# Antenna Design for the Laptop Radar Project*

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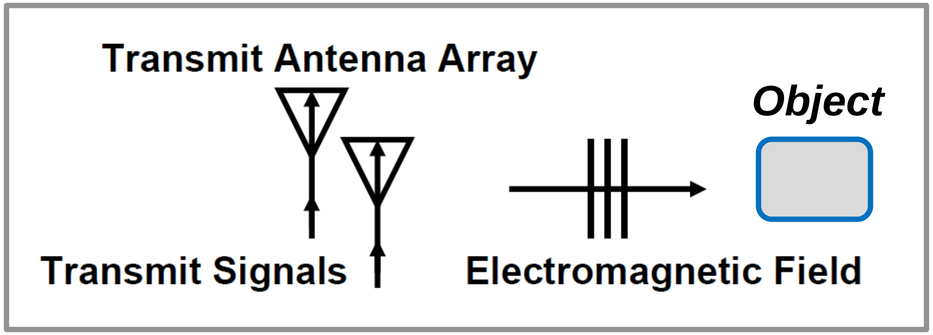
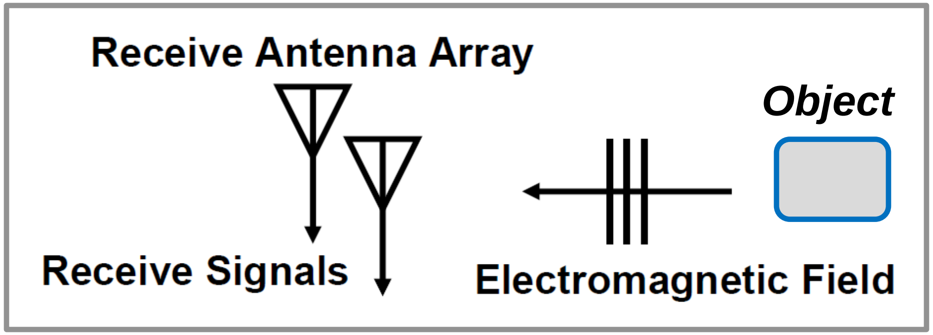
# Introduction

- 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

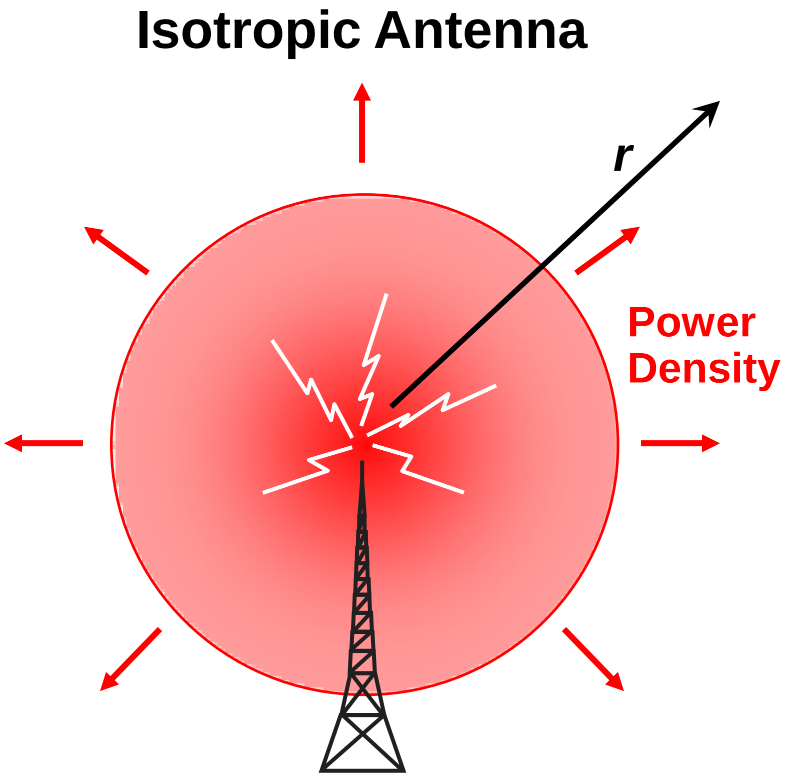
- **An antenna can be either single or multiple *transducer*s that can convert a signal voltage on a transmission line to a transmitted electromagnetic (EM) wave (also receives EM waves)**
  - **Radar transmitter induces a time-varying microwave signal that travels along coaxial cable to the transmit 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**

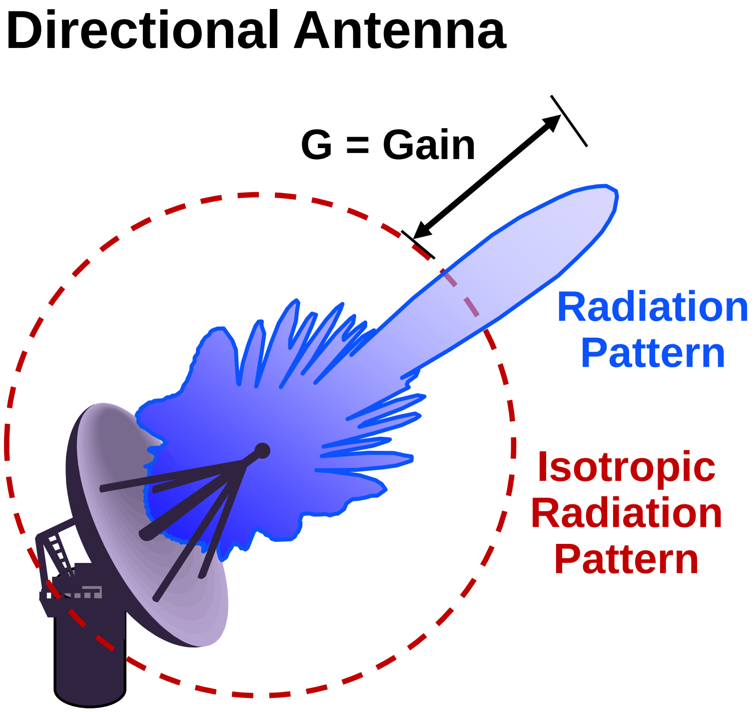




# Antenna Power Density and Gain

## Isotropic and Directional Antennas

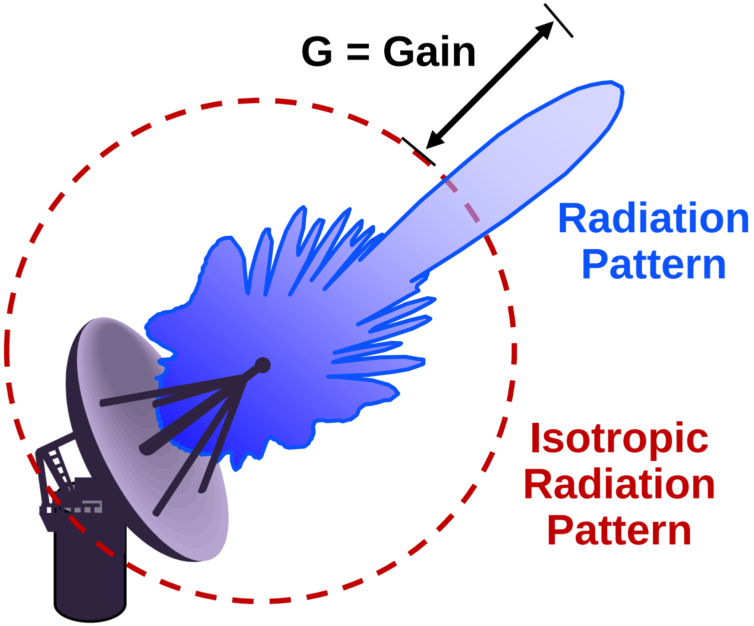




Source: R.M. O'Donnell, http://ocw.mit.edu/resources/res-ll-001-introduction-to-radar-systems-spring-2007/

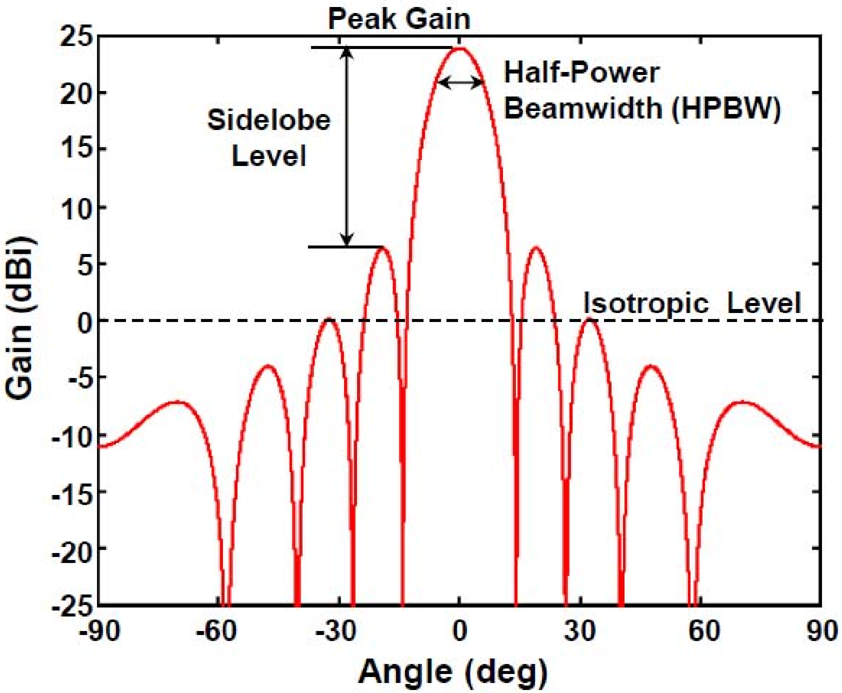
- **Power density ($W/m^2$) decreases as range *r* increases, Gain is relative to isotropic antenna**
- **Directional antenna produces a gain radiation pattern that depends on the aspect angle**
- **Peak gain and peak power density increase for a directional antenna compared to an isotropic antenna**

# Antenna Gain Radiation Pattern Characteristics



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

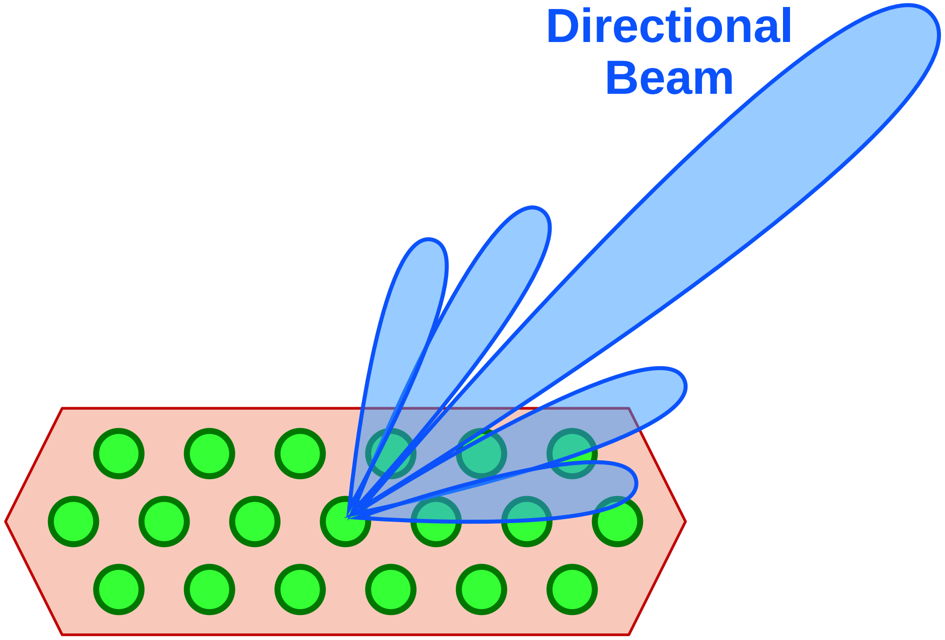
**Gain Pattern for Circular Aperture, 5 Wavelengths Diameter**



- 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**

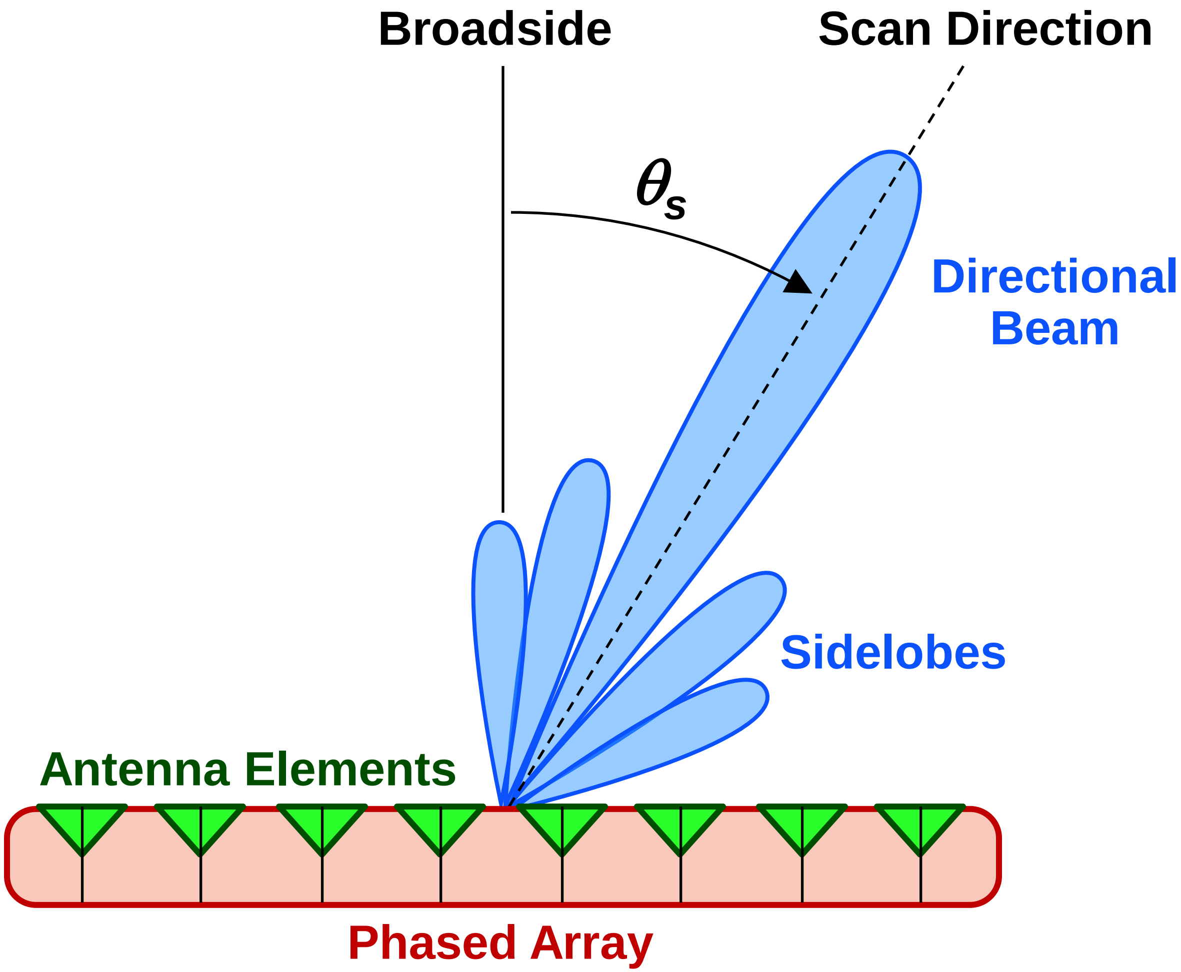


**Phased Array Antenna**

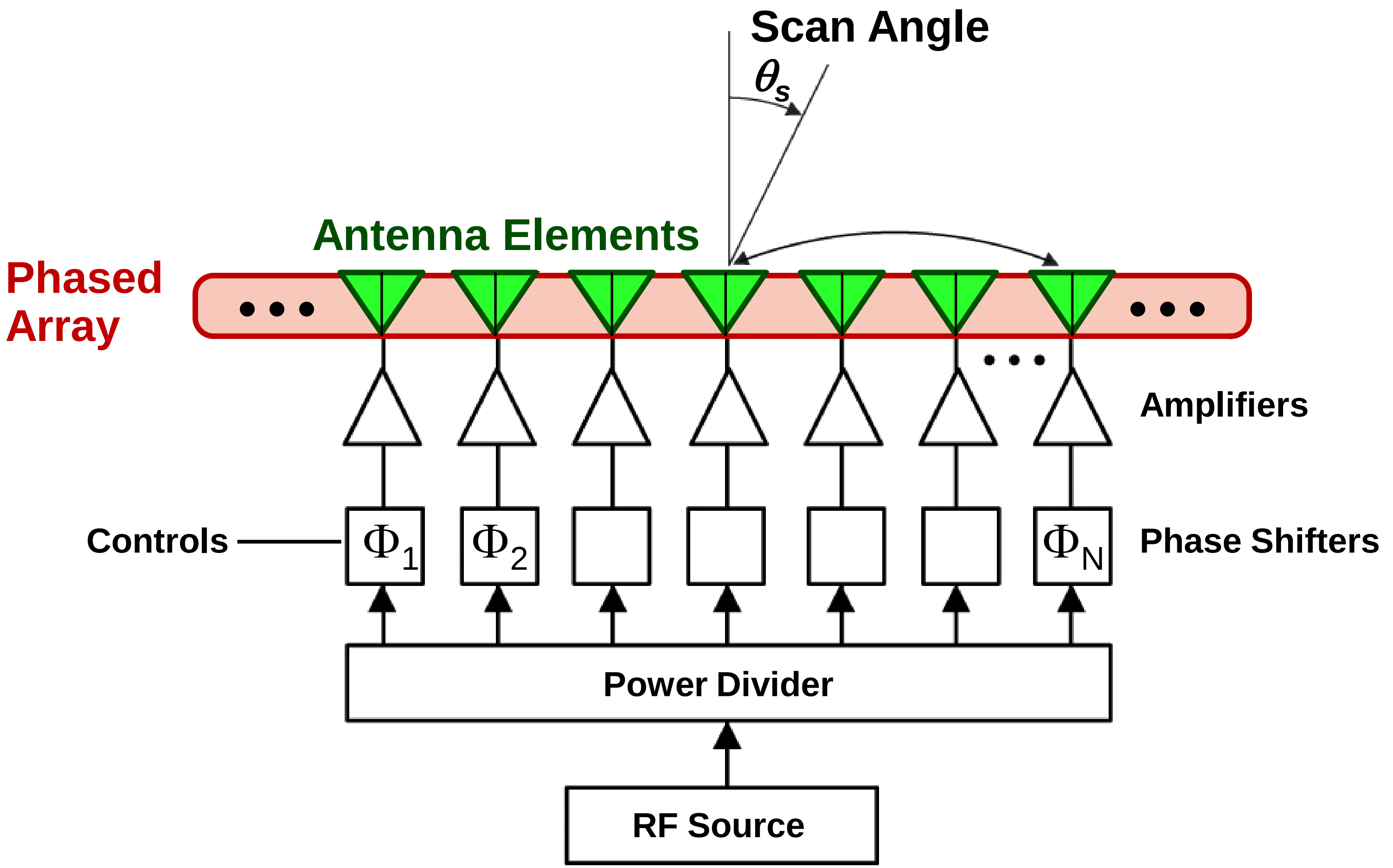
**Ref: Online Course, MIT OpenCourseWare: A.J. Fenn, *Adaptive Antennas and Phased Arrays*,**
**http://ocw.mit.edu/resources/res-6-007-adaptive-antennas-and-phased-arrays-spring-2010/**

**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



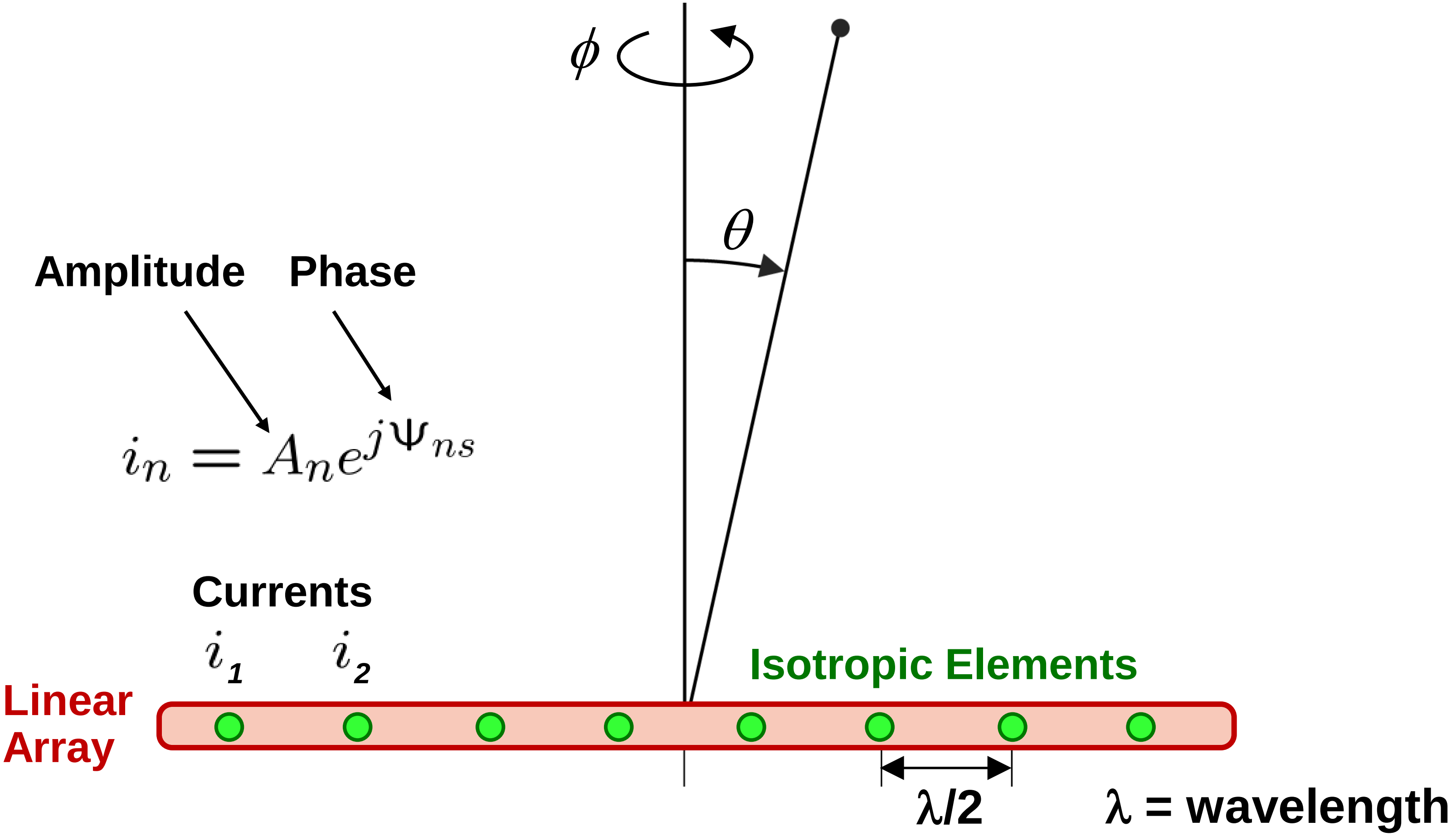
# Transmit Phased Array Antenna Block Diagram



**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 $p_e(\theta,\varphi) = 1$**



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

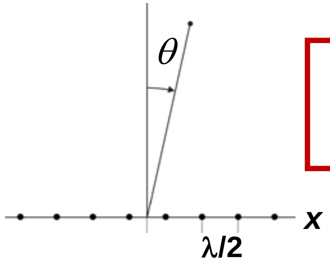
**Array Factor** →

$$\mathrm{AF}(\theta,\phi) = \sum_{n=1}^{N} i_n e^{j\Psi_n} \qquad i_n = A_n e^{j\Psi_{ns}} \qquad \mathrm{AF}(\theta,\phi) = \sum_{n=1}^{N} A_n e^{j(\Psi_n+\Psi_{ns})}$$

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

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

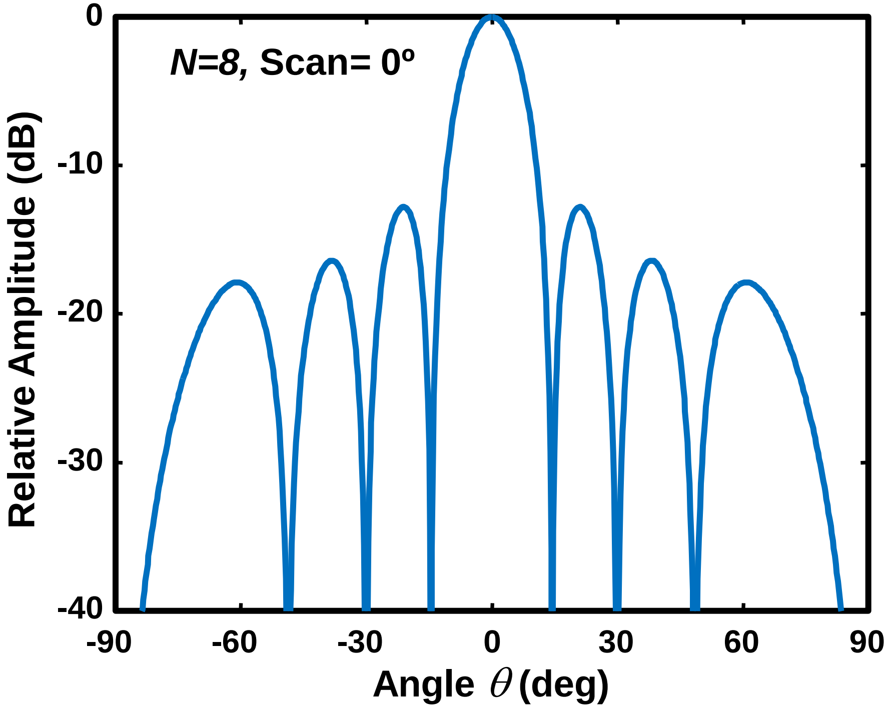
**$\beta = 2\pi/\lambda$ (is the phase constant)**



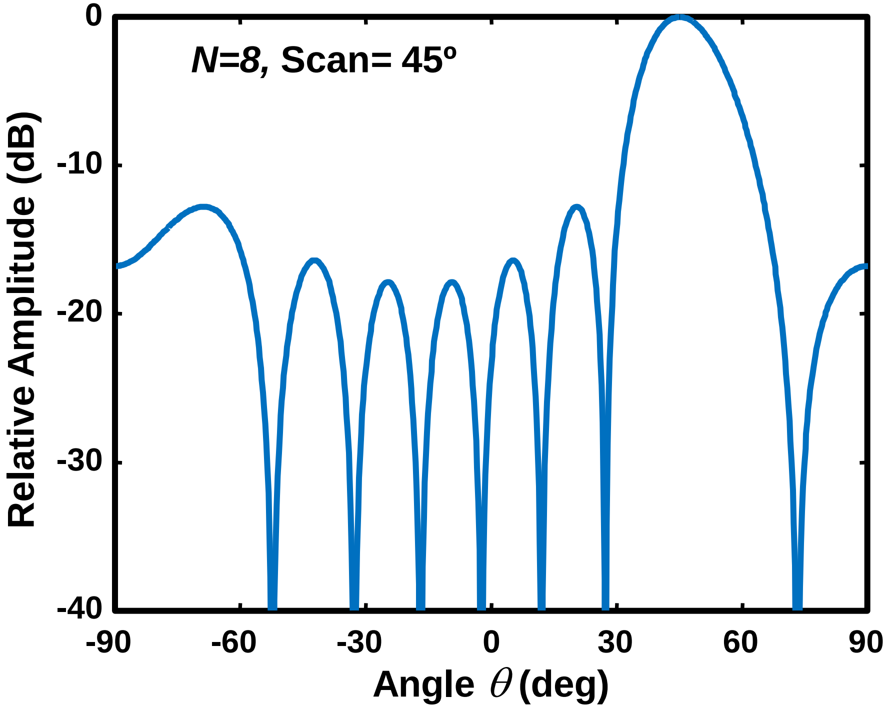
***Radiation Pattern***

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

$\theta_s$=0°, $\phi$ = $\phi_s$=0°



$\theta_s$=45°, $\phi$ = $\phi_s$=0°

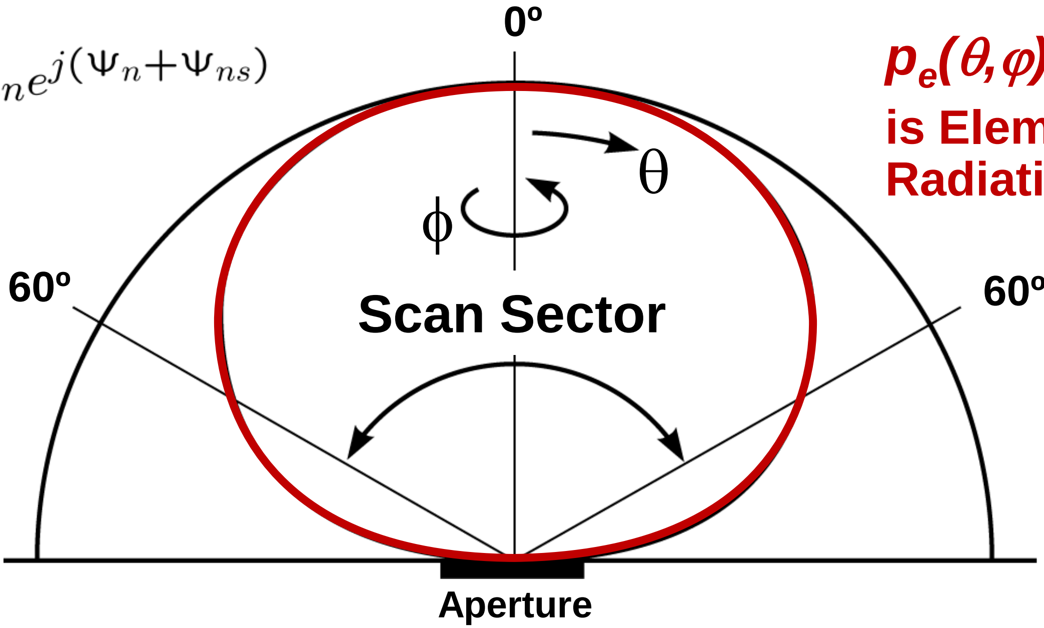


# Example Element Radiation Pattern

## Array Pattern, Radiation Intensity, Directivity

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

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



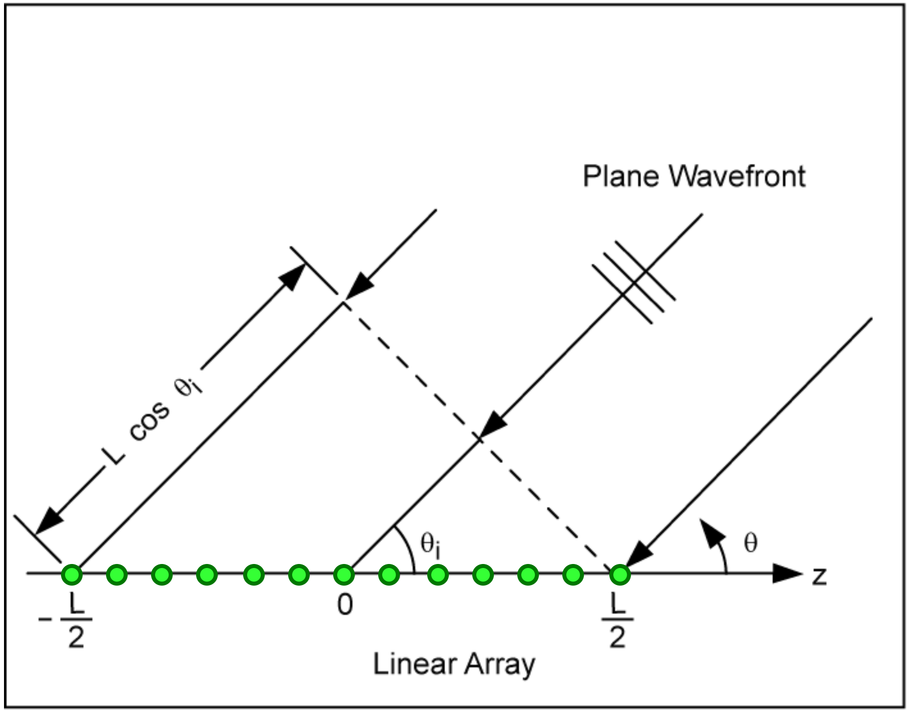
**$p_e(\theta,\varphi)$ is Element Radiation Pattern**

| Array Pattern | Radiation Intensity (normalized) | Directivity |
|---|---|---|
| $P(\theta,\phi) = p_e(\theta,\phi)\mathsf{AF}$ | $U(\theta,\phi) = \lvert P(\theta,\phi)\rvert^2$ | $D(\theta,\phi) = \dfrac{U(\theta,\phi)}{U\mathsf{ave}}$ |

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

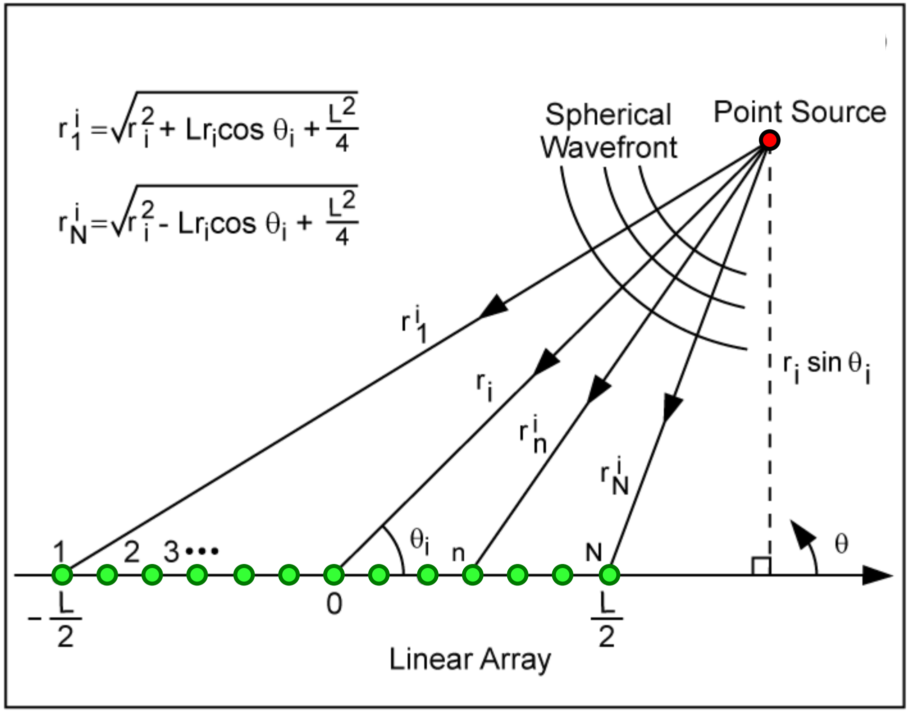
## Far-field (Plane Wave)

**Far-Field Source**



## Near-field (Spherical Wave)

**Near-Field Source**



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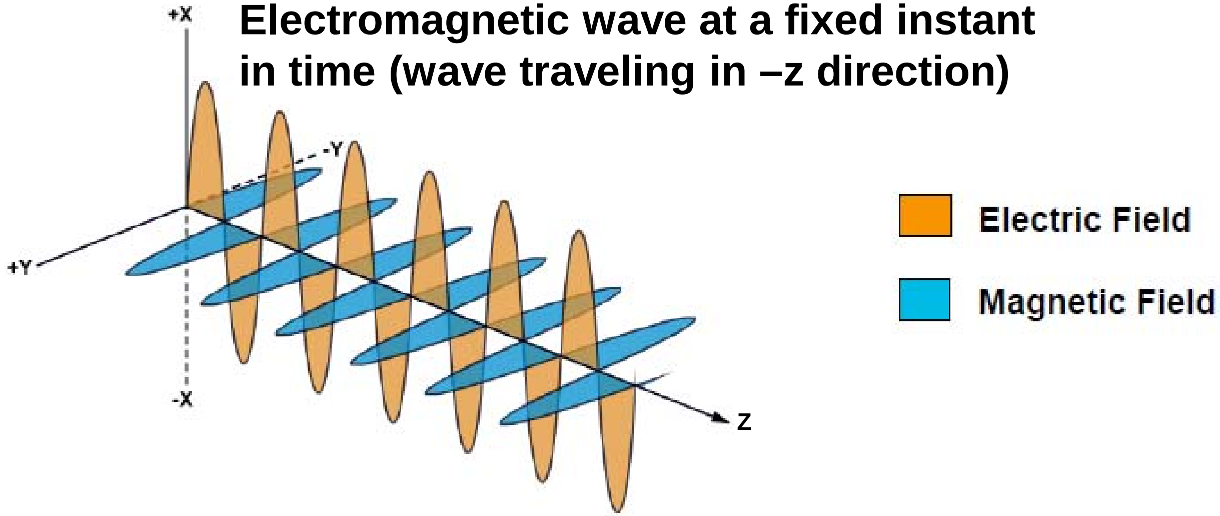
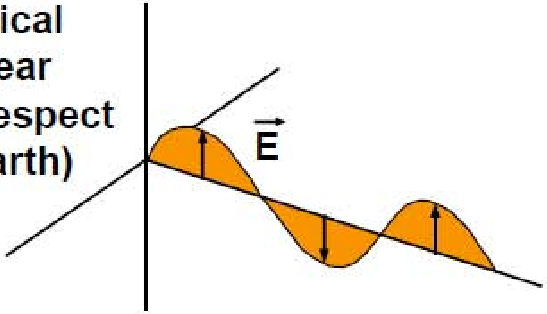
- Linear array can be implemented by using a *physical array aperture or a synthetic array aperture* (single element moved over an aperture)
- Array can be focused either in the far-field or near-field region [Fenn, 2008, Chapter 3]

# Polarization of Electromagnetic Waves

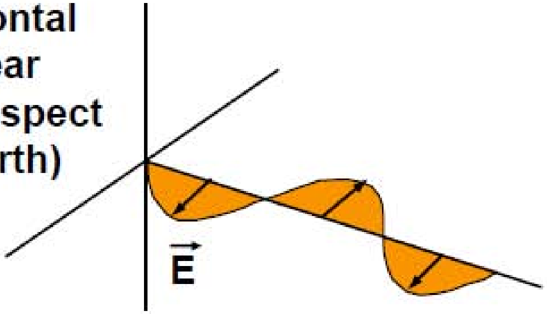
**Electromagnetic wave at a fixed instant in time (wave traveling in –z direction)**



Vertical Linear (with respect to Earth)



Horizontal Linear (with respect to Earth)



Source: R.M. O'Donnell, http://ocw.mit.edu/resources/res-ll-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:

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

where $A_e$ is the antenna effective aperture area and $\lambda$ is the wavelength

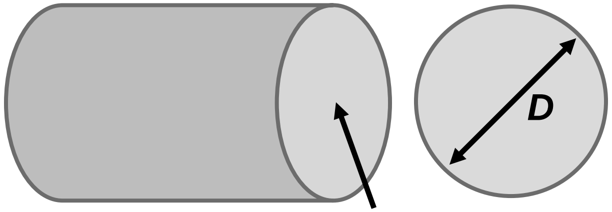
**Example**

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

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

Antenna half-power beamwidth is approximately: $\mathrm{HPBW} = 58° \lambda / D$ (3)

Circular Waveguide



*Laptop radar uses a simple circular waveguide antenna*

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 $G_t(\theta,\varphi)$

  $$\mathrm{EIRP}(\theta,\varphi) = P_t\,G_t(\theta,\varphi) \qquad (4)$$

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

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

- 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)

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

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

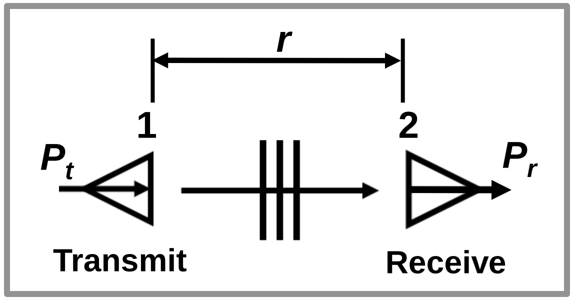
  $$P_r(\theta,\varphi)/\,P_t = G_t(\theta,\varphi)\,G_r(\theta,\varphi)\,\lambda^2\,/\,(4\pi r)^2 \qquad (7)$$

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



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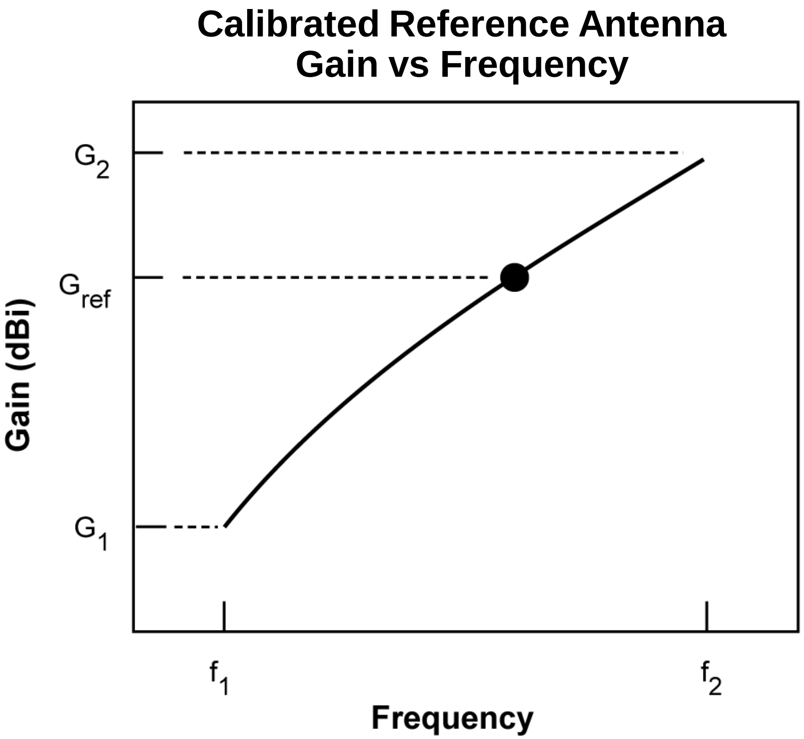
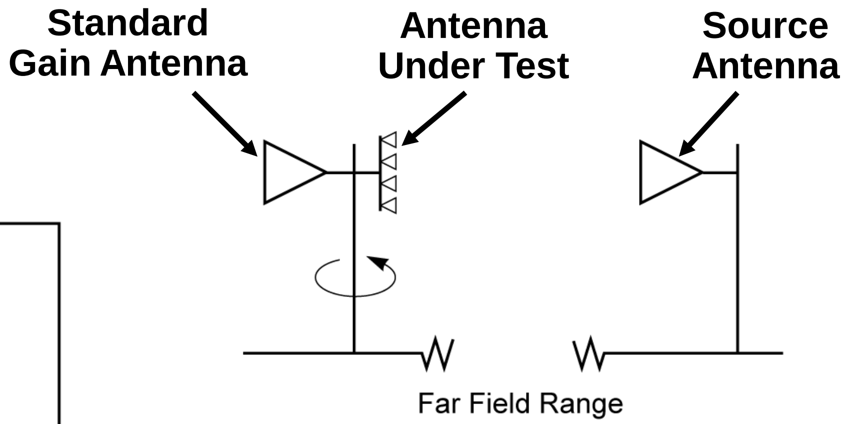
- Let the frequency be 2.4 GHz, $\lambda$=0.125 m (-18.1 dB)
- Network analyzer measures the power coupling ($P_r/P_t$ in dB)
- Assume that the measured power coupling is -24 dB at r = 1 meter
- With r = 1 meter, then $20 \log_{10} 4\pi = 22$ dB
- Using Eq. (10): $\boxed{G_{dBi} = \tfrac{1}{2}[-24 +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

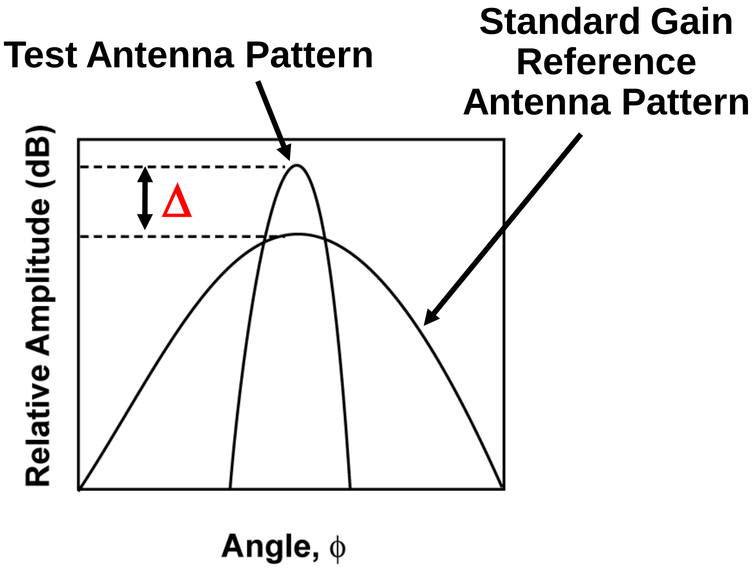
* Power coupling in dB is the same as “antenna mutual coupling” in dB or S-parameter S21 in dB

# Antenna Gain Measurement by Comparison with Standard Gain Antenna



**Antenna gain = $G_{ref}$ + Δ**

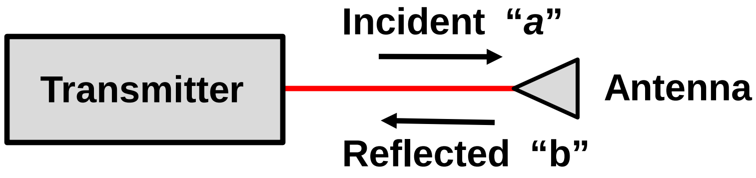




Ref: A.J. Fenn, *Adaptive Antennas and Phased Array for Radar and Communications*, Artech, Norwood, MA, 2008, p. 201.

# 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)**

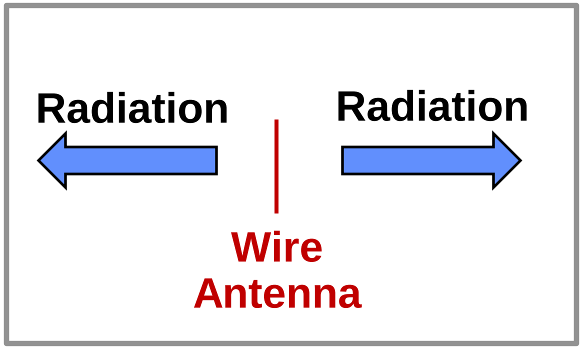
**VSWR = voltage standing wave ratio**

# Microwave Phase Shift for an Antenna Near a Metal Wall

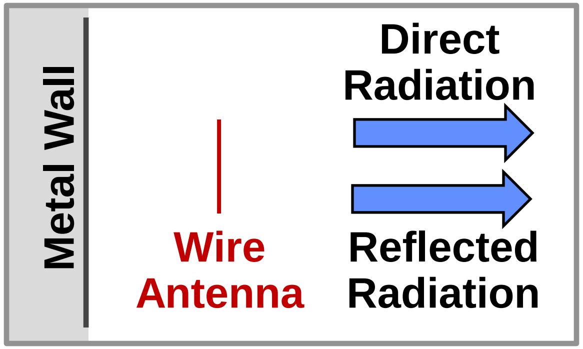
- **Electromagnetic wave has 1/*r* field attenuation and a phase shift as it traverses a distance *r***
  - **Electric Field: $E(r) = \exp(-j\,\beta r)\ /\ r$ , where $\beta = 2\pi/\lambda$ is the phase constant**

    **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° + 180° + 90° = 360°)**

**Antenna in free space**



**Antenna $\lambda/4$ from metal wall**

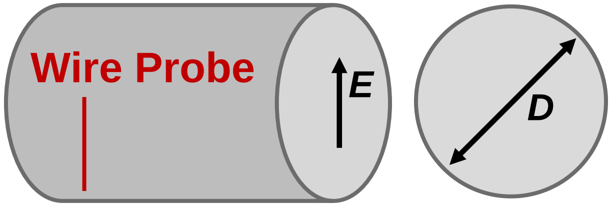


# Wavelengths, Different Types

## Free Space, Cutoff, Guide Wavelength

- **Wavelength $\lambda$ of electromagnetic wave in free space**
  - $\lambda = c / f$, where $c$ is the speed of light, $f$ is the frequency
- **TE11 mode cutoff wavelength $\lambda_c$ 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 $\lambda_g$**
  - Wavelength is longer in waveguide compared to wavelength in free space
  - $\lambda_g = \lambda / \mathrm{sqrt}(1 – (\lambda/(1.705\ D))\verb|^|2)$

**Circular Waveguide**



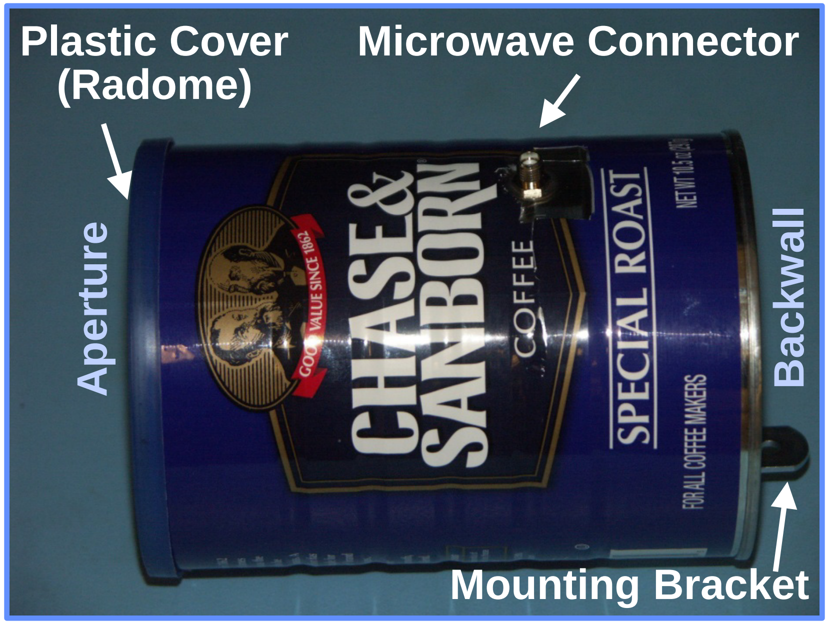
**Example: Circular Waveguide (coffee can)**
**Diameter = 3.9” (9.9 cm), Frequency = 2.4 GHz**

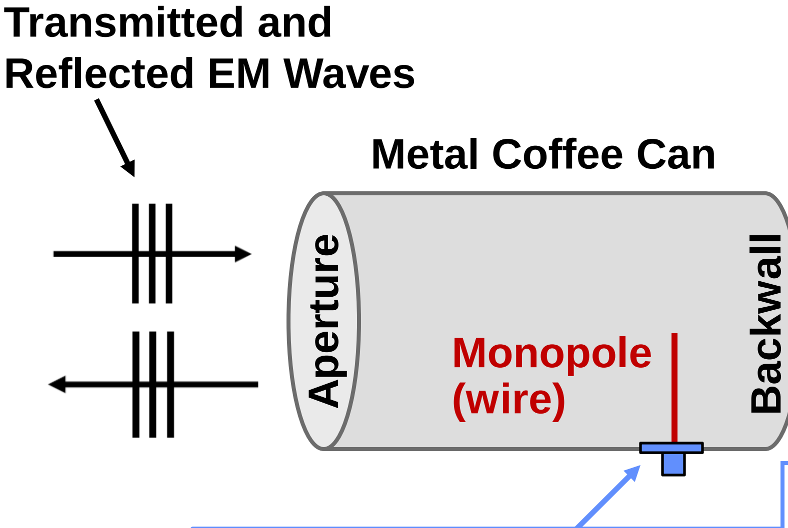
| Parameter | Value |
|---|---|
| Wavelength (free space), $\lambda$ | 4.9” (12.5 cm) |
| Cutoff Frequency, $f_c$ | 1.8 GHz |
| Guide Wavelength, $\lambda_g$ | 7.3” (18.5 cm) |

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

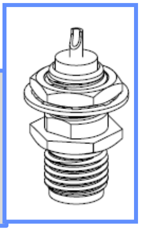
# Example Metal Can Antenna Design for 2.4 GHz

## Circular Waveguide Antenna





Microwave Connector
(Amphenol P/N: 901-9889-RFX,
SMA bulkhead receptacle jack)



**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 ~ $\lambda$ /4 in free space)**

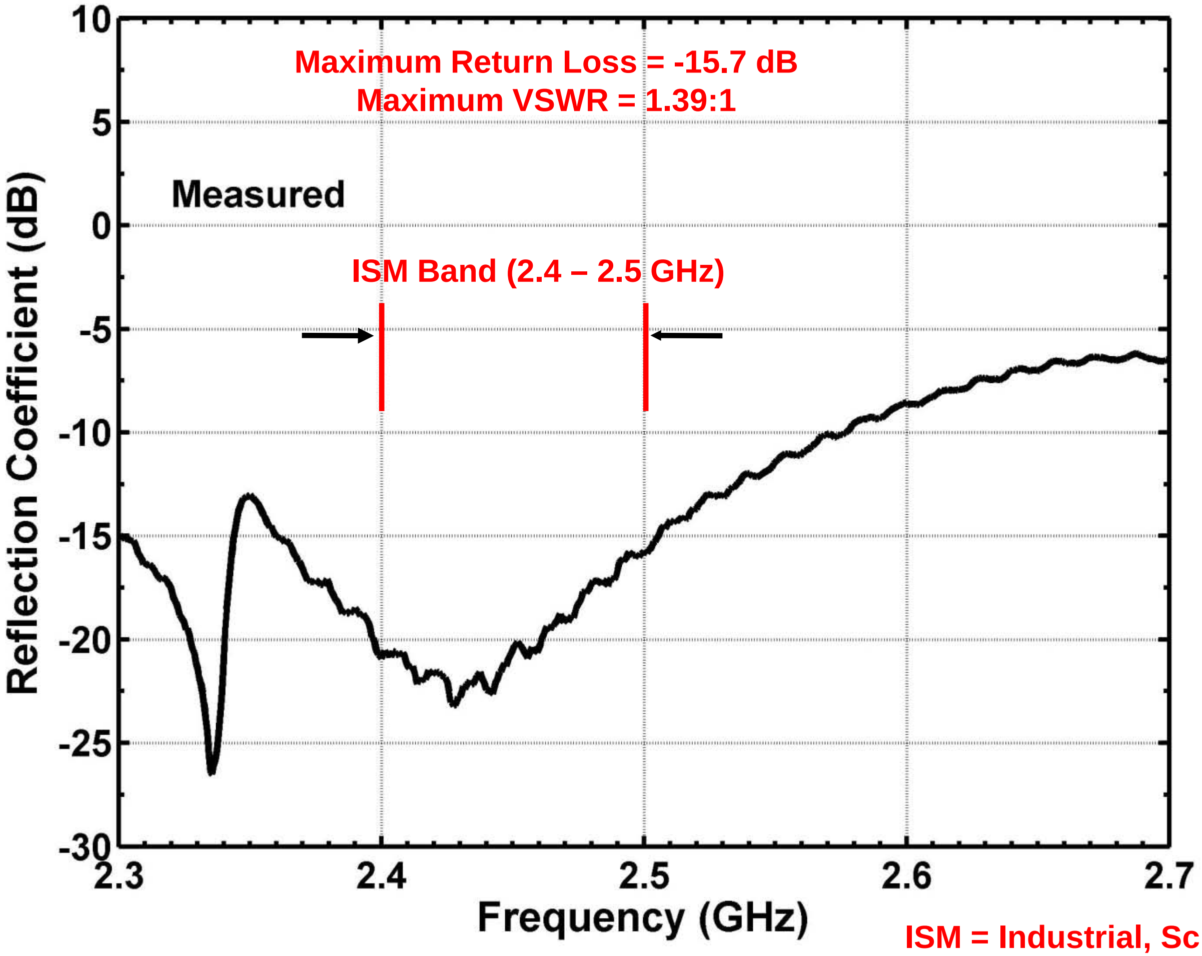
**Spacing from monopole wire to backwall = 1.8” (4.6 cm) (at 2.4 GHz ~$\lambda_g$ /4 in waveguide – see Slide 20)**

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

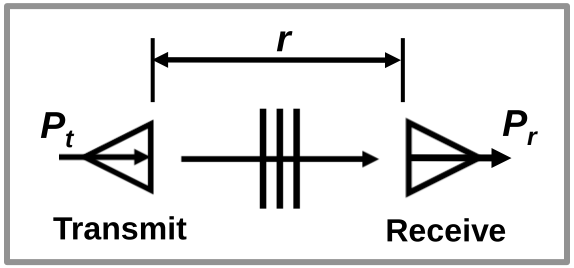
# Network Analyzer Measurement of Reflection Coefficient (Return Loss) for Laptop Radar Antenna #6



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)



- $P_r(\theta,\varphi)/ P_t = G_t(\theta,\varphi)\, G_r(\theta,\varphi)\, \lambda^2 / (4\pi r)^2$ (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)
- $G_{dBi} = ½[10 \log_{10} (P_r(\theta,\varphi)/ P_t) + 20 \log_{10} (4\pi r / \lambda)]$ (10)

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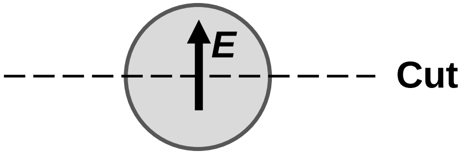
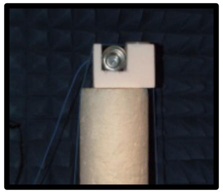
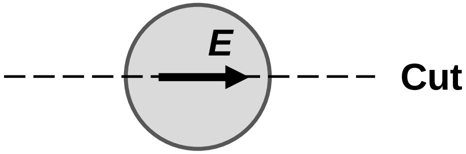
- Let the frequency be 2.4 GHz, $\lambda$=0.125 m (-18.1 dB)
- Network analyzer measures the power coupling ($P_r$ /$P_t$ in dB)
- *Measured power coupling is -23.3 dB at r=1 meter*
- With r = 1 meter, then 20 $\log_{10} 4\pi$ = 22 dB
- Eq. (10): $G_{dBi}$ = ½[ -23.3 + 22 + 18.1] = 8.4 dBi (antenna gain, *r* = 1m)
- 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

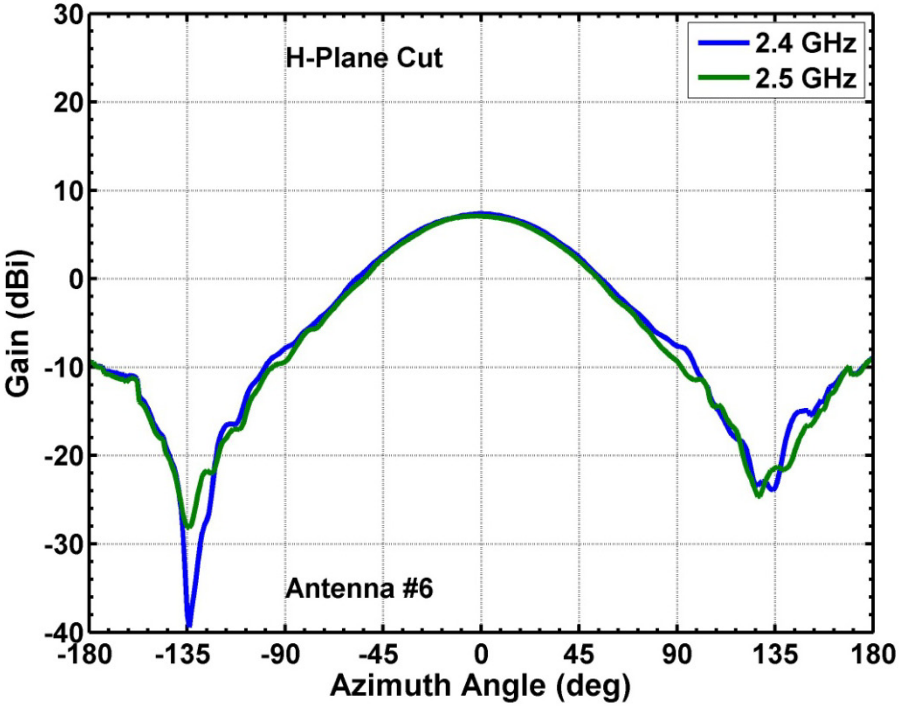
# Far-Field Measured Gain Patterns*

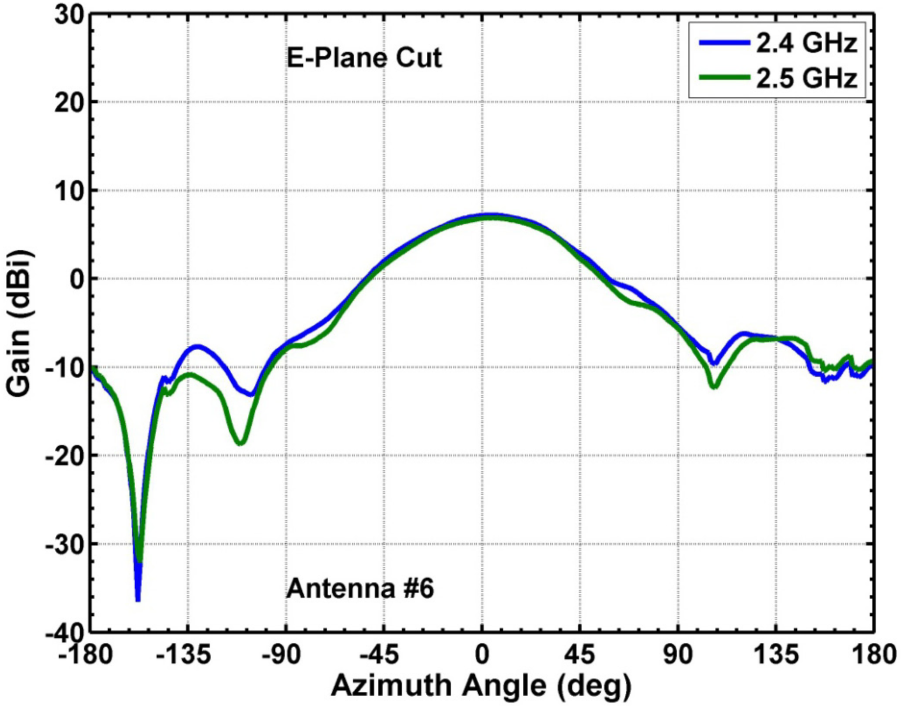
## Laptop Radar Antenna #6 (range = 8.5 meters)











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

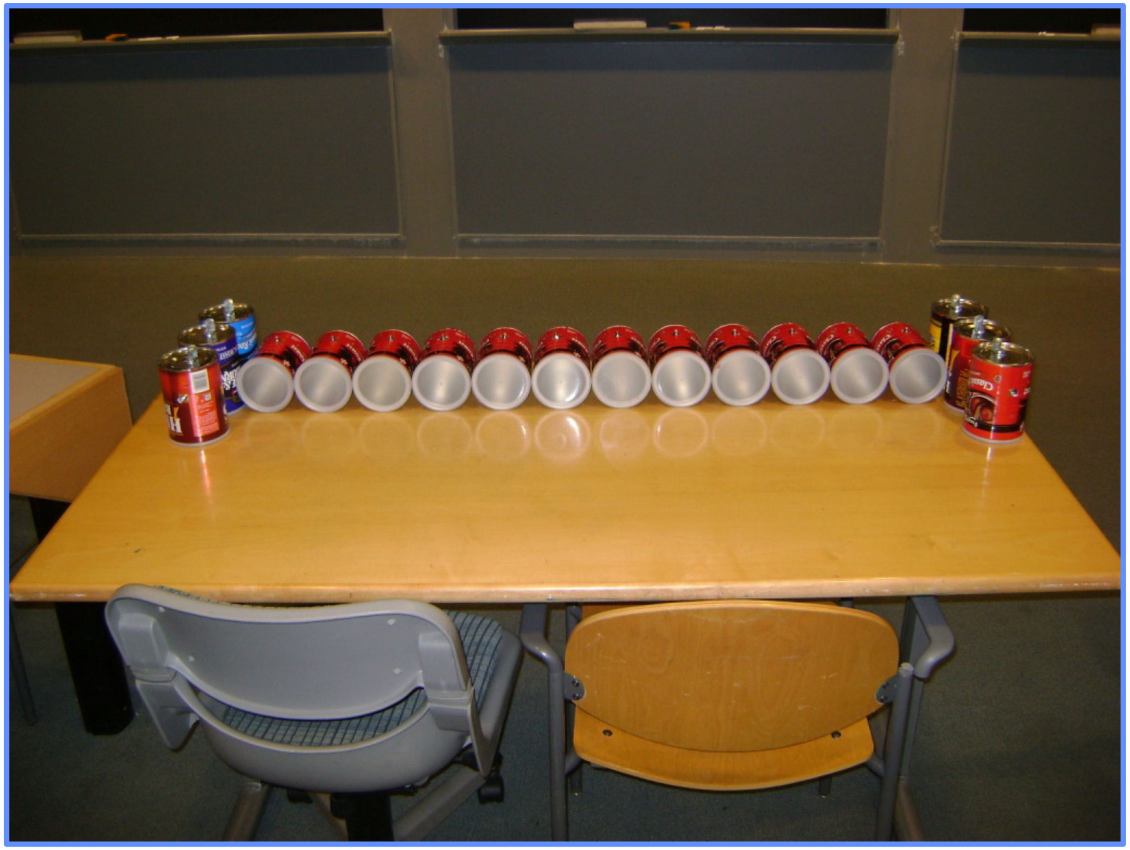
**Peak gain = 7.3 dBi, Half-power beamwidth = 70°**

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

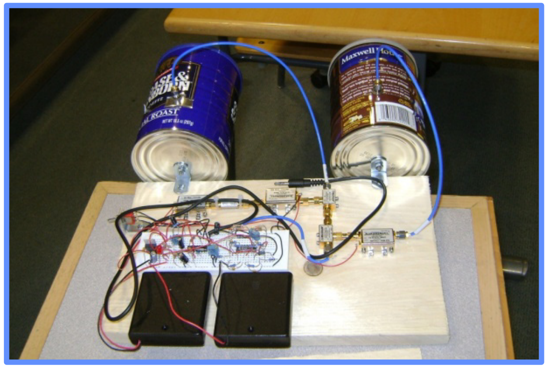
*Gain with respect to standard gain antenna

# 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

# 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