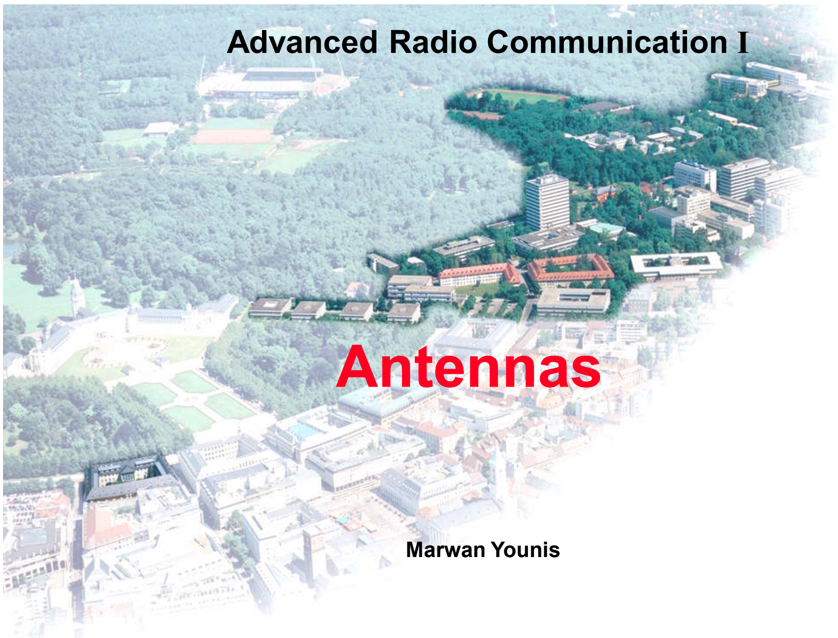
Advanced Radio Communication I



Antennas

Marwan Younis

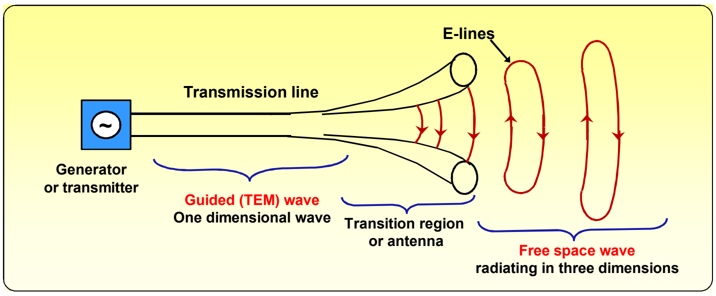
What should you learn from the antenna chapter

- Formulate the purpose of an antenna.
- Understand the mathematical formulation of a travelling electromagnetic wave
- Relate the condition for the operation of an antenna to Maxwell's equations.
- Know about different types of antennas and their way of functioning
- Present an engineering approach in quantifying antennas.
- Study the parameters used to describe antennas based on mathematical models.
- Develop the ability to understand the interaction between various antenna parameters, specifically for antenna arrays.

If somebody talks about antennas you should be able to understand and participate in the conversation.

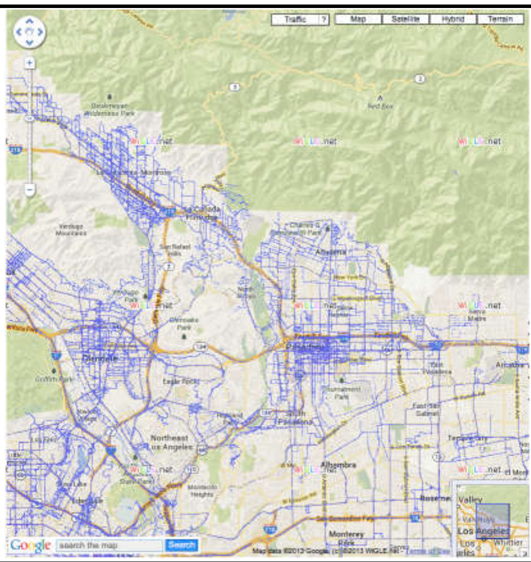
Basic Antenna Concept

The Antenna is a region of transition between a wave guided by transmission line and a free-space wave. The transmission line conductor separation is a small fraction of a wavelength while the separation at the open end of the transition region or antenna may be many wavelength.



Antennas *radiate (or receive) energy*, transmission lines *guide energy.*

Do We Need Antennas?



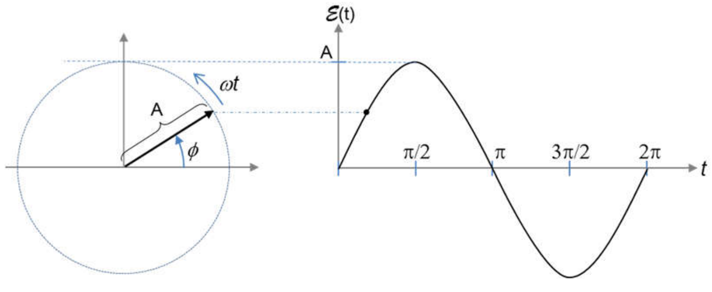
source: www.WiGLE.net

Travelling Waves

The term *Electromagnetic Radiation* is used to describe a *time varying* electric and magnetic filed that can propagate through space from one point to another. Such a propagating *oscillatory phenomenon* has the properties of a *wave.*

Meys, R. P. (2000). A summary of the transmitting and receiving properties of antennas. IEEE Antenna and Propagation Magazine, 42(3):49–53.

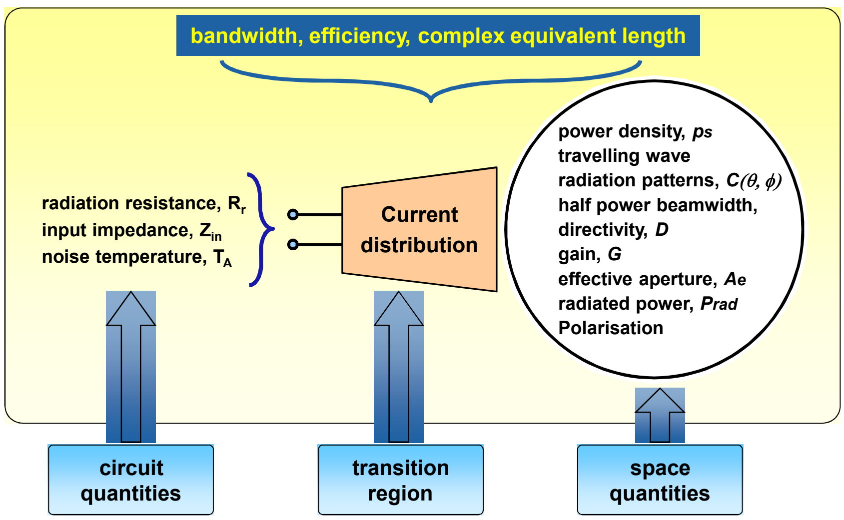
Phasor Representation



Antennas

What does an Antenna Do? How?

Schematic Diagram of Basic Antenna Parameters



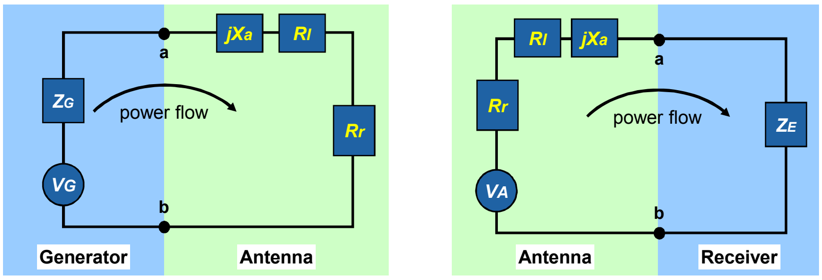
Equivalent Electric Circuit Diagramm

$Z_A = R_A + jX_a$

$R_A = R_l + R_r$

Antenna input impedance Z_A

- R_r radiation resistance
- R_l series resistance (losses)
- X_a reactance due to stored energy



Equivalet electric circuit for a transmit antenna

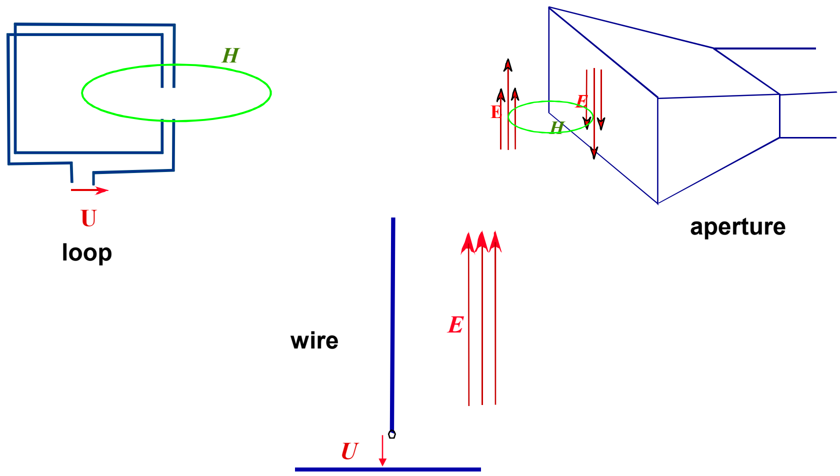
Equivalent electric circuit for a receive antenna

Advanced Radio Communication I

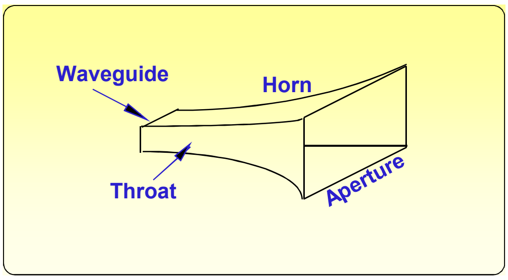
Antennas

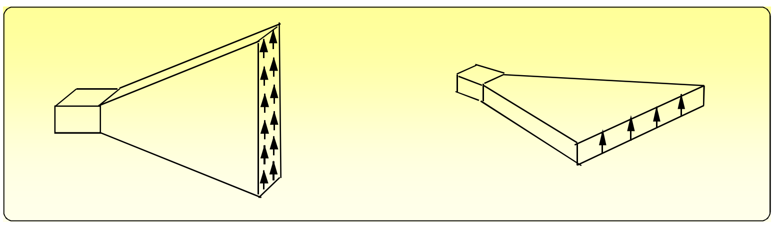
Types of Antennas

Principal Forms of Antennas

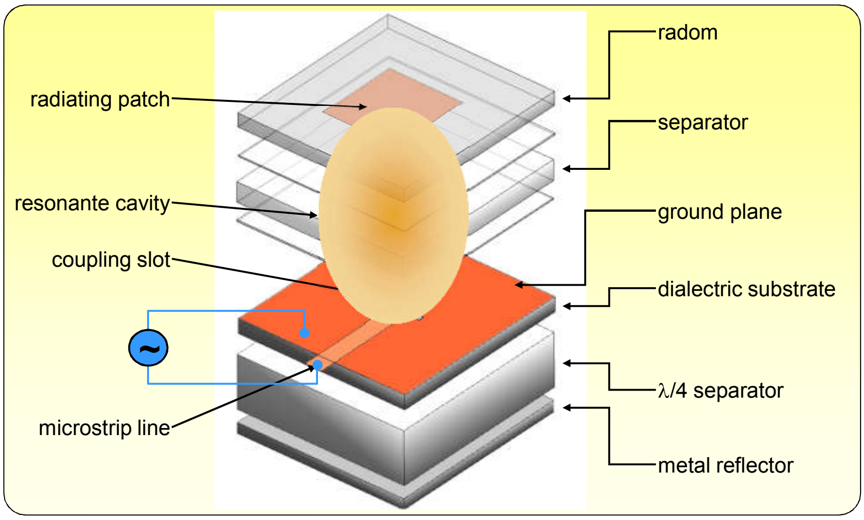


Antenna Types: Aperture Antennas

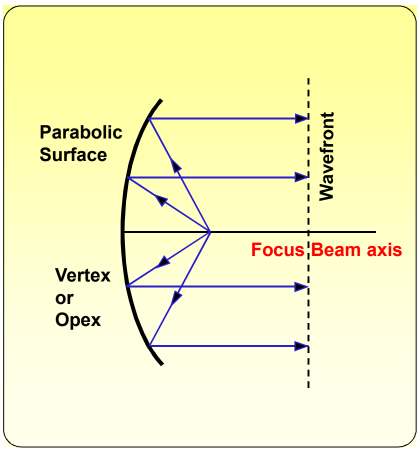


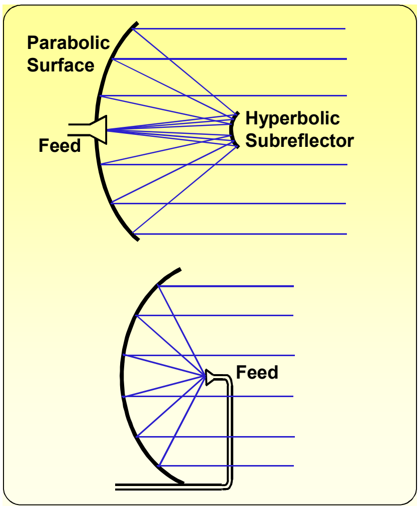


Antenna Types: Microstrip Antennas

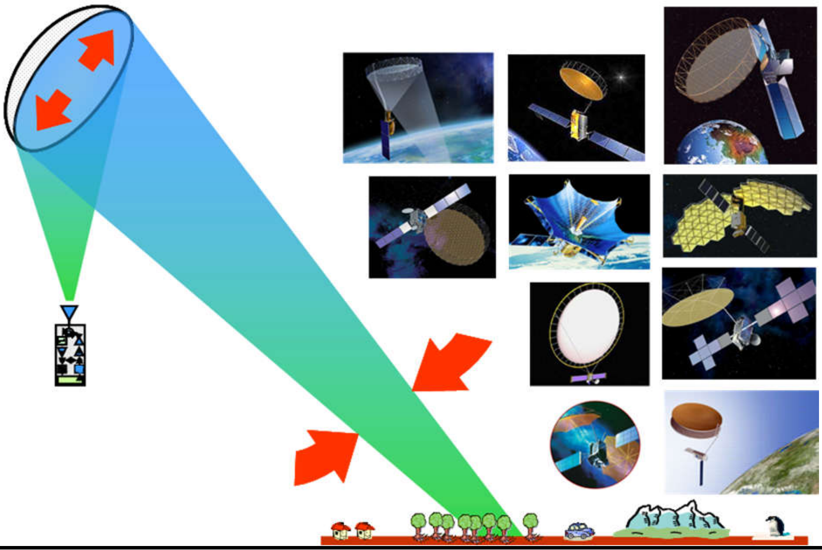


Antenna Types: Reflector Antennas

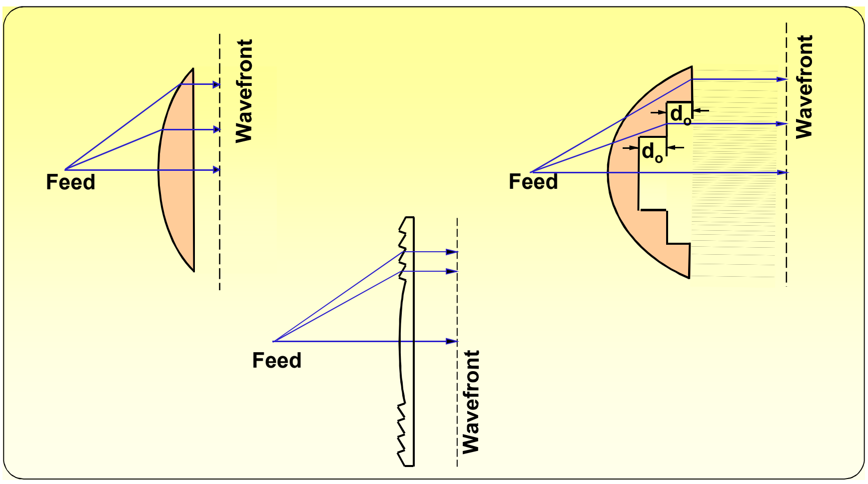




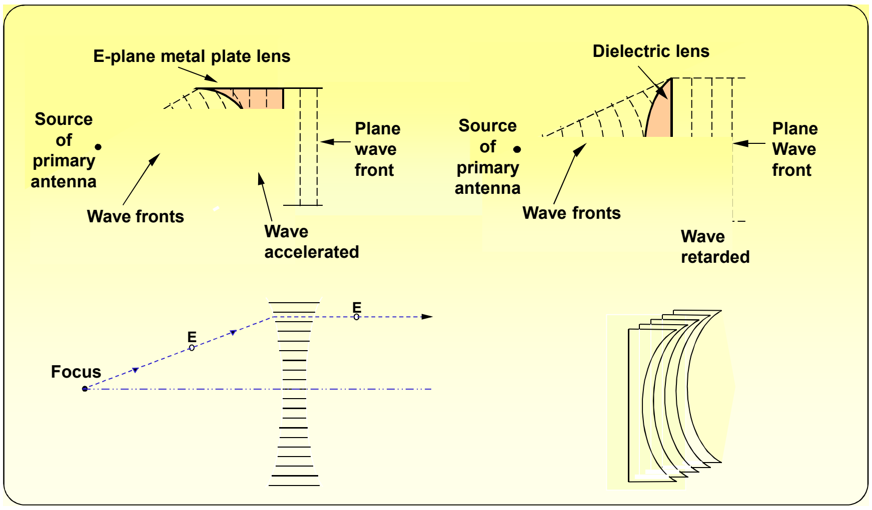
Deployable Reflector Antennas



Antenna Types: Lens Antennas 1

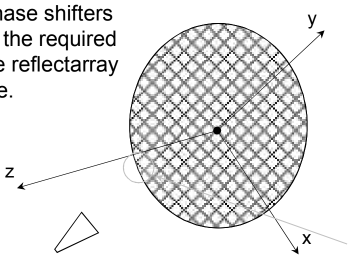


Antenna Types: Lens Antennas 2

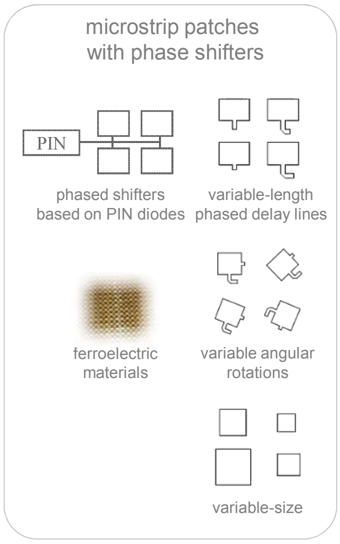


Antenna Types: Reflectarray

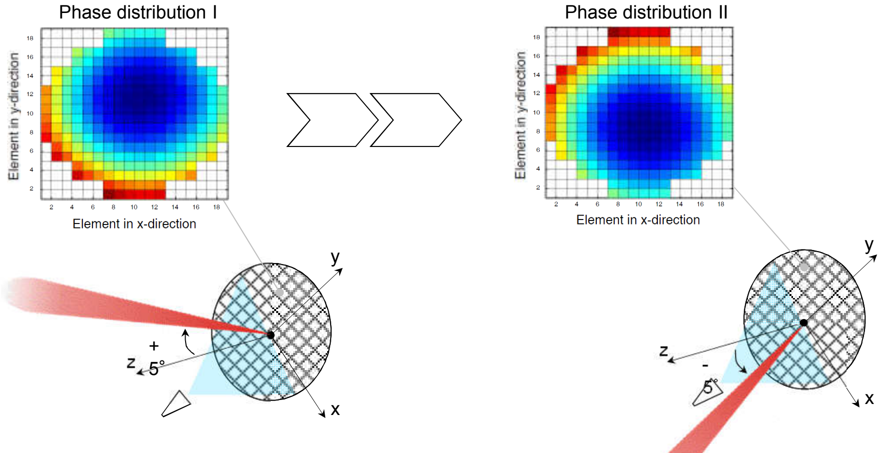
The system of phase shifters allows to achieve the required phase front on the reflectarray surface.



Large inflatable reflectarray system concept (Ka-Band), JPL. This is a future 30-60 m diameter class.

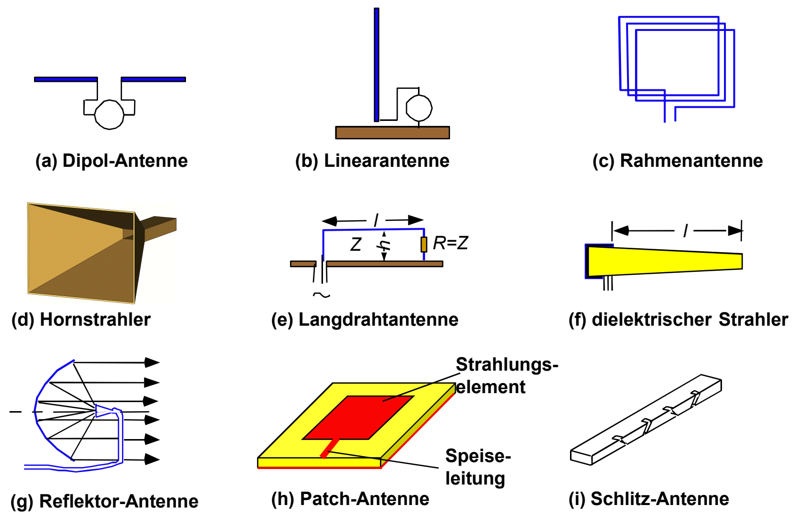


Operation Principle of Reflectarrays



Changing the phase distribution on the reflectarray surface the required beam shape is formed.

Typical Shapes of Antennas



Antennas Designed and Built by the IHE

The Sky's the Limit

Developments and Trends in the Communication Systems of Satellites

by

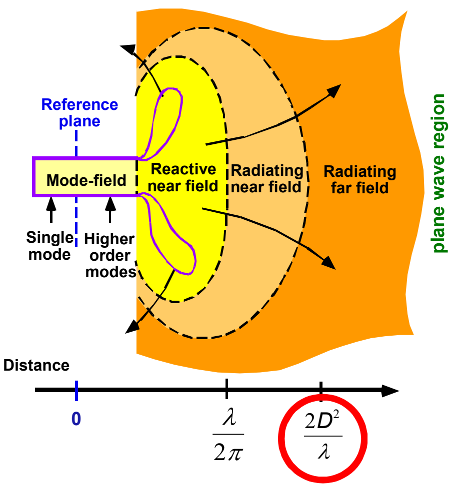
R. Emrick, P. Cruz, N. B. Carvalho, S. Gao, R. Quay, and P. Waltereit

IEEE Microwave Magazine – March/April 2014

Universität Karlsruhe (TH)
Research University • founded 1825

Institut für Hochfrequenztechnik
und Elektronik

Antenna Field Regions



In the *far field* of an antenna the radiated fields can be treated as local *plane waves emerging from and imaginary phase center.*

Advantages of plane wave treatment:

- There exist only transversal field components
- *E* and *H* are orthogonal to each other and in phase

$$\frac{E}{H} = Z_{FO} = \sqrt{\frac{\mu_o}{\varepsilon_o}} = 120\pi\ \Omega = 377\ \Omega$$

Z_{FO} = Impedance of free space

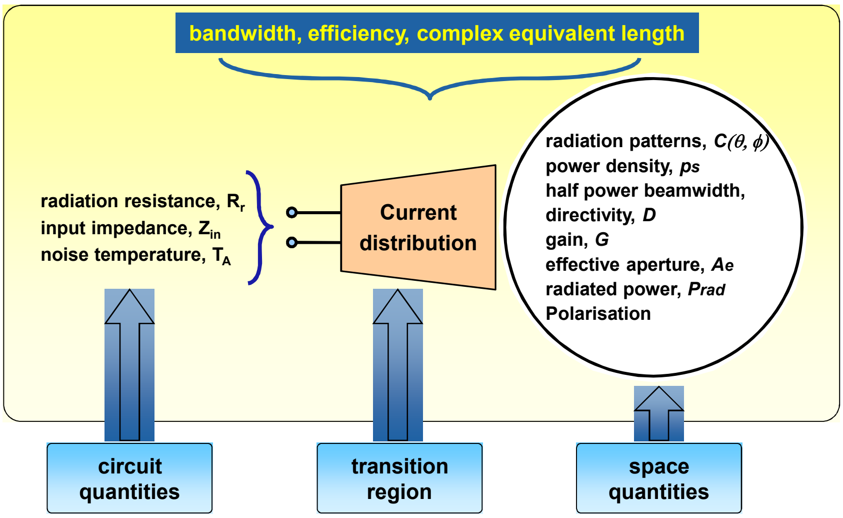
Advanced Radio Communication I

Antennas

Electric Field Radiated by an Oscillating Charge

(Complex Equivalent length)

Schematic Diagram of Basic Antenna Parameters

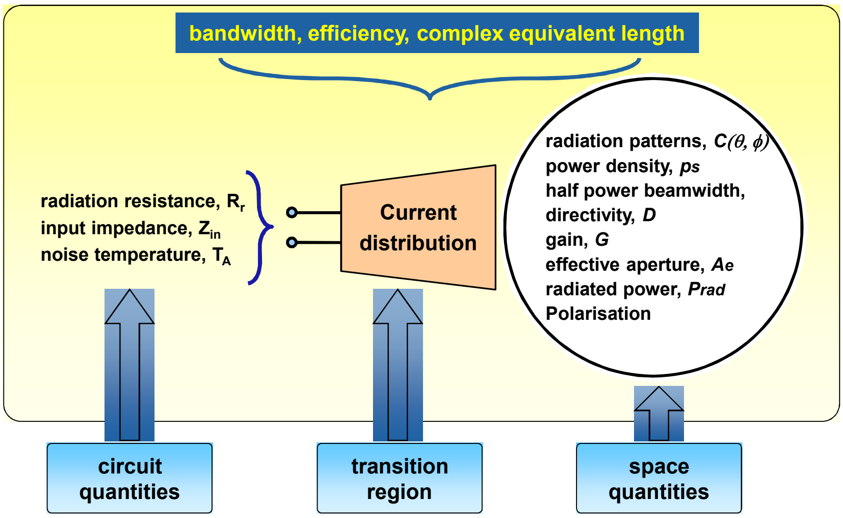


Advanced Radio Communication I

Antennas

Antenna Parameters

Schematic Diagram of Basic Antenna Parameters



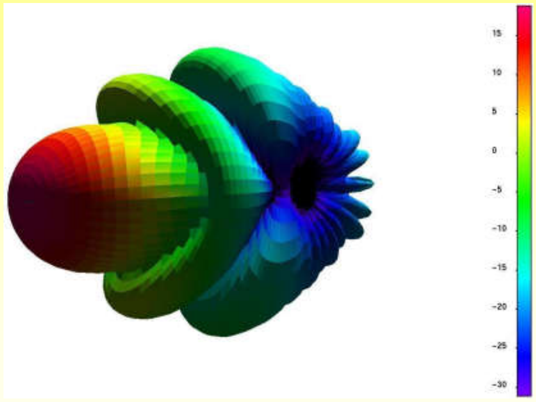
Advanced Radio Communication I

Antennas

Radiation Pattern

Antenna Radiation Pattern

A mathematical function of a graphical representation of the radiation properties of the antenna as a function of space coordinates



Definitions of the Antenna Characteristic

The radiation pattern gives the ratio of the field strength in a given direction to the maximum field strength at a constant distance from the antenna

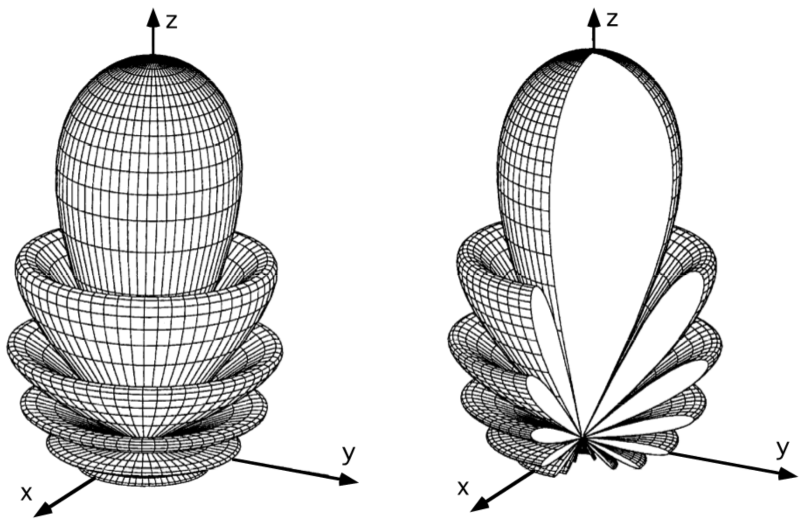
Scalar antenna characteristic:

$$C(\theta,\psi) = \left.\frac{|E(r,\theta,\psi)|}{|E(r,\theta,\psi)|_{\max}}\right|_{r=const\to\infty} = \left.\frac{|H(r,\theta,\psi)|}{|H(r,\theta,\psi)|_{\max}}\right|_{r=const\to\infty}$$

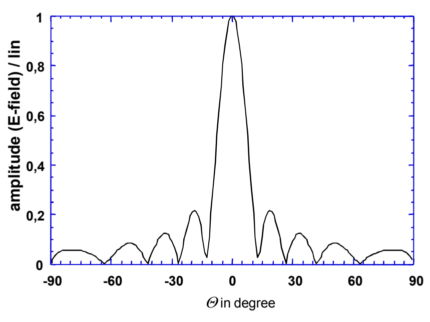
Complex antenna characteristic:

$$\vec{C}(\theta,\psi) = \left.\frac{\vec{E}\ (r,\theta,\psi)\cdot e^{jk_0 r}}{\left|\vec{E}\ (r,\theta,\psi)\cdot e^{jk_0 r}\right|_{\max}}\right|_{r=const\to\infty}$$

Antennen Pattern, 3-D Representation

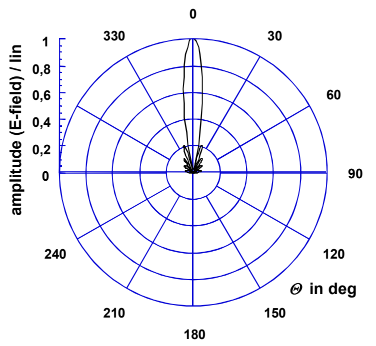


Antenna Characteristic, Linear

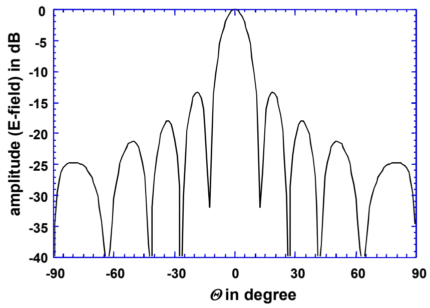


Rectangular plot, magnitude linear

Polar plot, magnitude linear

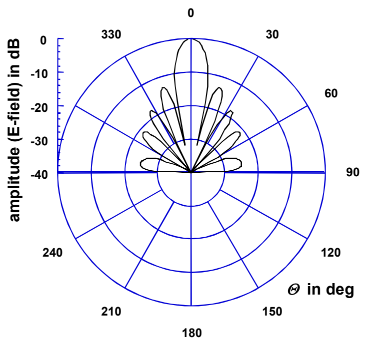


Antenna Characteristic, Logarithmic



Rectangular plot, magnitude in dB

Polar plot, magnitude in dB



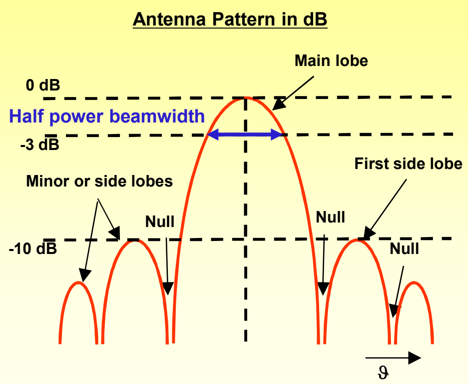
Antenna Pattern

$$C(\upsilon,\psi) = \frac{|\vec{E}(\upsilon,\psi)|}{|\vec{E}_{max}|} = \frac{|\vec{H}(\upsilon,\psi)|}{|\vec{H}_{max}|}\Bigg|_{\substack{r=const.\\ r\to\infty}}$$

$0 \le C \le 1$

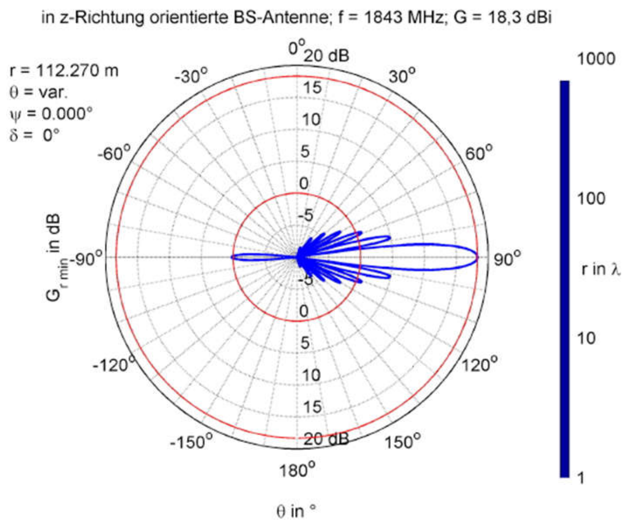
Usual presentation formats:

planar cuts:	**vertical cut,**
	horizontal cut
	E-plane cut
	H-plane cut
3D plots	
vertical scale:	**linear**
	dB



All antennas radiate with different intensities in different directions. An antenna that radiates with the same intensity in all directions is called **isotropic radiator**. An isotropic radiator is not realizable and represents a mathematical model.

Radiation Pattern of Base Station Antenna



Advanced Radio Communication I

Antennas

(Radiated Power)

Directivity

Gain

Equivalent Electric Circuit Diagramm

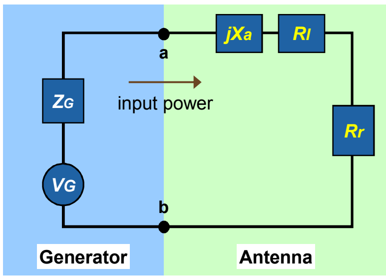
$$Z_a = R_a + jX_a$$
$$R_a = R_r + R_l$$

Antenna input impedance Z_a

Rr radiation resistance

Rl loss resistance

Xa reactance



Equivalet electric circuit for a transmit antenna

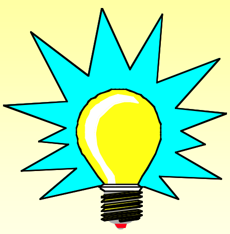
Radiated Power

$$P_{rad} = \frac{1}{2}|I_a|^2 R_r$$

$$P_{rad} = \oint p_S \, dA$$

Antenna Basics - Isotropic Radiator

Optical Analogy

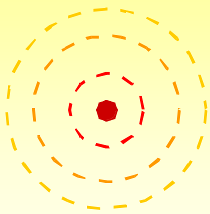


Light Bulb

$$p_S = \frac{P_{rad}}{4\pi R^2}$$

Power Density Equation

Antenna

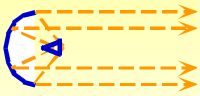


Isotropic Antenna

radiates the same in ALL directions

Antenna Basics - Focusing Property of Antennas

Optical Analogy

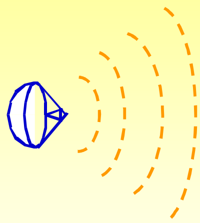


Headlight

$$p_S = \frac{P_{rad} \cdot G_T \cdot C(\vartheta,\varphi)}{4\pi R^2}$$

Power Density Equation

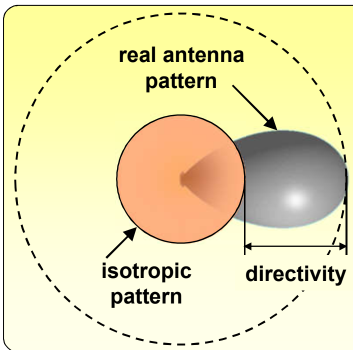
Antenna



Directional Antenna

Radiation of Energy is a Function of Azimuth and Elevation Angle

Directivity and Gain



Directivity

$$D = \frac{p_\Omega}{\frac{1}{4\pi} P_{rad}}$$

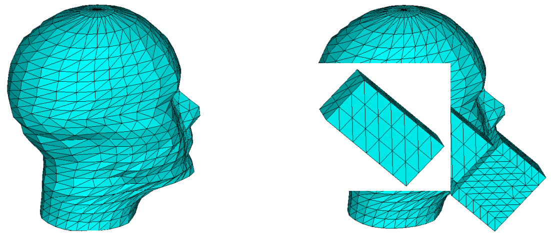
Gain

$$G = \frac{p_\Omega}{\frac{1}{4\pi} P_{in}}$$

Directivity is the ratio between the radiation intensity of the given antenna and the radiation intensity of an isotropic antenna radiating the same power

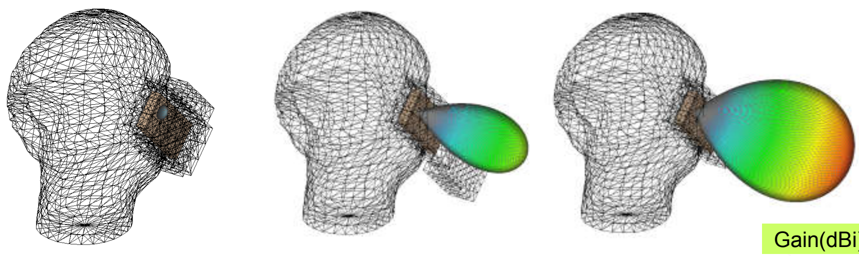
Gain is the ratio between the radiation intensity of the given antenna and the radiation intensity of an isotropic antenna having the same input power

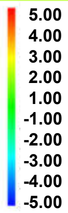
Influence of Hand on Radiation of Mobile Phone



hand position 1 | hand position 2 | without Hand

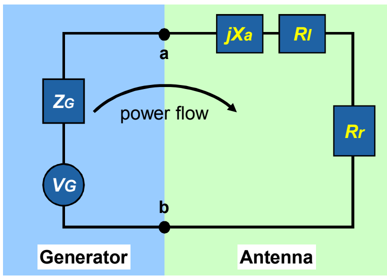
Radiation Pattern and Gain





hand position 1 | hand position 2 | without hand

Equivalent Electric Circuit Diagramm



Equivalet electric circuit for a transmit antenna

Radiated vs. input Power

$$P_{rad} = \eta_{cd} P_{in}$$

$$\Rightarrow G = \eta_{cd} D$$

The gain includs antenna losses

Antenna efficiency

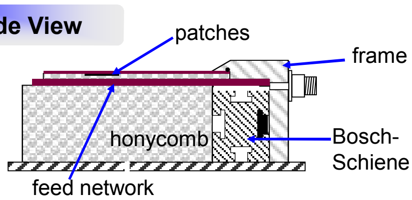
$$\eta_{cd} = \frac{R_r}{R_l + R_r}$$

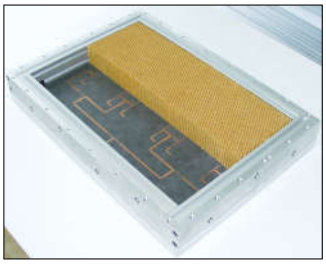
Antenna input impedance Z_A

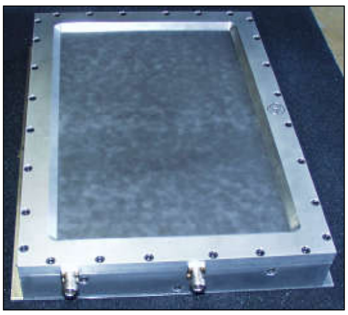
- R_r radiation resistance
- R_l los resistance
- X_a reactance due to stored energy

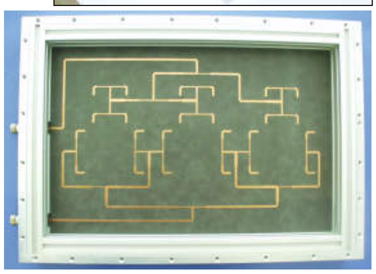
Mechanical Construction

Side View

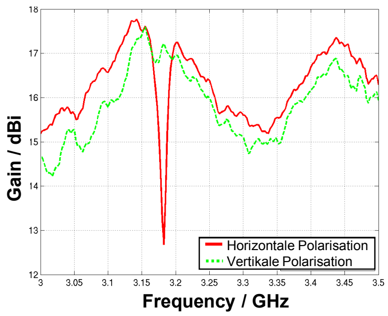


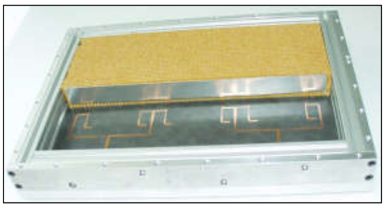


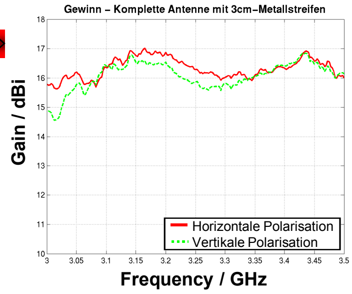




Influence of Frame







- sharp gain fall-off at one frequency
- resonance modes inside the cavity

Advanced Radio Communication I

Antennas

Input Impedance

Effective Aperture

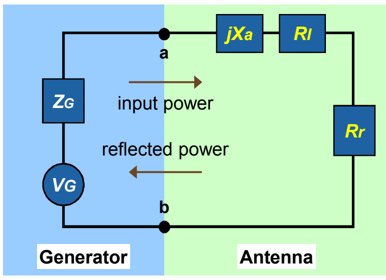
Bandwidth

Equivalent Electric Circuit Diagramm

$$Z_a = R_a + jX_a$$
$$R_a = R_r + R_l$$

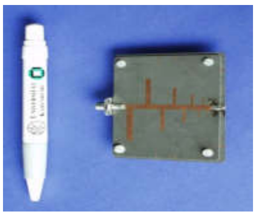
Antenna input impedance Za

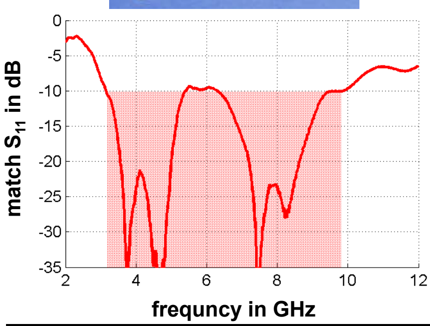
- R_r radiation resistance
- R_l loss resistance
- X_a reactance

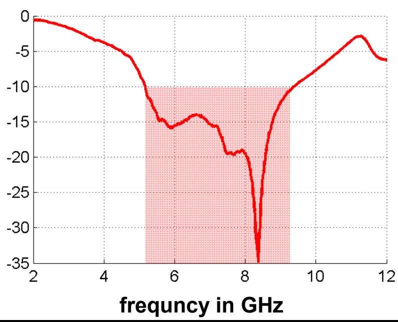


Equivalet electric circuit for a transmit antenna

Examples of Antenna Input Impedance



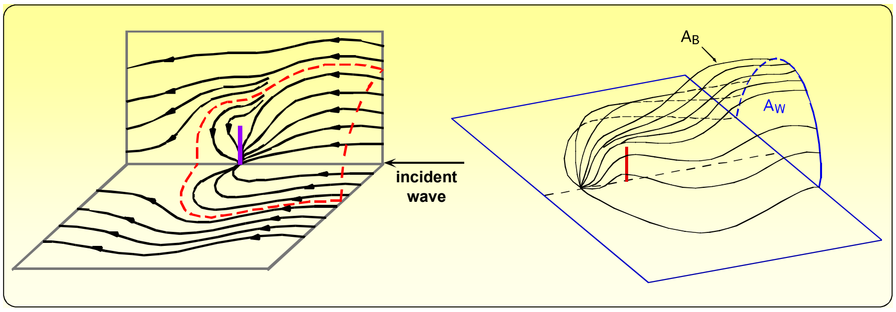




Effective Aperture

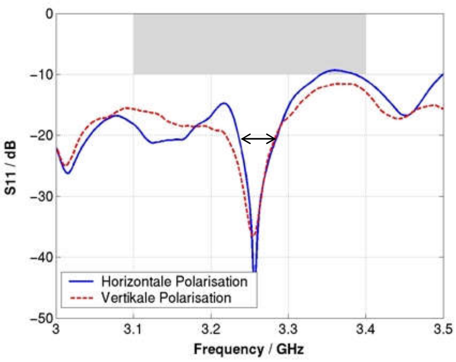
The *effective aperture* (effective receiving area) *Ae* is a measure for the amount of power an antenna can extract from an incident plane wave field.

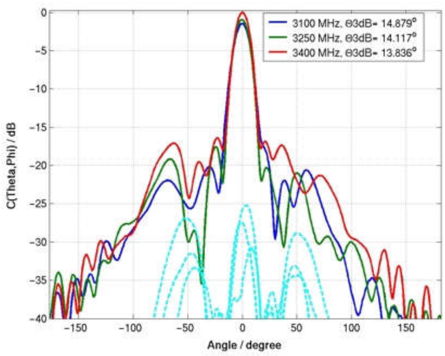
$$\text{received power} = \text{effective aperture} \cdot \frac{\text{incident power}}{\text{unit area}}$$



Bandwidth

The bandwidth is, in general, the **range of frequencies over which the antenna operates within a certain performance**. In order to stress which parameter is considered, terms like *impedance bandwidth* or *pattern bandwidth* may beused.





Advanced Radio Communication I

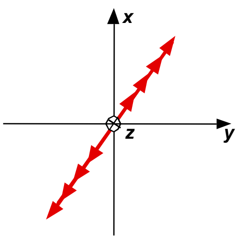
Antennas

Polarization

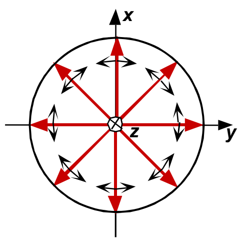
Polarization - Definition

According to the *IEEE Standard Definitions for Antennas*, the *polarization of a radiated wave* is defined as „that property of a radiated electromagnetic wave describing the time-varying direction and relative magnitude of the electric field vector at a fixed location in space, and the sense in which it is traced as observed along the direction of propagation“. In other words, polarization is **the curve traced out by the end point of the arrow representing the instantaneous electric field**.

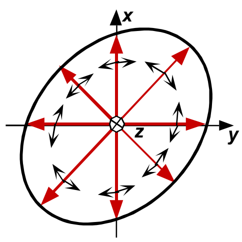
Linear polarization



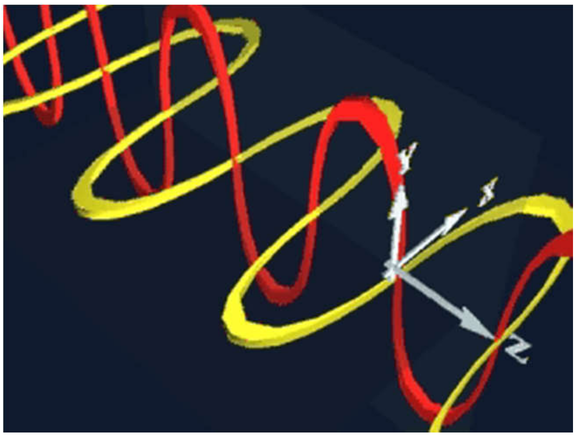
Circular polarization



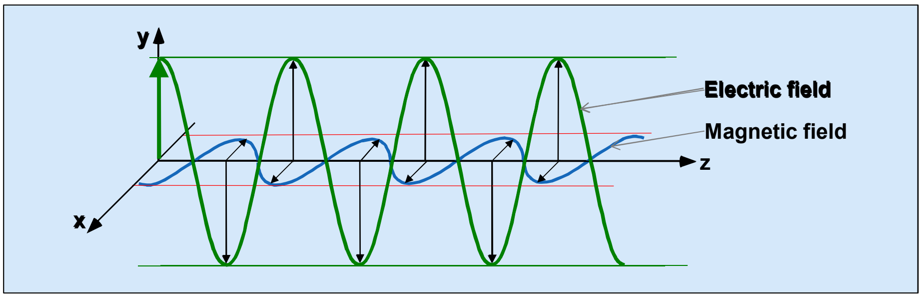
Elliptical polarization



Polarization



Polarization of Electromagnetic Wave



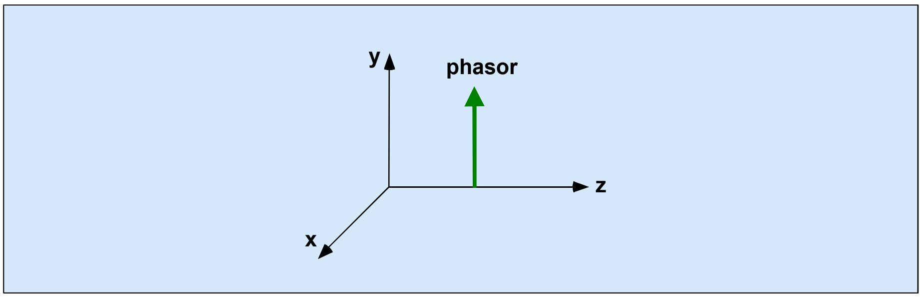
Electric Field Equation

The description of the electric field of an electromagnetic wave of angular frequency $\omega = 2\pi f$ and wave number $\beta = 2\pi/\lambda$ propagating along the ***z***-direction:

$$\vec{\mathcal{E}}(z,t) = E_1 \sin(\beta z - \omega t + \phi_1)\hat{\mathbf{e}}_{\mathbf{y}}$$

the amplitude of the electric filed is E_1, its initial phase ϕ_1 and it is polarized in the ***y***-direction.

Polarization of Electromagnetic Wave



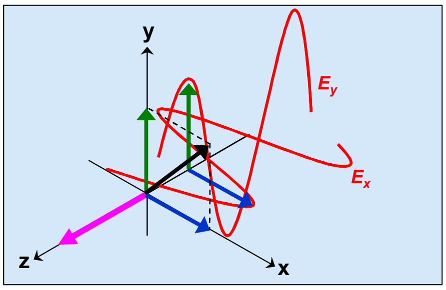
Phasor Representation

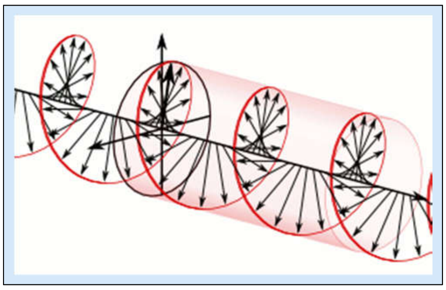
description of the electric field of an electromagnetic wave of angular frequency ω=2πf and wave number β=2π/λ propagating along the **z**-direction:

$$\vec{E} = \underline{E}_1 \hat{\mathbf{e}}_\mathbf{y}$$

the complex amplitude of the electric filed is $\underline{E}_1$, and it is polarized in the **y**-direction.

Linear and Circular Polarization





Linear 45º Polarization

$$\vec{E} = 1\hat{\mathbf{e}}_\mathbf{x} + 1\hat{\mathbf{e}}_\mathbf{y}$$

Circular Polarization

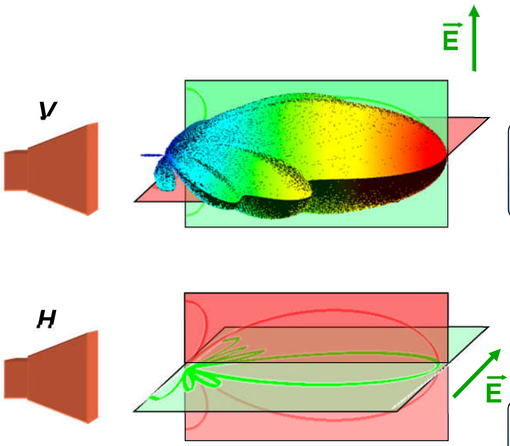
Right:

$$\vec{E} = 1\hat{\mathbf{e}}_\mathbf{x} + j\hat{\mathbf{e}}_\mathbf{y}$$

Left:

$$\vec{E} = 1\hat{\mathbf{e}}_\mathbf{x} - j\hat{\mathbf{e}}_\mathbf{y}$$

Definition of E- and H-Plane for the Radiation Pattern



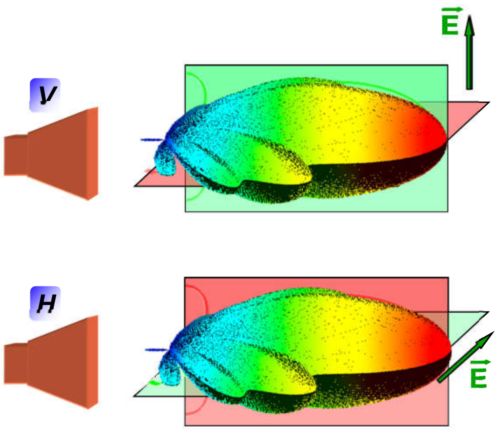
Vertikal Polarisation

- *H-Plane* in Azimuth
- *E-Plane* in Elevation

Horizontal Polarisation

- *E-Plane* im Azimut
- *H-Plane* in Elevation

Definition of E- and H-Plane for the Radiation Pattern



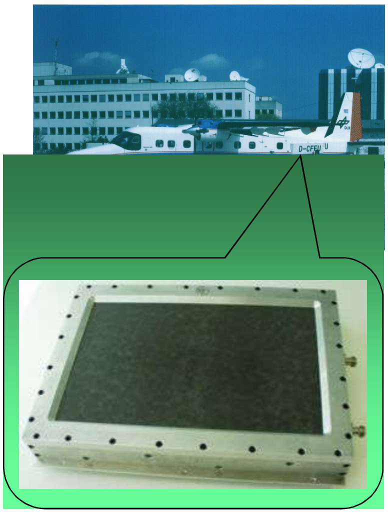
Vertikal Polarisation

- *H-Plane* in Azimuth
- *E-Plane* in Elevation

Horizontal Polarisation

- *E-Plane* im Azimut
- *H-Plane* in Elevation

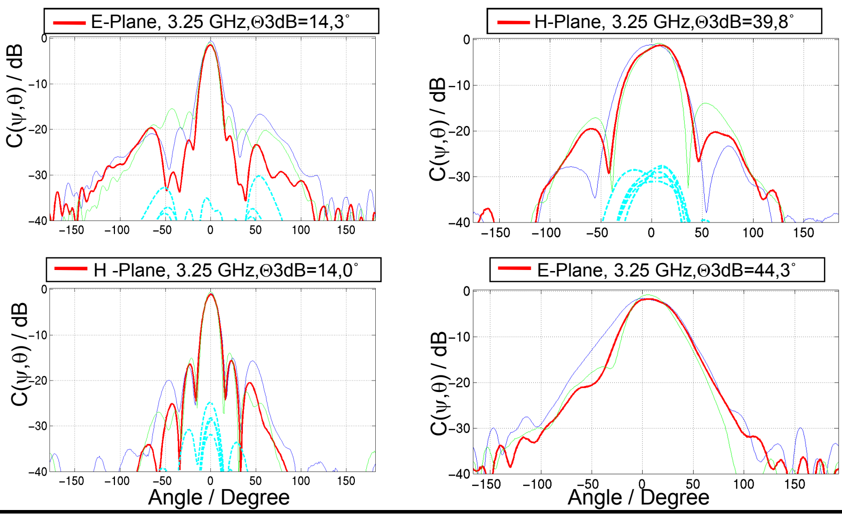
Example Antenna Specification



Aplication	*polarimetric SAR Interferometrie*
Polarisation	*dual - linear*
Frequency	*3.25 GHz*
Bandwidth	*300 MHz (9.3 %)*
Gain	*17 dBi*
Input Match	*< -10 dB*
Beamwidth	*35° - 37° Elevation* *13° - 17° Azimuth*
X-Pol. suppression	*< -25 dB*
Side lobe level	*< -15 dB*
Gain difference	*< 1 dB*

Measured Radiation Patterns

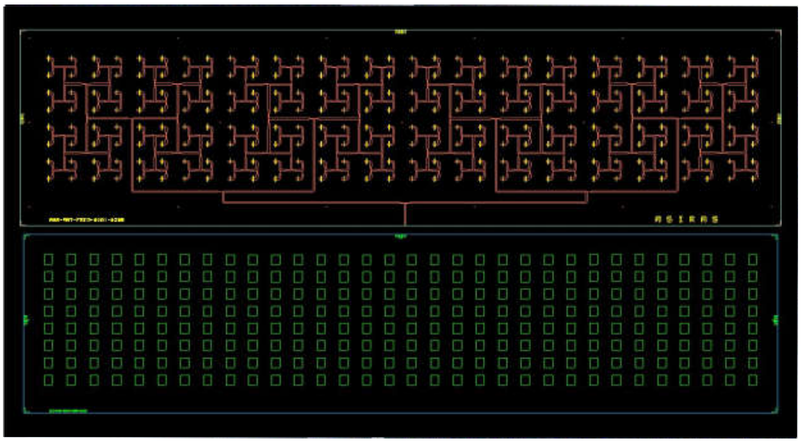
Azimuth | **Elevation**



Antenna Arrays

Most applications require antennas with characteristics which are difficult to achieve using one single radiating element. Several radiating elements are combined, in order to obtain the required radiating pattern and gain. The resultant structure is known as antenna array

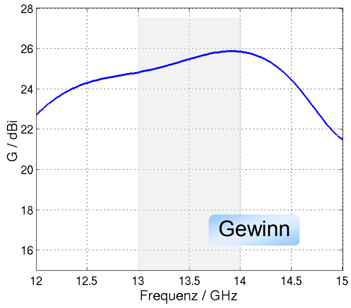
Platinenfertigung

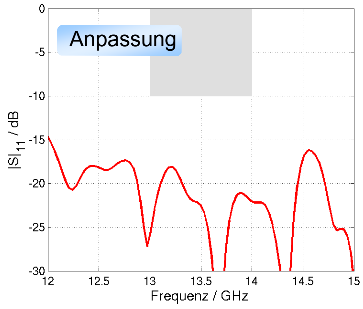


256 Elemente
255 Teiler, 21 verschiedene

ca. 45 cm Leitungslänge zu jedem Einzelelement
ca. 4,5 dB Leitungsdämpfung

8 x 32 Array Gewinn und Anpassung





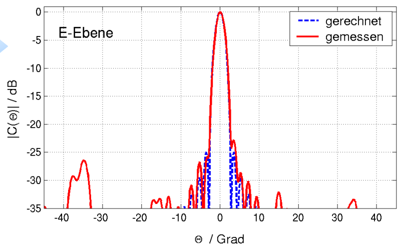
Direktivität = 32 dBi
(gerechnet)

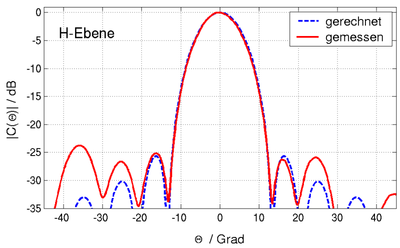
Leitungsverluste,
gerechnet m. ADS = 4,5 dB

Richtdiagramm des 8 x 32 Array

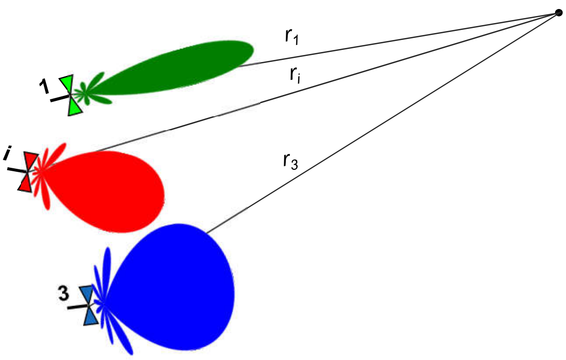
13,5 GHz
Freiraum-Messstrecke
kein Gating

Frequenz	$\Theta_{3dB\ E}$	$\Theta_{3dB\ H}$
13 GHz	2,2°	10,4°
13,5 GHz	2,2°	9,4°
14 GHz	2,1°	9,4°



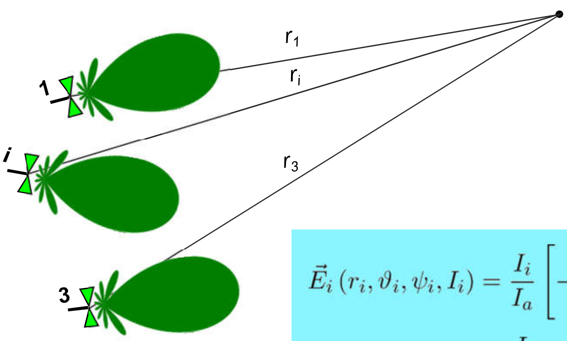


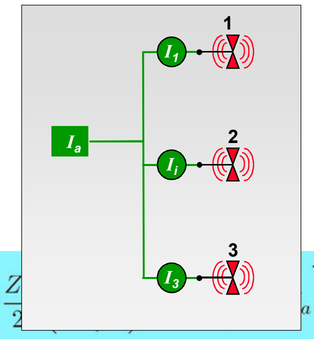
Array Factor



$$\vec{E}(r,\vartheta,\psi) = \sum_{\text{radiators}} \vec{E}_i\left(r_i,\vartheta_i,\psi_i,I_i\right)$$

Array Factor





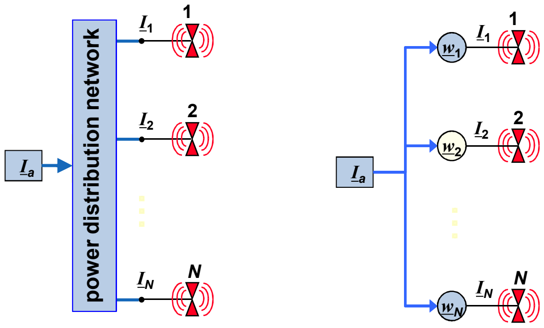
$$\vec{E}_i\left(r_i,\vartheta_i,\psi_i,I_i\right) = \frac{I_i}{I_a}\left[-j\frac{Z}{2} \cdots a\right]$$

$$= \frac{I_i}{I_a}\vec{E}_{\text{single}}\left(r_i,\vartheta_i,\psi_i,I_a\right)$$

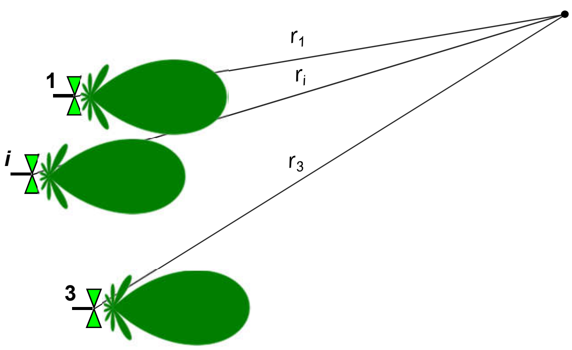
$$\vec{E}(r,\vartheta,\psi) = \sum_{\text{radiators}} \vec{E}_i\left(r_i,\vartheta_i,\psi_i,I_i\right)$$

$$\vec{E}(\vartheta,\psi) = \sum_{\text{radiators}} \frac{I_i}{I_a}\vec{E}_{\text{single}}\left(r_i,\vartheta_i,\psi_i,I_a\right)$$

Controlling the Pattern through the Feeding Current

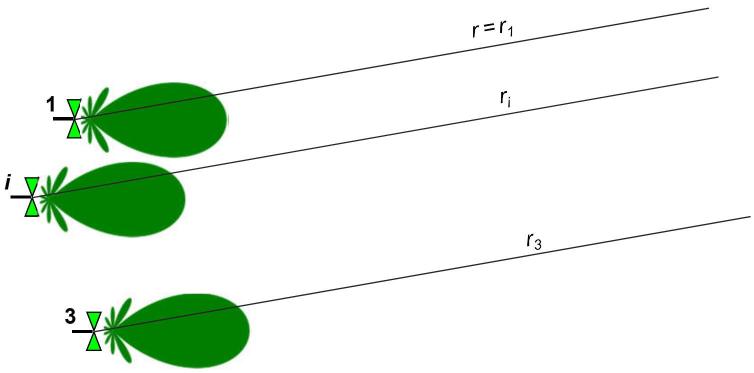


Array Factor



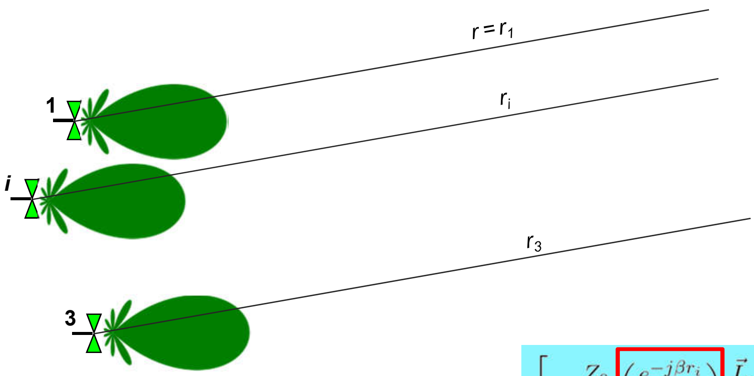
$$\vec{E}(r,\vartheta,\psi) = \sum_{\text{radiators}} \frac{I_i}{I_a} \vec{E}_{\text{single}}\left(r_i,\vartheta_i,\psi_i,I_a\right)$$

Array Factor



$$\vec{E}(r,\vartheta,\psi) = \sum_{\text{radiators}} \frac{I_i}{I_a} \vec{E}_{\text{single}}\left(r_i, \vartheta_i, \psi_i, I_a\right)$$

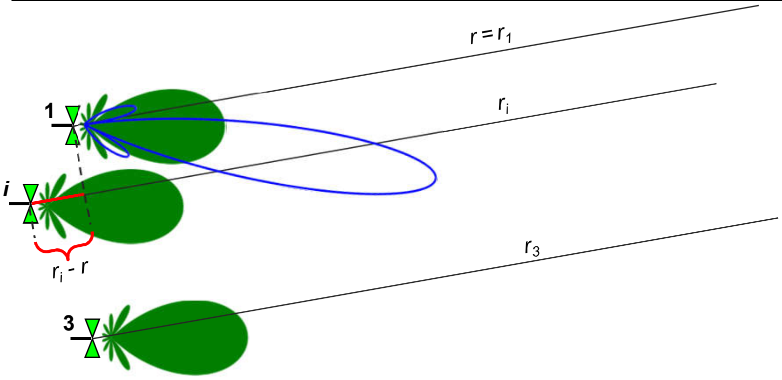
Array Factor



$$\left[-j\frac{Z_0}{2} \left(\frac{e^{-j\beta r_i}}{r_i} \right) \frac{\vec{L}_e(r_i, \vartheta_i, \psi_i)}{\lambda} I_a \right]$$

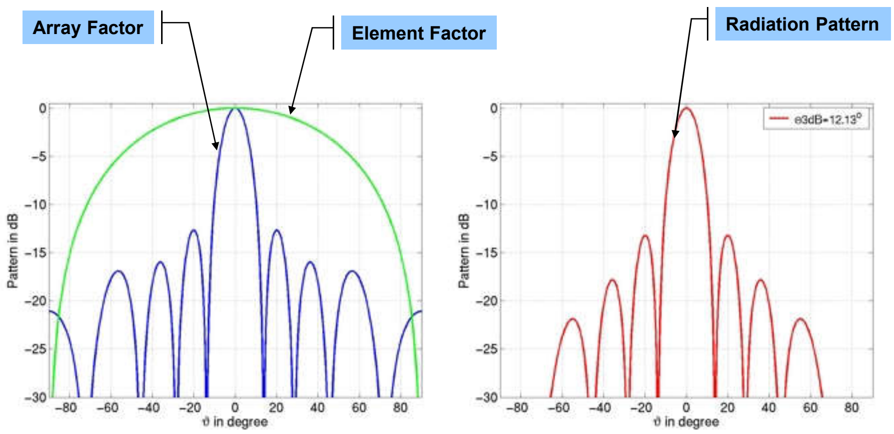
$$\vec{E}(r,\vartheta,\psi) = \sum_{\text{radiators}} \frac{I_i}{I_a} \vec{E}_{\text{single}}\left(r_i, \vartheta \ , \psi \ , I_a\right)$$

Array Factor

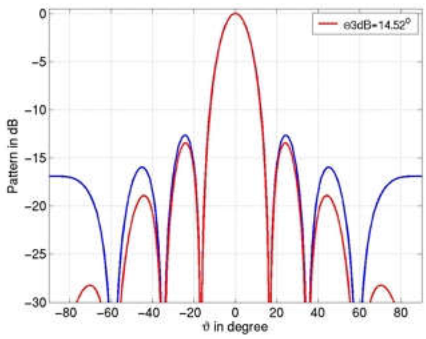


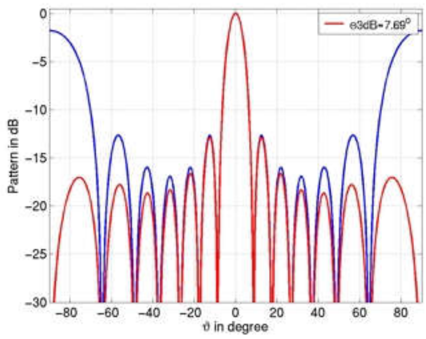
$$\vec{E}(r,\vartheta,\psi) = \vec{E}'_{\text{single}}(r,\vartheta,\psi,I_a) \cdot \frac{e^{-j\beta r}}{r} \cdot \sum_{\text{radiators}} \frac{I_i}{I_a} e^{-j\beta(r_i - r)}$$

Radiation Pattern for Antenna Array



Element Separation

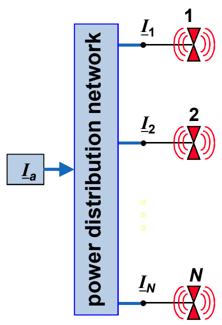


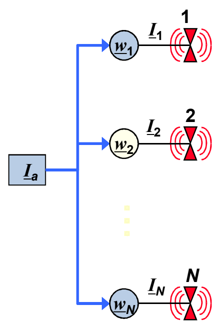


element separation $d = 0.5\lambda$
beamwidth $\Theta_{3dB} = 14.5°$

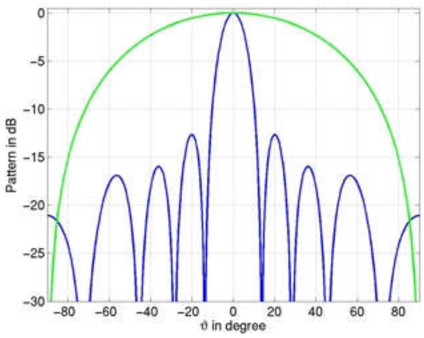
element separation $d = 0.95\lambda$
beamwidth $\Theta_{3dB} = 7.7°$

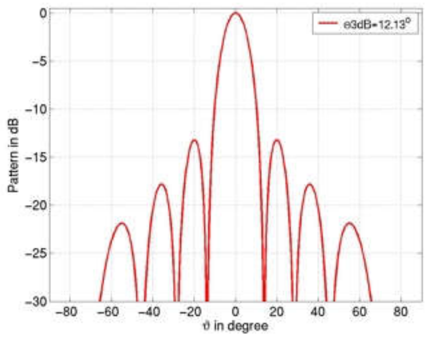
Controlling the Pattern through the Feeding Current





Scanning to θ = 0°

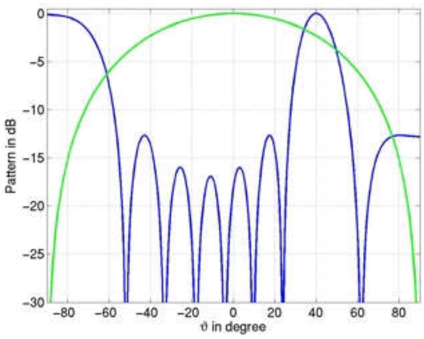


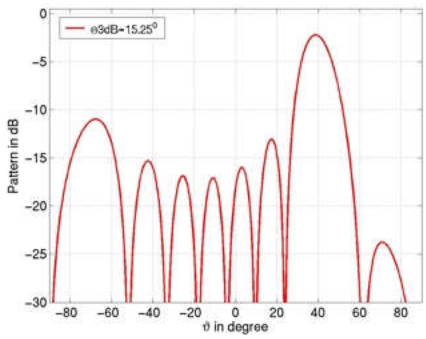


element factor EF
array factor AF

radiation pattern
beamwidth Θ_{3dB} **= 12.1°**

Scanning to θ = 40°

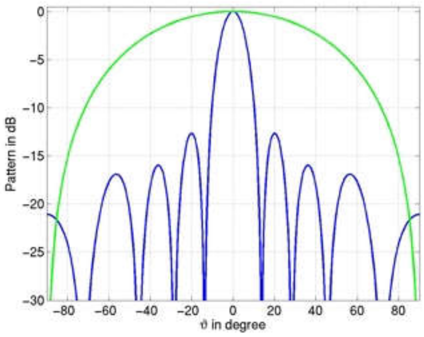




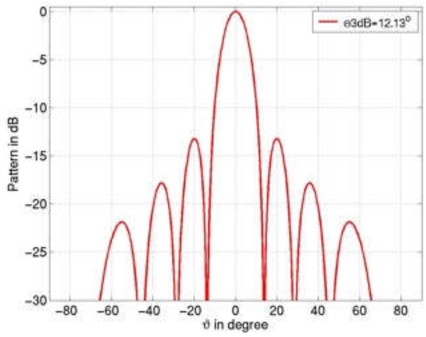
element factor EF
array factor AF

radiation pattern
beamwidth Θ_{3dB} **= 15.2°**

Constant Amplitude Taper

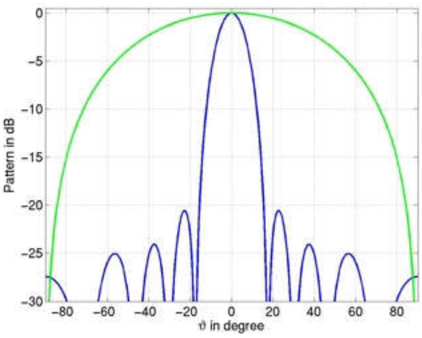


element factor EF
array factor AF

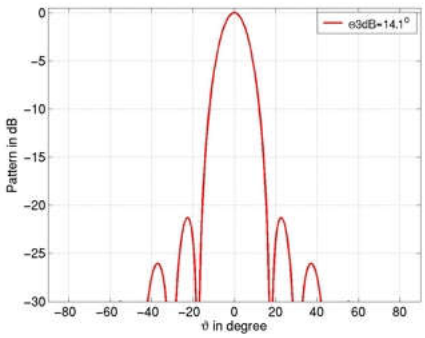


normalized radiation pattern

Triangular Amplitude Taper



element factor EF
array factor AF



normalized radiation pattern

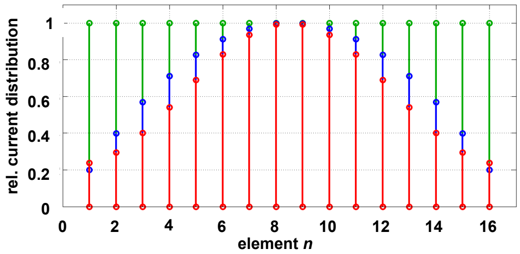
Excitation Coefficients and Pattern

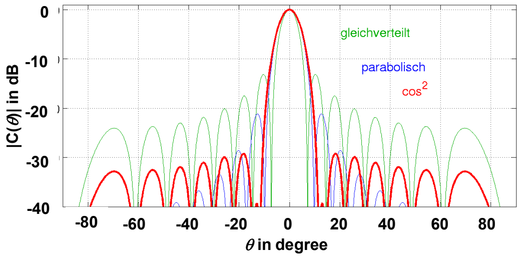
pattern of array

taper

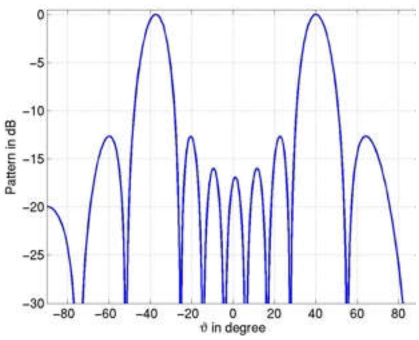
$\circ\!\!-\!\!\bullet$ $\mathcal{F}$

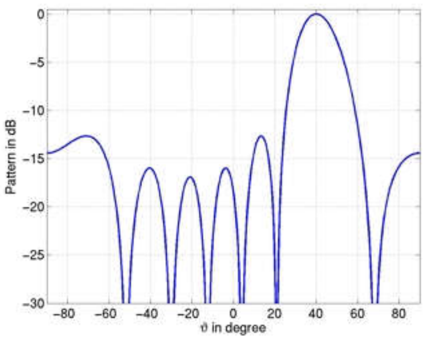
array factor





Grating Lobes





element separation $d = 0.8\lambda$
scan angle $\theta_o = 40°$

element separation $d = 0.5\lambda$
scan angle $\theta_o = 40°$

Influence of Element Factor on Grating Lobes