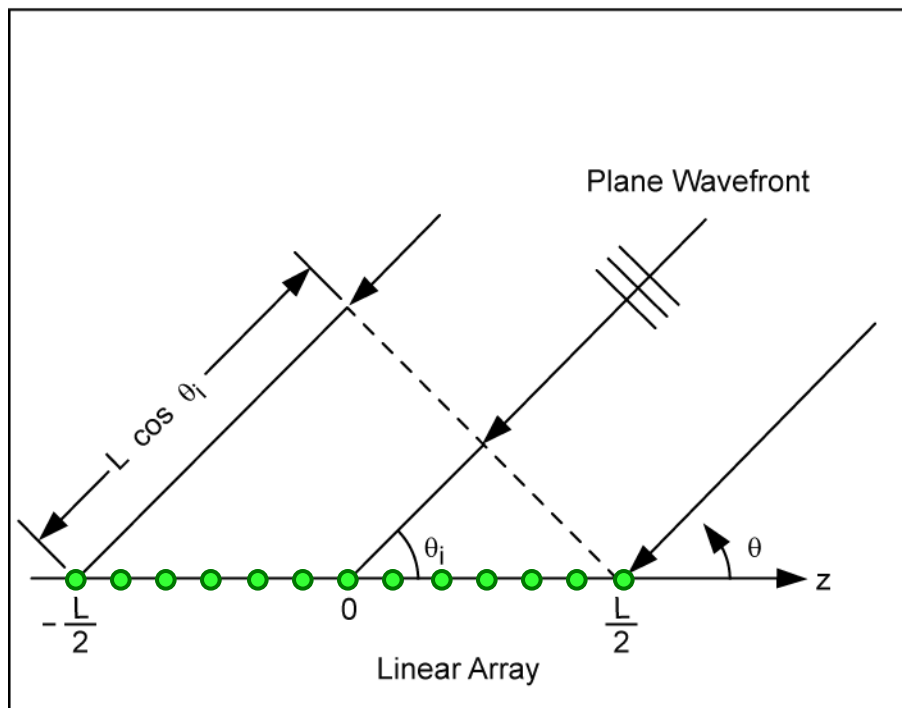


Array Pattern	Radiation Intensity (normalized)	Directivity
$P(\theta, \phi) = p_e(\theta, \phi)AF$	$U(\theta, \phi) = P(\theta, \phi) ^2$	$D(\theta, \phi) = \frac{U(\theta, \phi)}{U_{ave}}$

Geometry of Plane-Wave and Spherical-Wave Incidence for a Linear Array (**Physical Array or Synthetic Array**)

Far-field (Plane Wave)

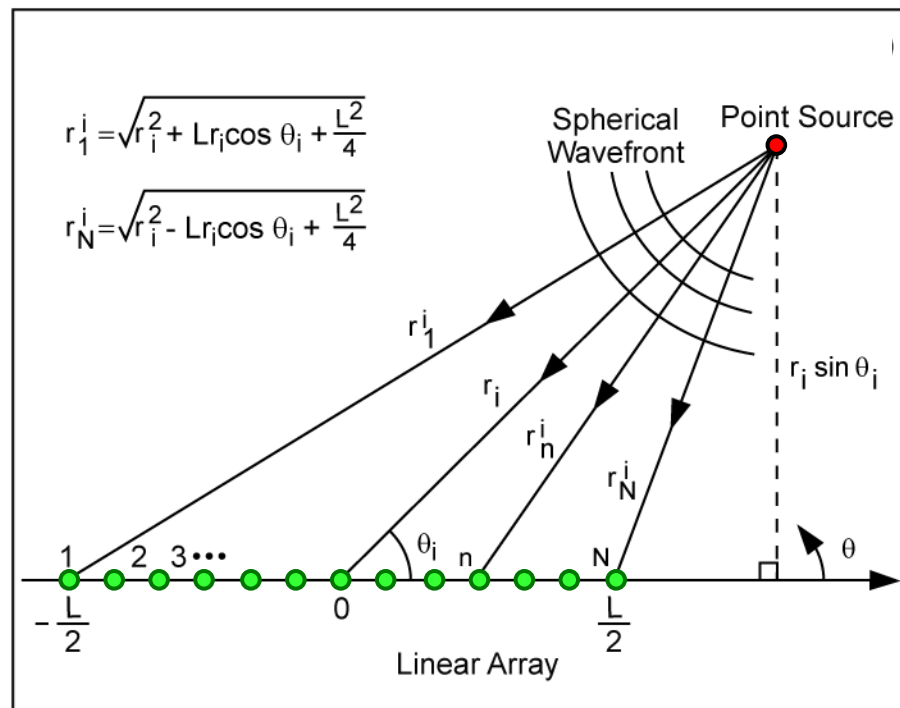
Far-Field Source



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Near-field (Spherical Wave)

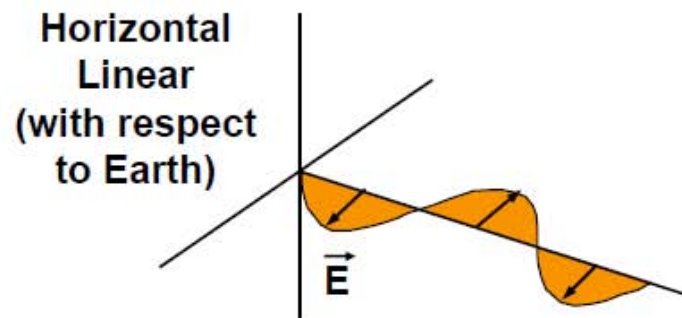
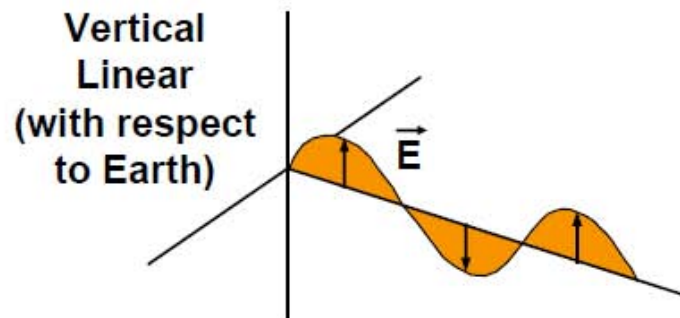
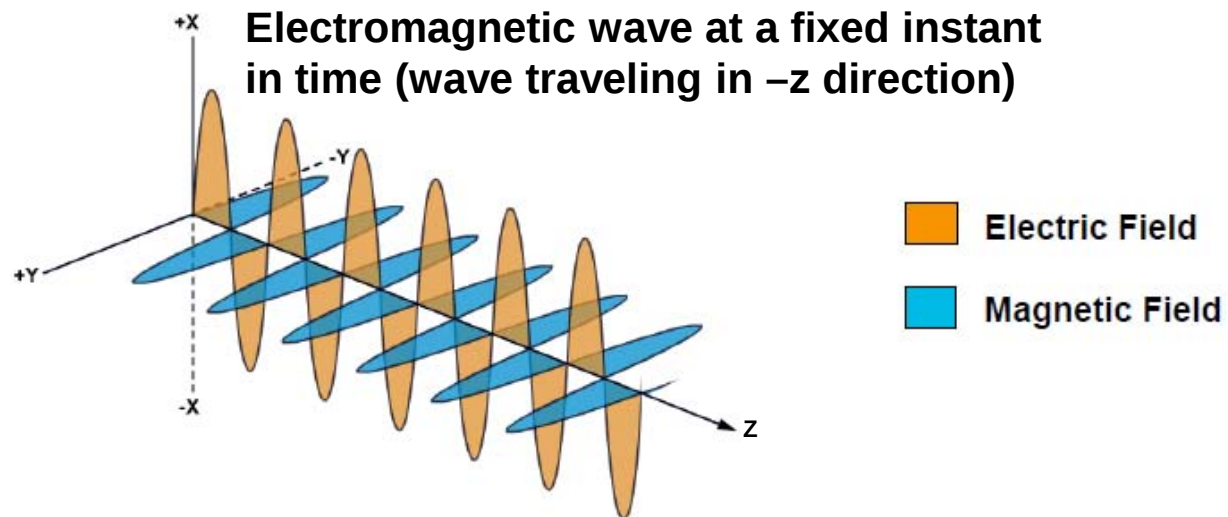
Near-Field Source



- Linear array can be implemented by using a *physical array aperture* or a *synthetic array aperture* (single element moved over an aperture)
- Array can be focused either in the far-field or near-field region [Fenn, 2008, Chapter 3]



Polarization of Electromagnetic Waves



Source: R.M. O'Donnell, <http://ocw.mit.edu/resources/res-II-001-introduction-to-radar-systems-spring-2007/>

The laptop radar antenna uses linearly polarized electromagnetic waves

Antenna Aperture Gain and Beamwidth

- The gain G (relative to an isotropic radiator) of an antenna aperture of arbitrary shape is given by the following expression:

$$G = 4\pi A_e / \lambda^2 \quad (1)$$

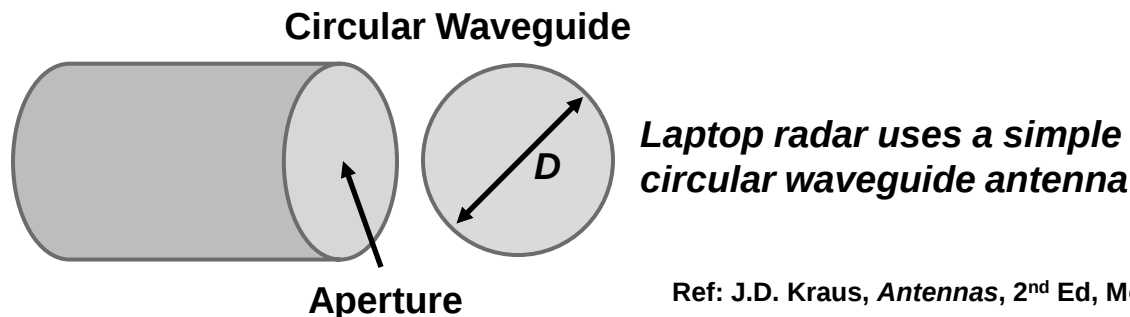
where A_e is the antenna effective aperture area and λ is the wavelength

Example

Example: An antenna with circular aperture (diameter D) has a maximum gain value in dBi (relative to isotropic) equal to

$$G_{m, \text{dBi}} = 10 \log_{10} (\pi D / \lambda)^2 \quad (2)$$

Antenna half-power beamwidth is approximately: $\text{HPBW} = 58^\circ \lambda / D \quad (3)$



Ref: J.D. Kraus, *Antennas*, 2nd Ed, McGraw Hill, 1988.



Transmit Power Density and Receive Power

- Effective isotropic radiated power (EIRP) is a function of the transmitted power P_t times the gain of the transmit antenna $G_t(\theta, \varphi)$

$$\text{EIRP}(\theta, \varphi) = P_t G_t(\theta, \varphi) \quad (4)$$

- Radiated power density P_d at a distance r from the transmit aperture is given by

$$P_d(\theta, \varphi) = \text{EIRP} / 4\pi r^2 = P_t G_t(\theta, \varphi) / 4\pi r^2 \quad (5)$$

- Power received P_r by an aperture is the product of the incident power density P_{di} and the effective aperture area A_e (refer to Eq. 1)

$$P_r = P_{di} A_e \quad (6)$$

- Relative power coupled between two antennas (transmit and receive)

$$P_r(\theta, \varphi) / P_t = G_t(\theta, \varphi) G_r(\theta, \varphi) \lambda^2 / (4\pi r)^2 \quad (7)$$

If the relative power coupled between two identical antennas ($G_r = G_t = G$) is measured, the antenna gain can be calculated

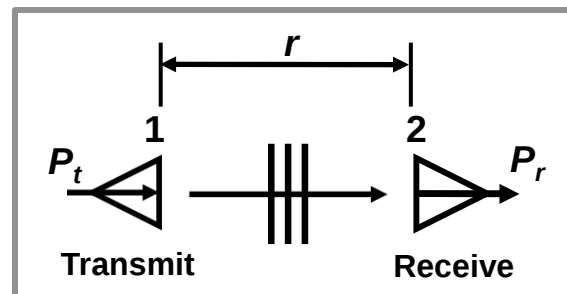
Ref: J.D. Kraus, *Antennas*, 2nd Ed, McGraw Hill, 1988.

Example Gain Calculation from Measured Power Coupling* Between Two “Identical” Antennas

- $P_r(\theta, \varphi) / P_t = G_t(\theta, \varphi) G_r(\theta, \varphi) \lambda^2 / (4\pi r)^2$ (7)

- $P_r(\theta, \varphi) / P_t = G^2 \lambda^2 / (4\pi r)^2$ (8)

- $G^2 = P_r(\theta, \varphi) / P_t (4\pi r / \lambda)^2$ (9)



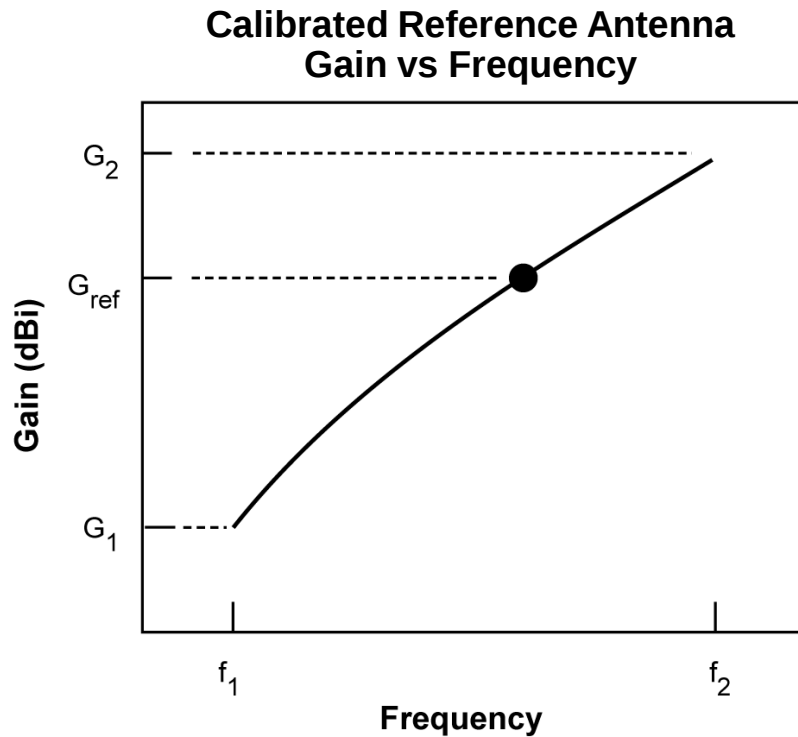
- $G_{dBi} = \frac{1}{2} [10 \log_{10} (P_r(\theta, \varphi) / P_t) + 20 \log_{10} (4\pi r / \lambda)]$ (10) **Antenna Gain**

- Let the frequency be 2.4 GHz, $\lambda = 0.125$ m (-18.1 dB)
- Network analyzer measures the power coupling (P_r / P_t in dB)
- **Assume** that the measured power coupling is -24 dB at $r = 1$ meter
- With $r = 1$ meter, then $20 \log_{10} 4\pi = 22$ dB
- Using Eq. (10): $G_{dBi} = \frac{1}{2} [-24 + 22 + 18.1] = 8.1$ dBi **Antenna Gain**

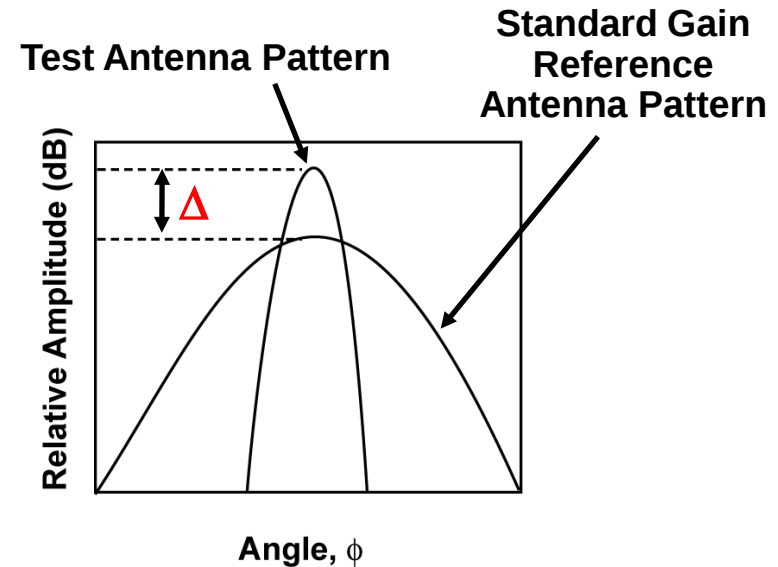
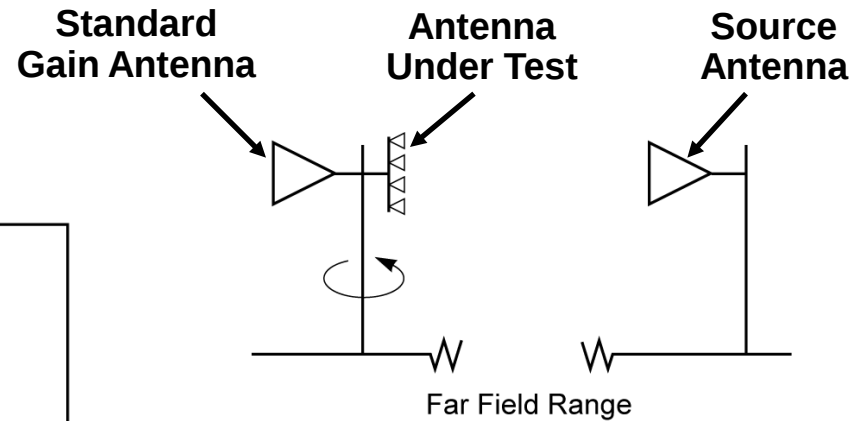
* Power coupling in dB is the same as “antenna mutual coupling” in dB or S-parameter S21 in dB



Antenna Gain Measurement by Comparison with Standard Gain Antenna



$$\text{Antenna gain} = G_{ref} + \Delta$$

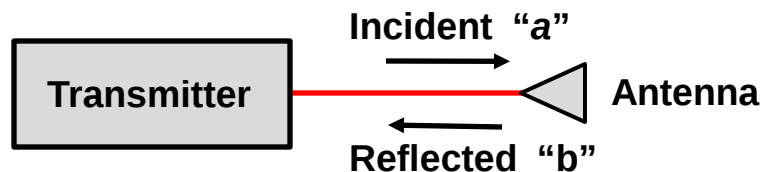


Ref: A.J. Fenn, *Adaptive Antennas and Phased Array for Radar and Communications*, Artech, Norwood, MA, 2008, p. 201.



Antenna Voltage Reflection Coefficient and Power Transmission Coefficient

- The voltage reflection coefficient (denoted R) of an antenna provides a quantitative measure of how much signal is reflected by the antenna relative to the incident signal
 - For a well-designed antenna, $|R|$ should be a small value
 - Reflection coefficient in dB also referred to as Return Loss in the literature
 - Reflection coefficient is also converted as $VSWR = (1 + |R|) / (1 - |R|)$
- The power transmission coefficient, $T^2 = 1 - |R|^2$, provides a quantitative measure of how much power is transmitted by the antenna relative to the incident power
 - For a well-designed antenna, T^2 should be close to unity
- The antenna reflection coefficient is often measured in decibels (dB) using the relation $10 \log_{10} |R|^2$
 - *If the antenna reflection coefficient is -10 dB, then $|R|^2 = 0.1$ and $T^2 = 0.9$ so that 90% of the available power is transmitted by the antenna (only about 0.5 dB of power is lost due to mismatch between the antenna and the transmission line)*



$R = b/a$ (reflection coefficient)

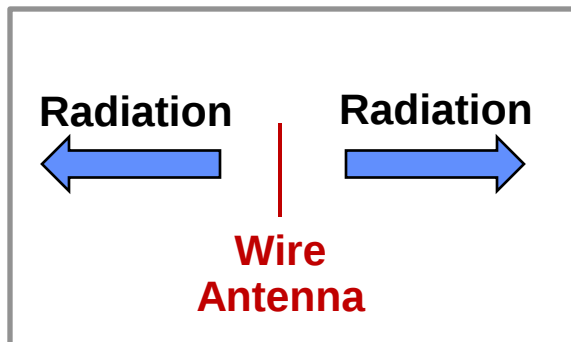
VSWR = voltage standing wave ratio



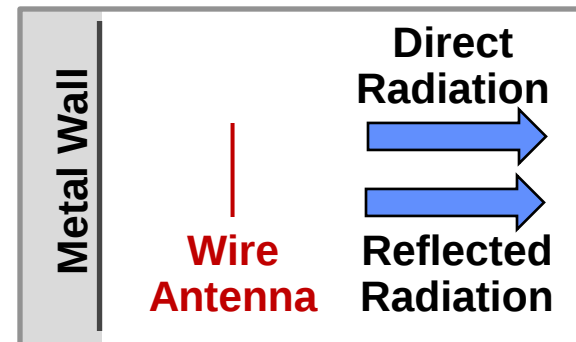
Microwave Phase Shift for an Antenna Near a Metal Wall

- Electromagnetic wave has $1/r$ field attenuation and a phase shift as it traverses a distance r
 - Electric Field: $E(r) = \exp(-j \beta r) / r$, where $\beta = 2\pi/\lambda$ is the phase constant
If an electromagnetic wave travels one-quarter of a wavelength the phase shifts by $\pi/2$ radians or 90 degrees
- Antenna polarized parallel to a metal wall: Antenna radiation that reflects from the wall has a 180 degree phase shift
- If it is desired to enhance the radiation in a particular direction, an antenna can be placed one-quarter of a wavelength from a metal wall (reflected wave adds with direct wave, $90^\circ + 180^\circ + 90^\circ = 360^\circ$)

Antenna in free space



Antenna $\lambda/4$ from metal wall



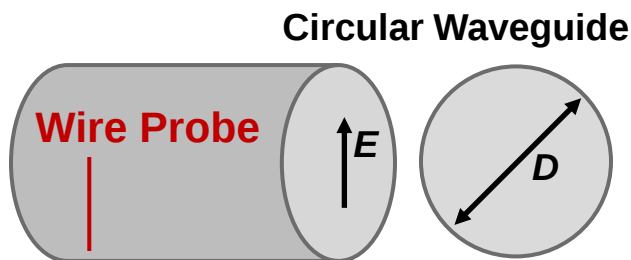


Wavelengths, Different Types

Free Space, Cutoff, Guide Wavelength

- **Wavelength λ of electromagnetic wave in free space**
 - $\lambda = c / f$, where c is the speed of light, f is the frequency
- **TE₁₁ mode cutoff wavelength λ_c in circular waveguide [$\lambda_c = c / f_c$]**
 - $\lambda_c = 1.705 D$, where D is the diameter of the circular waveguide
 - Dominant TE₁₁ mode will not propagate below corresponding cutoff frequency
- **Guide wavelength λ_g**
 - Wavelength is longer in waveguide compared to wavelength in free space
 - $\lambda_g = \lambda / \text{sqrt}(1 - (\lambda/(1.705 D))^2)$

Example: Circular Waveguide (coffee can)
Diameter = 3.9" (9.9 cm), Frequency = 2.4 GHz

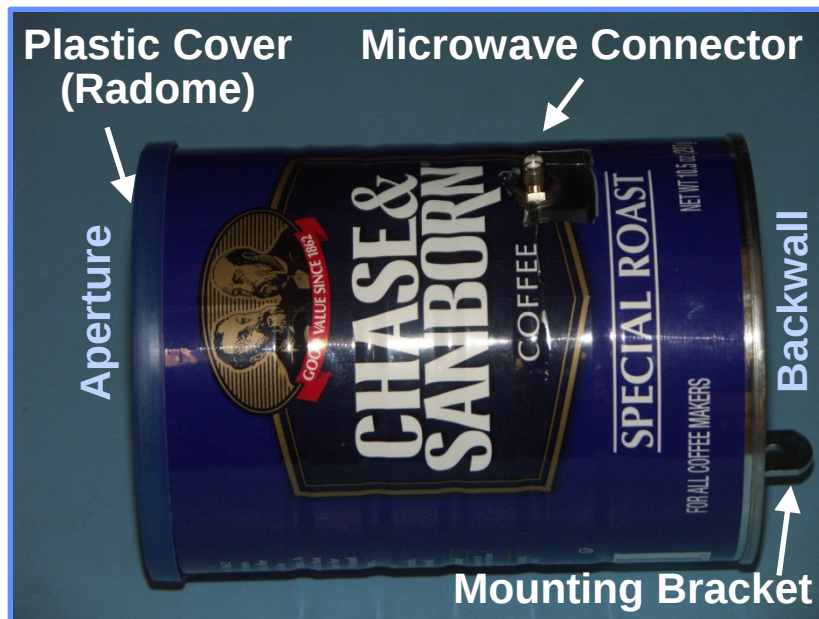


Parameter	Value
Wavelength (free space), λ	4.9" (12.5 cm)
Cutoff Frequency, f_c	1.8 GHz
Guide Wavelength, λ_g	7.3" (18.5 cm)

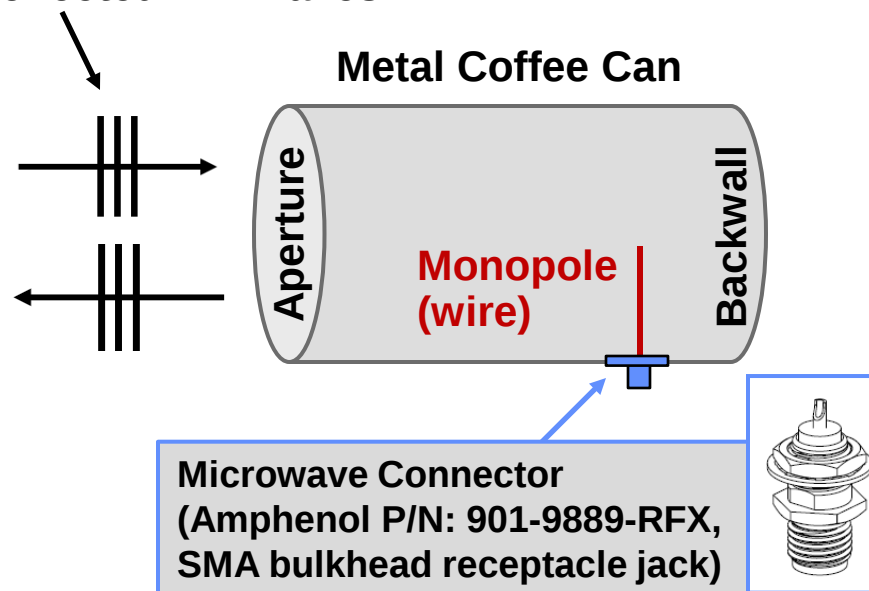
Ref: N. Marcuvitz, *Waveguide Handbook*, MIT Radiation Laboratory Series, New York, 1951, pp. 70-71.

Example Metal Can Antenna Design for 2.4 GHz

Circular Waveguide Antenna



Transmitted and Reflected EM Waves



Coffee can antenna dimensions:

Metal can length = 5.25" (13.3 cm)

Metal can diameter = 3.9" (9.9 cm) ($D=0.8 \lambda$, and $\lambda = 4.9"$ provides a 72.5° HPBW [see Slide 14, Eq. 3])

Monopole wire length = 1.2" (3 cm) (at 2.4 GHz $\sim \lambda / 4$ in free space)

Spacing from monopole wire to backwall = 1.8" (4.6 cm) (at 2.4 GHz $\sim \lambda_g / 4$ in waveguide – see Slide 20)

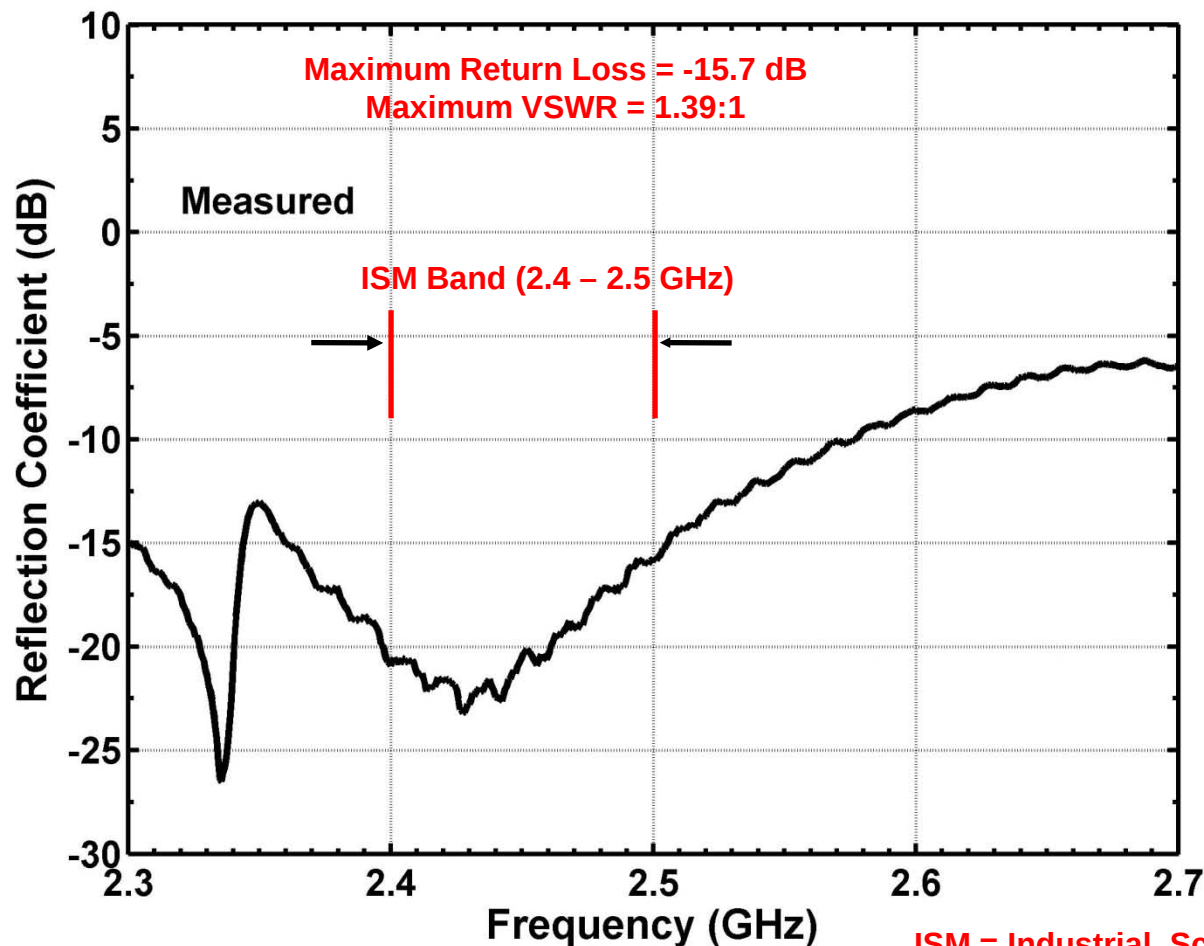
Ref: W.W.S. Lee and E.K.N. Yung, "The Input Impedance of a Coaxial Line Fed Probe in a Cylindrical Waveguide," *IEEE Trans. Microwave Theory and Techniques*, Vol. 42, No. 8, August 1994, pp. 1468-1473.



Laptop Radar Antenna Assembly and Test

- Drill hole in side of metal can for connector, 1.8" (4.57 cm) from backwall
- Attach microwave connector, with monopole wire approximately 1.5" (3.8 cm) long soldered onto the center pin of the connector
 - Connector grounded securely to metal surface of can
- Connect microwave coaxial cable from network analyzer to assembled coffee can antenna
- Trim the length of the monopole wire in small amounts until the measured reflection coefficient (return loss) is less than about -10 dB over the ISM band (2.4 to 2.5 GHz)
 - Final trimmed length of monopole wire should be about 1.2 inches (3 cm) as measured from the tip of the monopole to the base of the connector at the inside surface of the metal can
- Measure the relative power coupled between two assembled antennas facing each other 1 meter apart, and calculate the antenna gain based on Equation (10) at 2.4 GHz (see slide 16)
 - Polarization of antennas must be aligned with each other
- Antennas are now ready for integration with the laptop radar

Network Analyzer Measurement of Reflection Coefficient (Return Loss) for Laptop Radar Antenna #6



ISM = Industrial, Scientific, Medical

Measured reflection coefficient demonstrates good performance over the full ISM band

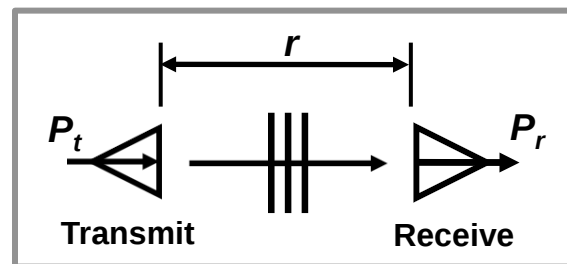
Gain Estimation from Measured Power Coupling Between Two Laptop Radar Antennas (#4 and #6)

$$P_r(\theta, \phi) / P_t = G_t(\theta, \phi) G_r(\theta, \phi) \lambda^2 / (4\pi r)^2 \quad (7)$$

$$P_r(\theta, \phi) / P_t = G^2 \lambda^2 / (4\pi r)^2 \quad (8)$$

$$G^2 = P_r(\theta, \phi) / P_t (4\pi r / \lambda)^2 \quad (9)$$

$$G_{dBi} = \frac{1}{2} [10 \log_{10} (P_r(\theta, \phi) / P_t) + 20 \log_{10} (4\pi r / \lambda)] \quad (10)$$

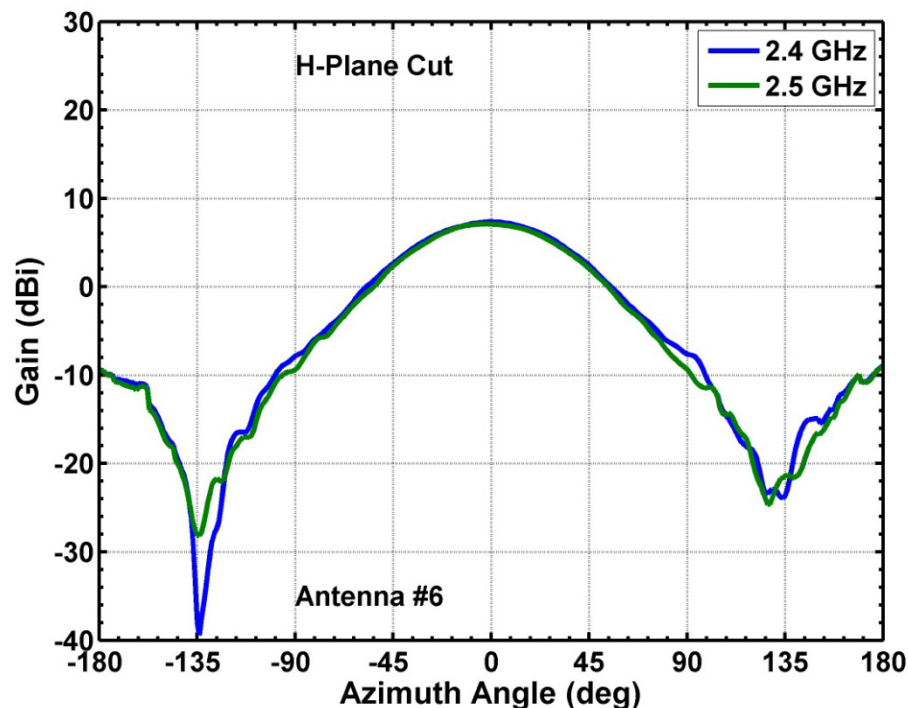
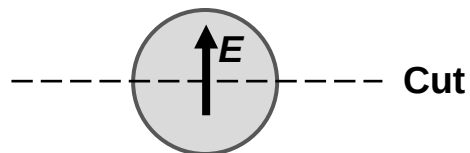


- Let the frequency be 2.4 GHz, $\lambda = 0.125$ m (-18.1 dB)
- Network analyzer measures the power coupling (P_r / P_t in dB)
- **Measured** power coupling is -23.3 dB at $r = 1$ meter
- With $r = 1$ meter, then $20 \log_{10} 4\pi = 22$ dB
- Eq. (10): $G_{dBi} = \frac{1}{2} [-23.3 + 22 + 18.1] = 8.4$ dBi (antenna gain, $r = 1$ m)
- Eq. (2): $G_{m, dBi} = 10 \log_{10} (\pi D / \lambda)^2 = 10 \log_{10} (\pi 0.1 \text{ m} / 0.125 \text{ m})^2 = 8.0$ dBi

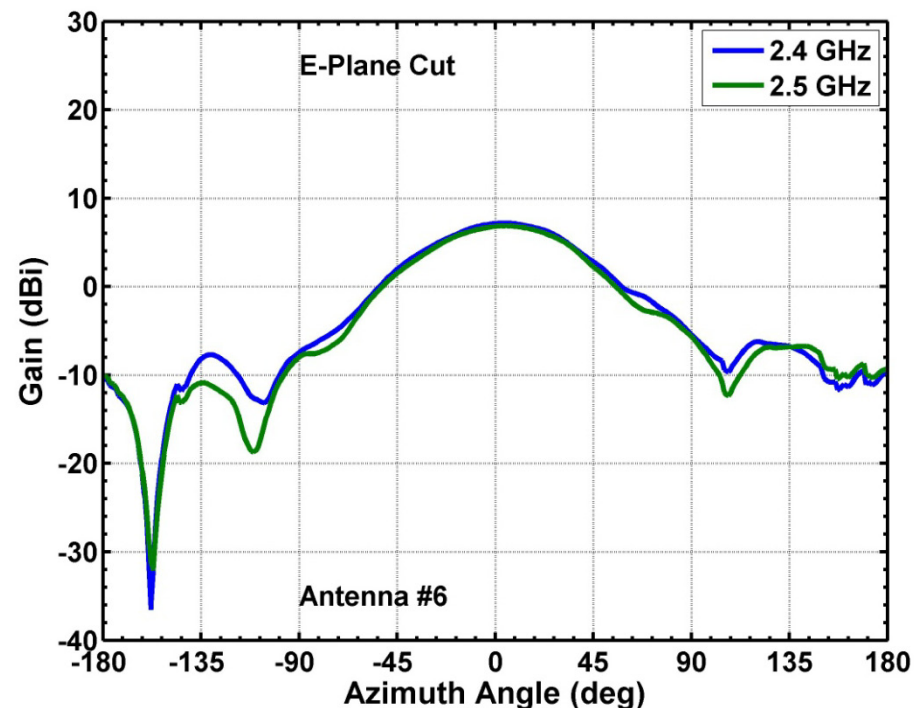
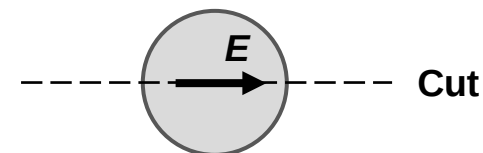
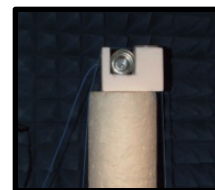


Far-Field Measured Gain Patterns*

Laptop Radar Antenna #6 (range = 8.5 meters)



Peak gain = 7.2 dBi, Half-power beamwidth = 72°



Peak gain = 7.3 dBi, Half-power beamwidth = 70°

Measured far-field gain patterns demonstrate good performance over the full ISM band

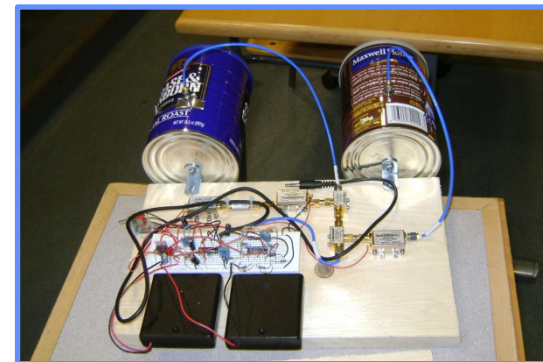


Circular Waveguide (coffee can) Antennas used by the MIT IAP Laptop Radar Teams

18 Antennas Distributed to the Laptop Radar Teams



Transmit and Receive Antennas Integrated with Radar Electronics





Summary

- **Some of the fundamental characteristics of antennas have been described**
- **Described the design of a simple circular waveguide antenna (made from a coffee can) that can be used as the transducer for the laptop radar system**
- **Described the materials and methods for fabricating and testing the laptop radar antenna**
- **Measured data for the laptop radar antenna indicate good performance over the full ISM band (2.4 to 2.5 GHz)**
 - **Reflection coefficient is better than -15.7 dB (VSWR < 1.4:1)**
 - **Peak gain is greater than 7 dBi**
 - **Half-power beamwidth is approximately 70 degrees**

MIT OpenCourseWare
<http://ocw.mit.edu>

Resource: Build a Small Radar System Capable of Sensing Range, Doppler, and Synthetic Aperture Radar Imaging
Dr. Gregory L. Charvat, Mr. Jonathan H. Williams, Dr. Alan J. Fenn, Dr. Steve Kogon, Dr. Jeffrey S. Herd

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