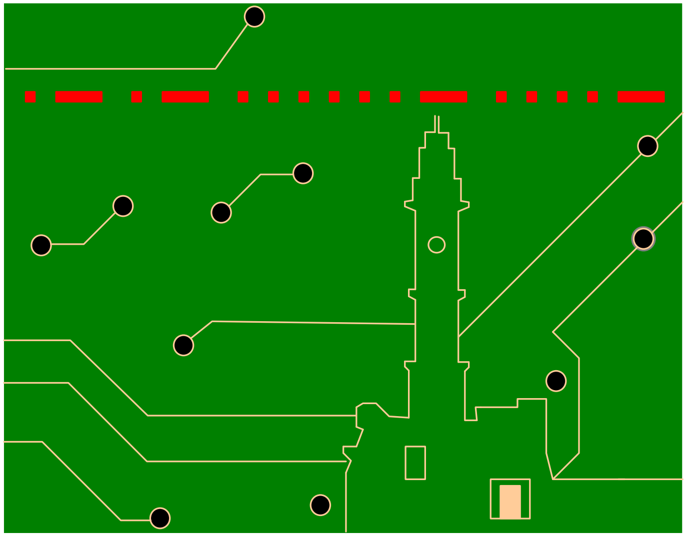
ΤΗΛ412 Ανάλυση & Σχεδίαση (Σύνθεση) Τηλεπικοινωνιακών Διατάξεων

Διαλέξεις 8-9



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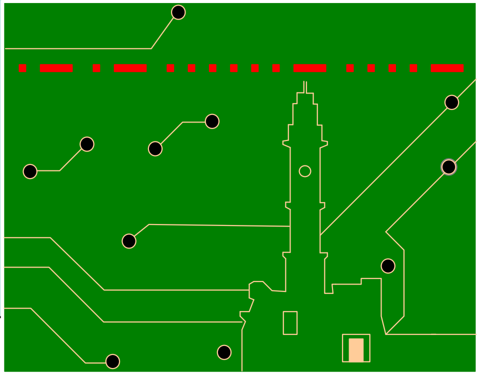
ΗΜΜΥ Πολυτεχνείου Κρήτης, Φθινόπωρο 2014

Διαλέξεις 8-9 – Κεραίες
(Από την οπτική γωνία του μηχανικού!)

- Εξισώσεις Helmholtz & Maxwell (&vector calculus).
- Far Field Coupling.
- Antenna Characteristics: VSWR, RL, Efficiency, Gain, Bandwidth, HPBW, Polarization.
- Rough Estimation in High-Gain Antennas.
- Polarization Mismatch



Για την σημερινή διάλεξη έχει χρησιμοποιηθεί υλικό κυρίως από το βιβλίο
Kai Chang, “RF and Microwave Wireless Systems”, Wiley Series in Microwave and Optical Engineering, John Wiley & Sons, 2000.

Βασική ερώτηση μαθήματος

ή

?

Κεραίες 2.4-2.5GHz

	Typical performance
Peak gain	2.2 dBi
Average gain	-1.0 dBi
Average efficiency	80%
Maximum Return Loss	-13 dB
Maximum VSWR	1.6:1

Frequency [GHz]	Gain [dBi]	Impedance [Nom]	VSWR	Polarization	Electrical Length	Radiation
2.4 – 2.5	2.0	50 Ω	≤ 2.0	Vertical	¼, dipole	Omni

Ορισμός

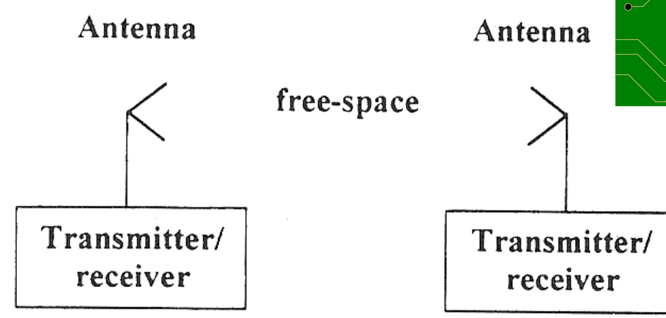
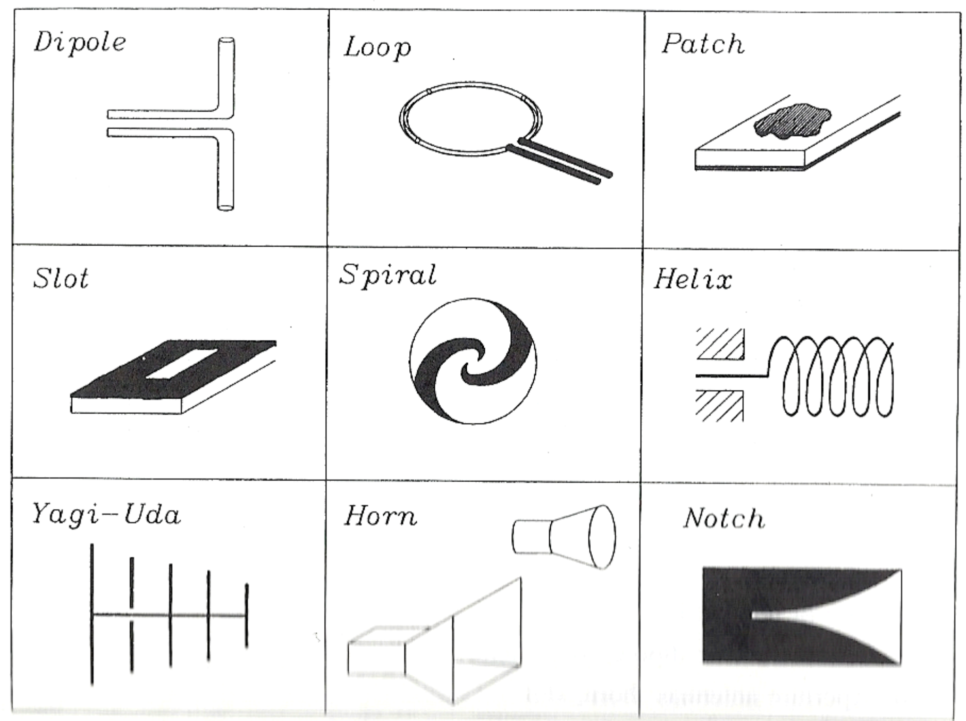


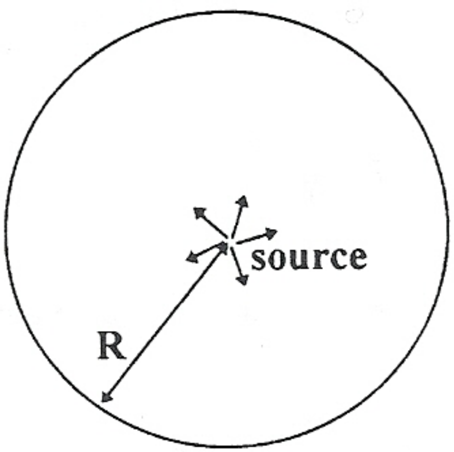
FIGURE 3.1 Typical wireless system.

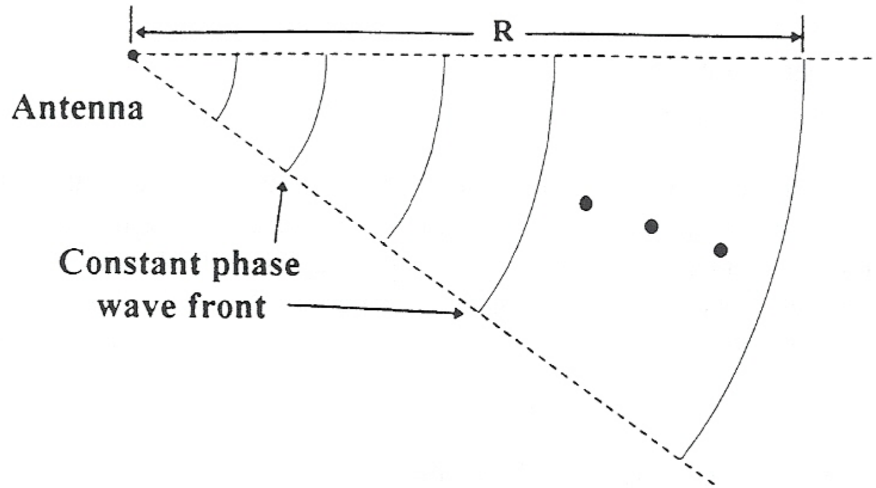
- Κεραία = διεπαφή (i.e. interface) μεταξύ κυμάτων/σημάτων.
- Κεραία ≡ συντονισμός
- Κεραία = μέγιστη ακτινοβολία.
- Κυματοδηγός = ελάχιστη ακτινοβολία.
- Χαρακτηρισμός: γεωμετρία, κέρδος, λωβός, εύρος ζώνης.



Ισοτροπικός Ακτινοβολητής και Επίπεδα Κύματα

$$\nabla^2\vec{E} + k_0^2\vec{E} = 0$$





- Θεωρητικό (και μόνο) εργαλείο.
- Μέτωπο κύματος σφαιρικό.
- Πυκνότητα ισχύος:

$$P_d = \frac{P_t}{4\pi R^2}$$

- Μεγάλο R => επίπεδο κύμα (όχι σφαιρικό)

- Η/Μ πεδίο: Εξίσωση Κύματος (Helmholtz).

Θυμάστε τις εξισώσεις του Maxwell?

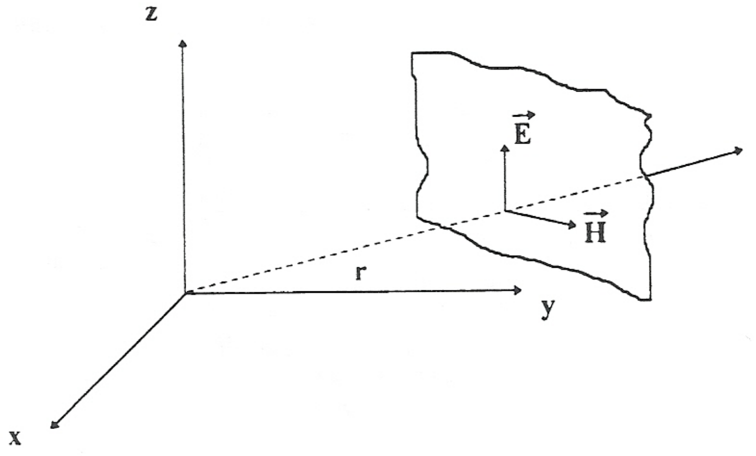
Div: Ροή διανυσματικού πεδίου ανά μονάδα όγκου

$$\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon} \quad \text{Gauss' law}$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \text{Faraday's law}$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \quad \text{Ampere's law}$$

$$\nabla \cdot \vec{B} = 0 \quad \text{flux law}$$



Curl: Κυκλοφορία διανυσματικού πεδίου ανά μονάδα επιφάνειας

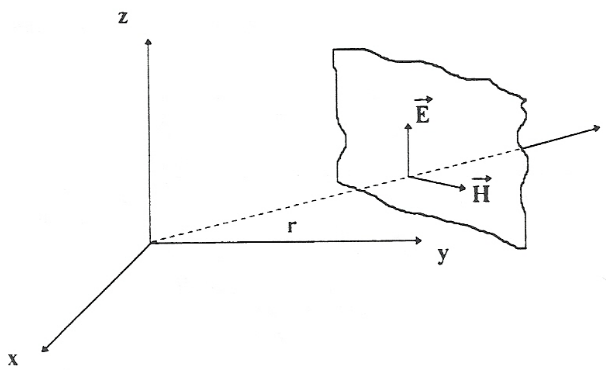
Basic E/M Units

- charge density ρ (Coulomb/m^3), current density J (Ampere/m^2)
- permittivity ε: Farad/m
- Electric Field E: Volt/m
- permeability μ: Henry/m
- Magnetic Field H: Ampere/m
- Magnetic flux density B=magnetic flux/surface=μ H: Tesla
- Magnetic flux Φ: Weber = Henry Ampere
- Electric Displacement D=ε E: Coulomb/m^2

Θυμάστε διανυσματική ανάλυση?

Let $f\colon \mathbf{R}^3 \to \mathbf{R}$ and $\mathbf{F}\colon \mathbf{R}^3 \to \mathbf{R}^3$. Write $\mathbf{F} = (f_1, f_2, f_3)$.
Similarly for g and $\mathbf{G}$.
Define:

$$\begin{aligned}
\mathrm{grad}(f) \equiv \nabla f &= \left(\frac{\partial f}{\partial x}, \frac{\partial f}{\partial y}, \frac{\partial f}{\partial z}\right) \\
\mathrm{div}(\mathbf{F}) \equiv \nabla \cdot \mathbf{F} &= \frac{\partial f_1}{\partial x} + \frac{\partial f_2}{\partial y} + \frac{\partial f_3}{\partial z} \\
\mathrm{curl}(\mathbf{F}) \equiv \nabla \times \mathbf{F} &= \left(\frac{\partial f_3}{\partial y} - \frac{\partial f_2}{\partial z}, \frac{\partial f_1}{\partial z} - \frac{\partial f_3}{\partial x}, \frac{\partial f_2}{\partial x} - \frac{\partial f_1}{\partial y}\right) \\
\mathrm{laplace}(f) \equiv \nabla^2 f &= \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2} \\
\mathrm{laplace}(\mathbf{F}) \equiv \nabla^2 \mathbf{F} &= \left(\nabla^2 f_1, \nabla^2 f_2, \nabla^2 f_3\right)
\end{aligned}$$



Θυμάστε διανυσματική ανάλυση?

Let $\phi(x,y,z)$ be a scalar field. The gradient is a vector

$$\text{grad}\ \phi = \left(\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}, \frac{\partial\phi}{\partial z}\right),$$

it is the derivative of ϕ in each direction. The gradient of a scalar field is a vector field. An alternative notation is to use the *del* or *nabla* operator, $\nabla\phi = \text{grad}\ \phi$.

<u>Divergence of a vector field</u>

Let F(x,y,z) be a vector field, continuously differentiable with respect to x,y and z. Then the divergence of F is defined by

$$\text{div}\ F = \frac{\partial F_1}{\partial x} + \frac{\partial F_2}{\partial y} + \frac{\partial F_3}{\partial z}.$$

div F is a scalar field it can also be written as $\text{div}\,\mathbf{F} = \nabla\cdot\mathbf{F}$

Laplacian

$$\Delta f = \nabla^2 f = \nabla\cdot\nabla f,$$

$$\Delta f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$$

$$\Delta f = \frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\frac{\partial f}{\partial\rho}\right) + \frac{1}{\rho^2}\frac{\partial^2 f}{\partial\theta^2} + \frac{\partial^2 f}{\partial z^2}$$

$$\Delta f = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\varphi}\frac{\partial}{\partial\varphi}\left(\sin\varphi\frac{\partial f}{\partial\varphi}\right) + \frac{1}{r^2\sin^2\varphi}\frac{\partial^2 f}{\partial\theta^2}$$

<u>Curl of a vector field</u>

Let F(x,y,z) be a vector field, continuously differentiable with respect to x,y and z. Then the curl of F is defined by

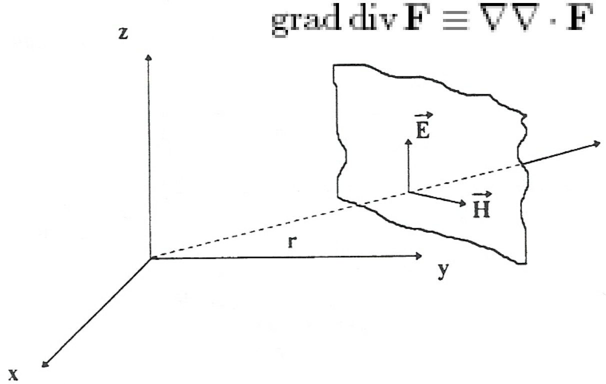
$$\begin{vmatrix} i & j & k \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ F_1 & F_2 & F_3 \end{vmatrix} = \text{curl}\ F = \left(\frac{\partial F_3}{\partial y} - \frac{\partial F_2}{\partial z}\right)i - \left(\frac{\partial F_3}{\partial x} - \frac{\partial F_1}{\partial z}\right)j + \left(\frac{\partial F_2}{\partial x} - \frac{\partial F_1}{\partial y}\right)k$$

curl F is a vector field it can also be written as $\nabla\times F$.

Notice that $\nabla\cdot(\nabla\times\mathbf{F}) = 0$

Θυμάστε διανυσματική ανάλυση?

$$
\begin{aligned}
\operatorname{grad}(f+g) \equiv \nabla(f+g) &= \nabla f + \nabla g \\
\operatorname{div}(\mathbf{F}+\mathbf{G}) \equiv \nabla\cdot(\mathbf{F}+\mathbf{G}) &= \nabla\cdot\mathbf{F} + \nabla\cdot\mathbf{G} \\
\operatorname{curl}(\mathbf{F}+\mathbf{G}) \equiv \nabla\times(\mathbf{F}+\mathbf{G}) &= \nabla\times\mathbf{F} + \nabla\times\mathbf{G} \\
\operatorname{grad}(fg) \equiv \nabla(fg) &= f\nabla g + g\nabla f \\
\operatorname{div}(f\mathbf{G}) \equiv \nabla\cdot(f\mathbf{G}) &= \nabla f\cdot\mathbf{G} + f\nabla\cdot\mathbf{G} \\
\operatorname{curl}(f\mathbf{G}) \equiv \nabla\times(f\mathbf{G}) &= \nabla f\times\mathbf{G} + f\nabla\times\mathbf{G} \\
\operatorname{grad}(\mathbf{F}\cdot\mathbf{G}) \equiv \nabla(\mathbf{F}\cdot\mathbf{G}) &= (\mathbf{F}\cdot\nabla)\mathbf{G} + (\mathbf{G}\cdot\nabla)\mathbf{F} + \mathbf{F}\times(\nabla\times\mathbf{G}) + \mathbf{G}\times(\nabla\times\mathbf{F}) \\
\operatorname{div}(\mathbf{F}\times\mathbf{G}) \equiv \nabla\cdot(\mathbf{F}\times\mathbf{G}) &= \mathbf{G}\cdot\nabla\times\mathbf{F} - \mathbf{F}\cdot\nabla\times\mathbf{G} \\
\operatorname{curl}(\mathbf{F}\times\mathbf{G}) \equiv \nabla\times(\mathbf{F}\times\mathbf{G}) &= \mathbf{F}(\nabla\cdot\mathbf{G}) - \mathbf{G}(\nabla\cdot\mathbf{F}) + (\mathbf{G}\cdot\nabla)\mathbf{F} - (\mathbf{F}\cdot\nabla)\mathbf{G} \\
\operatorname{div}\operatorname{grad} f \equiv \nabla\cdot\nabla f &= \nabla^2 f = \operatorname{laplace} f \\
\operatorname{curl}\operatorname{grad} f \equiv \nabla\times\nabla f &= 0 \\
\operatorname{div}\operatorname{curl}\mathbf{F} \equiv \nabla\cdot(\nabla\times\mathbf{F}) &= 0 \\
\operatorname{curl}^2\mathbf{F} \equiv \nabla\times(\nabla\times\mathbf{F}) &= \nabla\nabla\cdot\mathbf{F} - \nabla^2\mathbf{F} = \operatorname{grad}\operatorname{div}\mathbf{F} - \operatorname{laplace}\mathbf{F} \\
\operatorname{grad}\operatorname{div}\mathbf{F} \equiv \nabla\nabla\cdot\mathbf{F} &= \nabla\times(\nabla\times\mathbf{F}) + \nabla^2\mathbf{F} = \operatorname{curl}^2\mathbf{F} + \operatorname{laplace}\mathbf{F}
\end{aligned}
$$



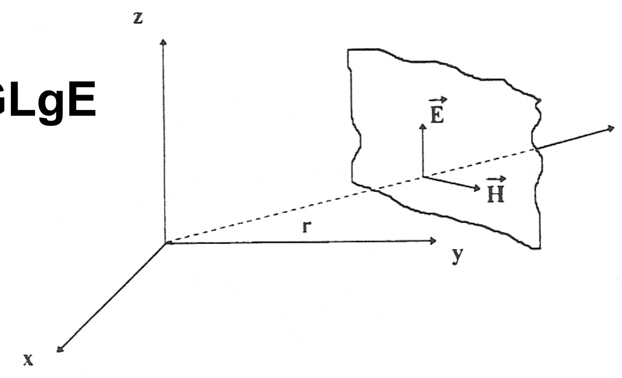
Θυμάστε διανυσματική ανάλυση?

Τα παρακάτω δείχνουν το Intuition...
(curl (rotation)= vector circulation per unit area, div=vector flux per unit of volume, grad=direction of rate of change)

Curl
http://www.youtube.com/watch?v=fYzoiWIBjP8

Div
http://www.youtube.com/watch?v=tOX3RkH2guE

Grad
http://www.youtube.com/watch?v=OB8b8aDGLgE



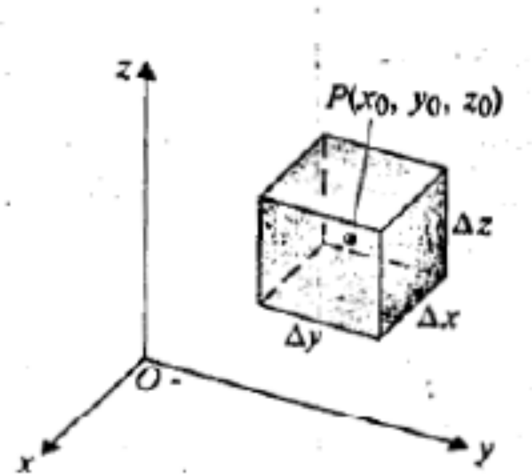
Divergence of A at a point:
net outward flux of A per unit volume, when the volume around the point of interest tends to zero.

$$divA \triangleq \lim_{\Delta v \to 0} \frac{\oint_s A \bullet ds}{\Delta v}$$

→ *The net outward flux*

→ *Measure of the strength of a flow source*

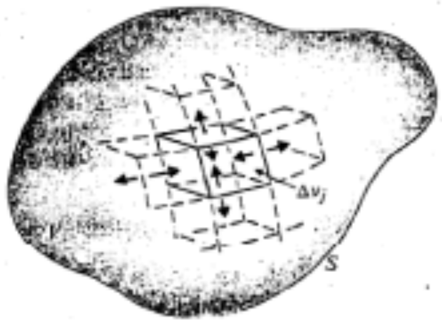
$$\oint_s \mathrm{A} \cdot d\hat{s} = \left[\int_{\substack{front\\face}} + \int_{\substack{back\\face}} + \int_{\substack{left\\face}} + \int_{\substack{right\\face}} + \int_{\substack{top\\face}} + \int_{\substack{bottom\\face}} \right] \mathbf{A} \cdot \mathbf{a}_n ds$$



Divergence Theorem (aka Gauss Theorem):

volume integral of of div of vector A = flux of A through bounding surface of that volume.

$$\int_v \nabla \bullet A dv = \oint_s A \bullet ds$$



$$divA \triangleq \lim_{\Delta v \to 0} \frac{\oint_s A \bullet ds}{\Delta v}$$

→ The net outward flux

→ Measure of the strength of a flow source

Curl of A at a point: vector, with

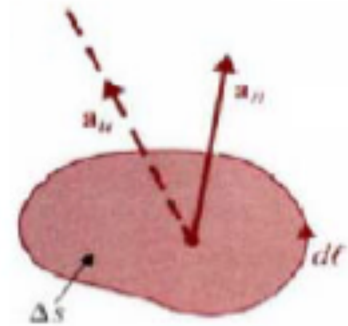
magnitude = the maximum net circulation of vector A per unit area around that point, as the area tends to zero,
direction = normal to area, when area is oriented such that circulation is maximized.

Circulation of A around contour C $\equiv \oint_c \mathbf{A} \cdot d\hat{l}$

A: force → circulation: work
A: E-field → circulation: electromotive force

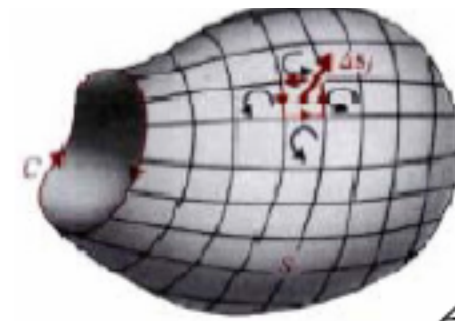
Circulation of A in closed path c = line integral of A over c.

$$curl\ \mathbf{A} \equiv \nabla \times \mathbf{A} = \lim_{\Delta s \to 0} \frac{1}{\Delta S} \left[\mathbf{a}_n \oint_c \mathbf{A} \cdot d\hat{l} \right]_{max}$$

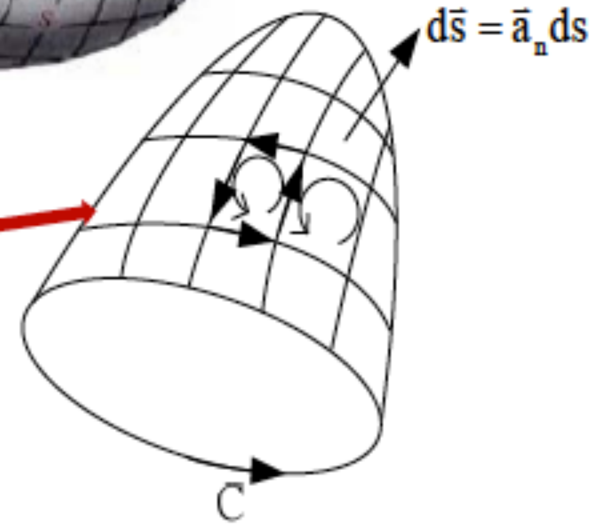


Curl Theorem (aka Stokes Theorem):

the surface integral of curl of a vector over an open surface
=
the closed line integral of the vect
over the bounding contour of of t
surface.

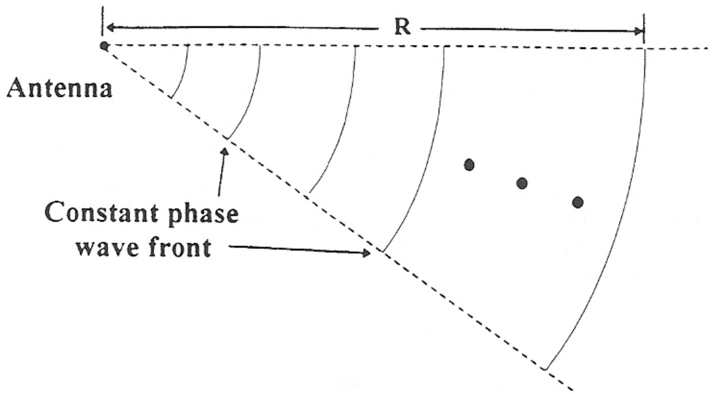


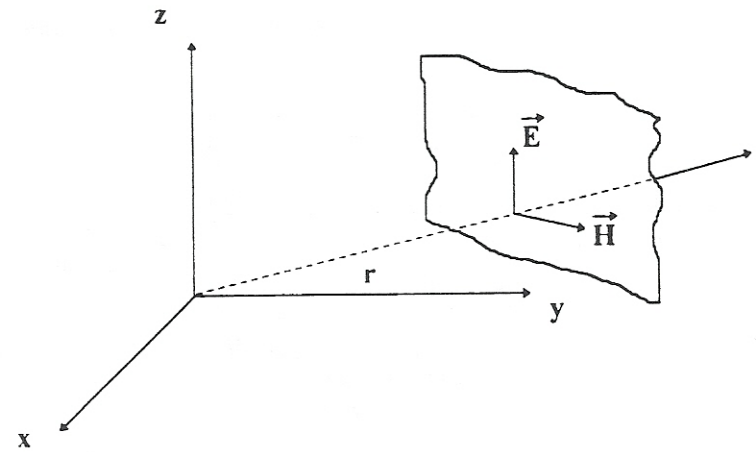
$$\oint_S \left(\nabla \times \vec{A}\right) \cdot d\vec{s} = \oint_C \vec{A} \cdot d\vec{\ell}$$



Question: what are the units of div($\vec{A}$), curl($\vec{A}$)?

Εξίσωση Κύματος (Εξίσωση Helmholtz): Επίλυση





$$k_0 = \frac{2\pi}{\lambda_0}, \vec{k}_0 = k_0 \vec{n}_0,$$

$$\vec{E} = \vec{E}_0 e^{-j\vec{k}_0 \vec{r}},$$

Λύση Helmholtz

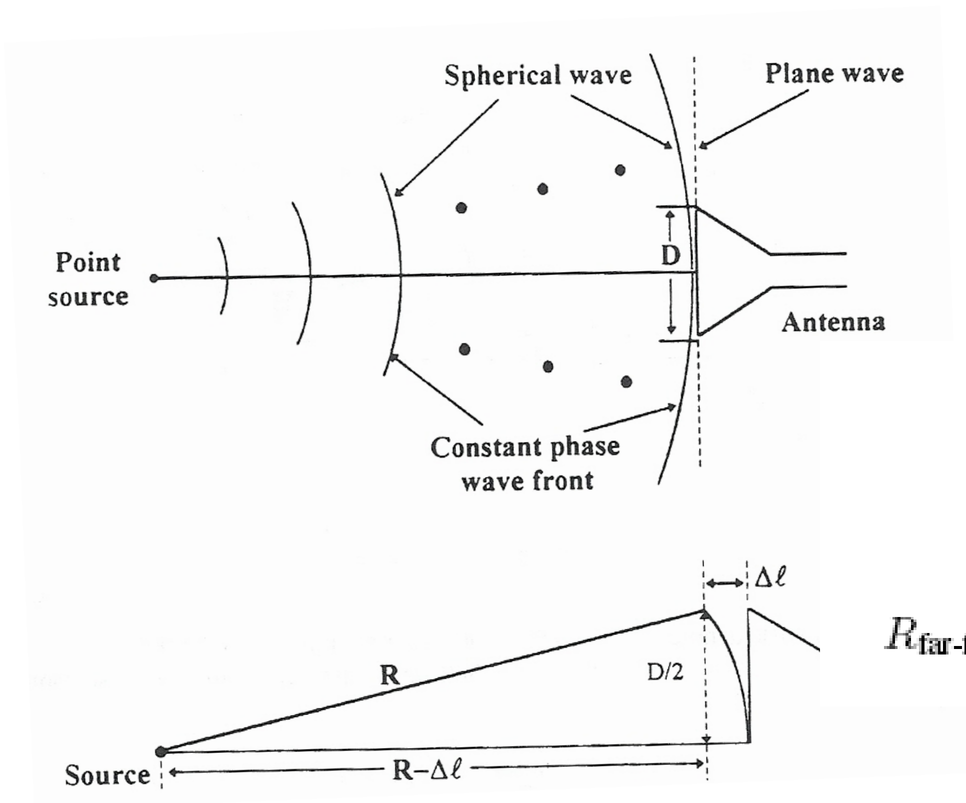
$$\vec{H} = -\frac{1}{j\omega\mu_0}\nabla \times \vec{E} = \sqrt{\frac{\epsilon_0}{\mu_0}}\, \vec{n} \times \vec{E}.$$ **Maxwell**

$$\eta_0 = \frac{|\vec{E}|}{|\vec{H}|} = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi.$$

Διαστάσεις σε Ωhm

$$P_d = \left|\frac{1}{2}\vec{E} \times \vec{H}^*\right| = \frac{1}{2}\frac{E_0^2}{\eta_0} \equiv \frac{P_t}{4\pi R^2} \Rightarrow E_0 = \frac{\sqrt{60P_t}}{R} = \sqrt{2}E_{\rm rms}.$$

Far Field Region



$$R^2 = (R - \Delta l)^2 + \frac{D^2}{4}, R^2 \approx R^2 + (\Delta l)^2 \Rightarrow$$

$$R = \frac{D^2}{8\Delta l}, \Delta l = \frac{1}{16}\lambda_0 \Rightarrow$$

$$R_{\text{far-field}} = \frac{2\ D^2}{\lambda_0}.$$

- Region where plane-wave is a "good" approximation!
- <u>Practically, where antenna patterns are independent of distance</u>.

Antenna Analysis (in one minute)

- Solution through inhomogeneous Helmholtz equation.

- Antenna with volume V and current J:

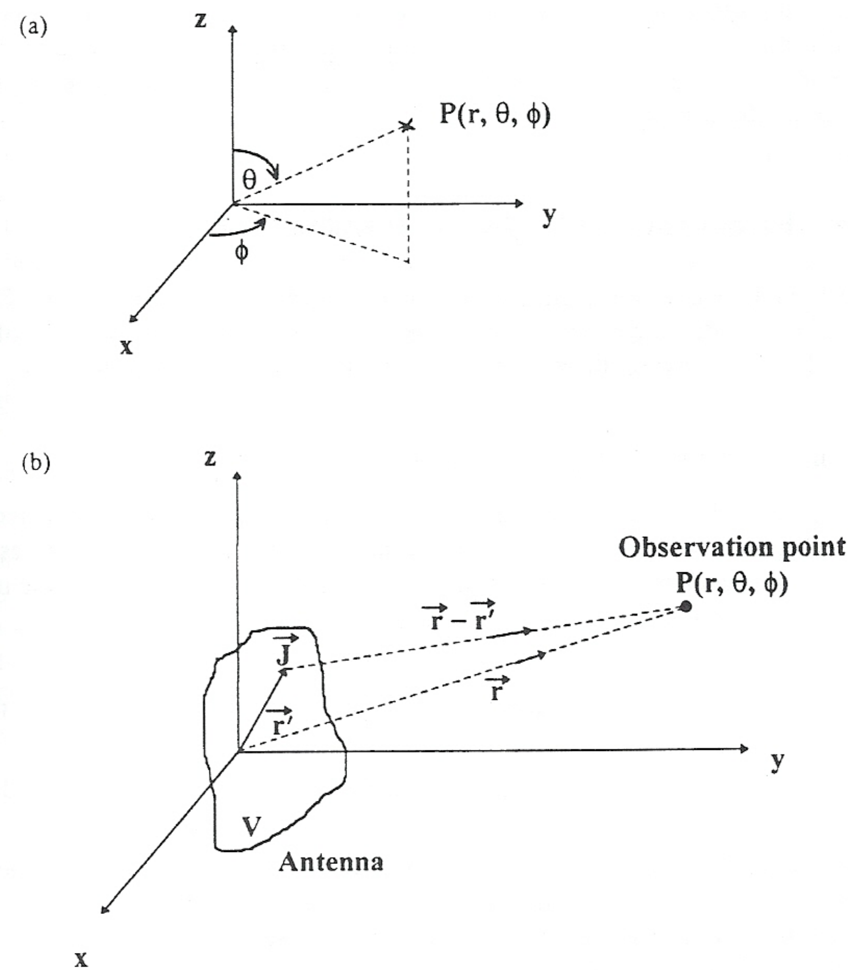
$$\nabla^2 \vec{A} + k_0^2 \vec{A} = -\mu \vec{J},$$

$$\vec{B} = \nabla \times \vec{A} = \mu_0 \vec{H},$$

$$\vec{A}(\vec{r}) = \frac{\mu}{4\pi} \int_V \vec{J}(\vec{r}') \frac{e^{-jk_0|\vec{r}-\vec{r}'|}}{|\vec{r}-\vec{r}'|}\, dV.$$

- Current distribution from Antenna geometry.

- Numerical methods.



Characteristics: Input VSWR & Impedance

We prove these in next lecture!

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|},$$

$$RL = \pm 20\log_{10}|\Gamma|,$$ **Return Loss**

$$Z_{\text{in}} = Z_0\frac{1+\Gamma}{1-\Gamma}.$$

$0 < |\Gamma|^2 < 1$,
sign depends on book/context

- $|\Gamma|^2$ shows the percentage of power lost due to mismatch (reflection).
- power coupled to antenna = $(1-|\Gamma|^2)$ times the power delivered from source.
- Typically, VSWR is less than 2:1.
- Example: VSWR = 2:1 means that 11% of delivered tx power to antenna is lost!

Characteristics: Bandwidth

➢ Various meanings, depending on context.

➢ Most common: impedance bandwidth.

➢ Impedance bandwidth: range of frequencies where VSWR below a threshold.

➢ Other definitions based on gain, efficiency, patterns etc.

➢ Operational bandwidth usually smaller.

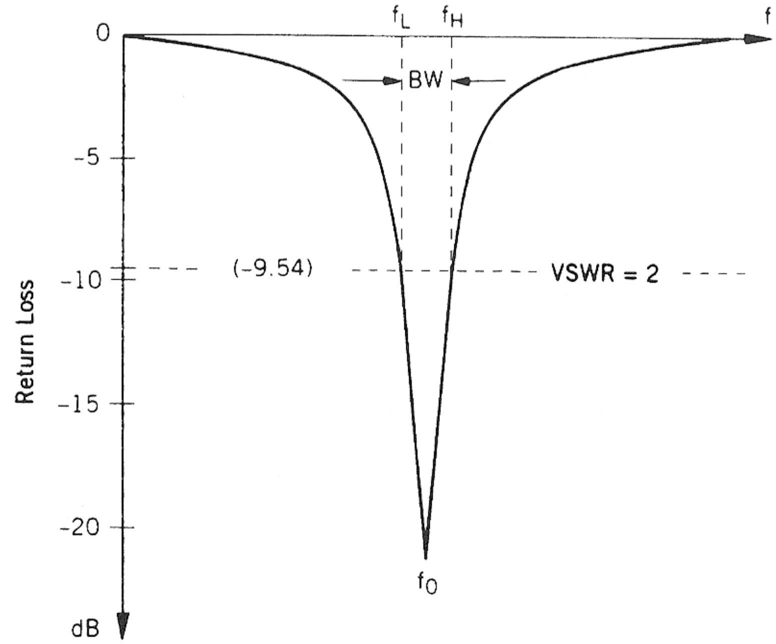
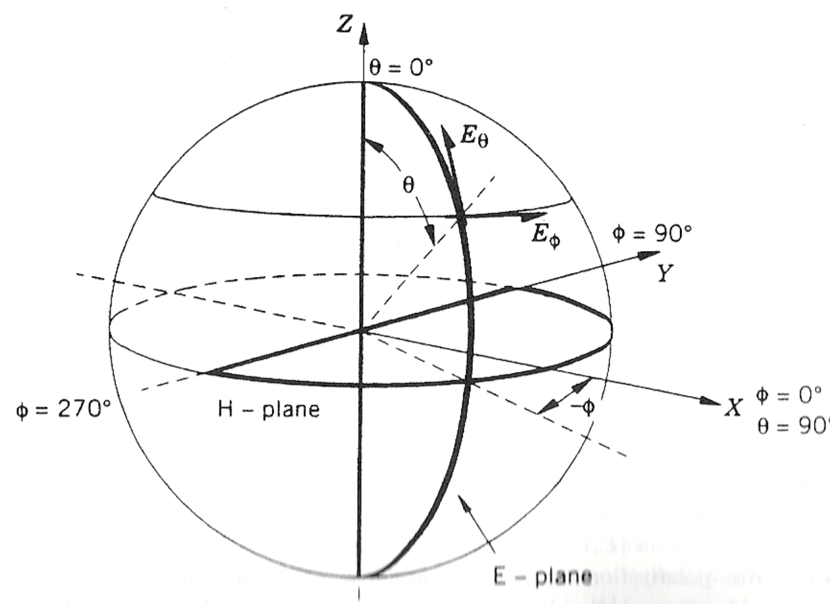


FIGURE 3.8 VSWR = 2 bandwidth [2].



Characteristics: Power Radiation Patterns

- Remember: far-field electric characteristics are independent of distance.
- <u>Typically, plot power density (Poynting vector across a sphere,centered at the ant.)</u>
- Simpler approach: draw electric and/or magnetic field at cut planes where the field is maximized.
- E-plane: E_θ plane.
- Cross-polarization component: E_φ

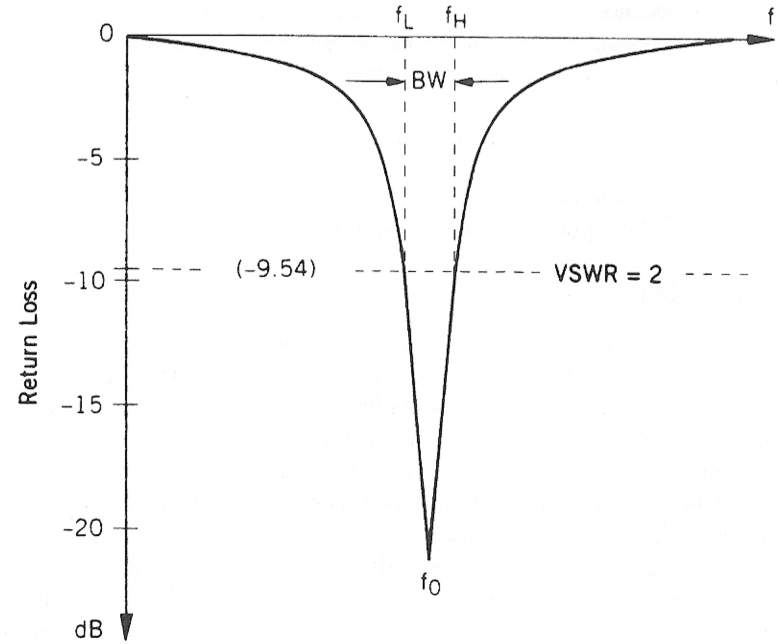
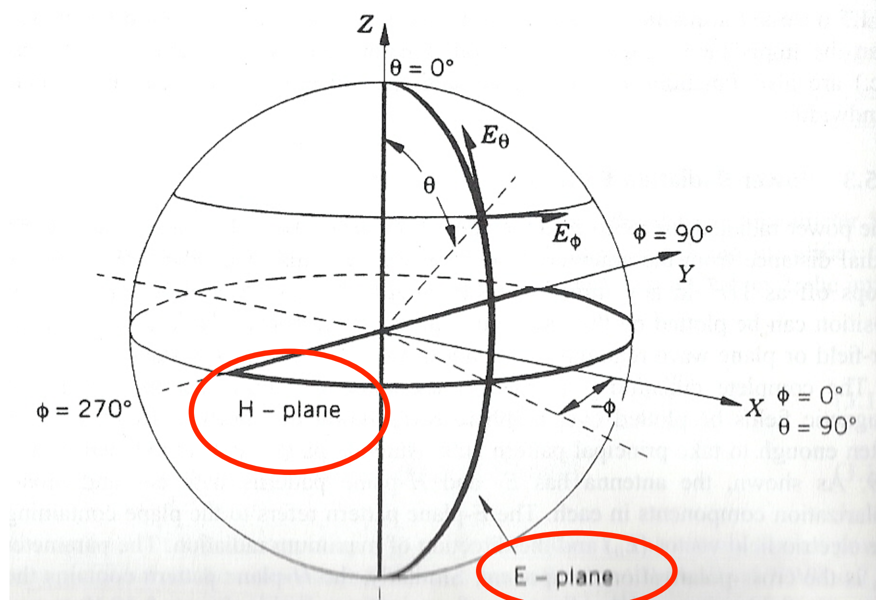
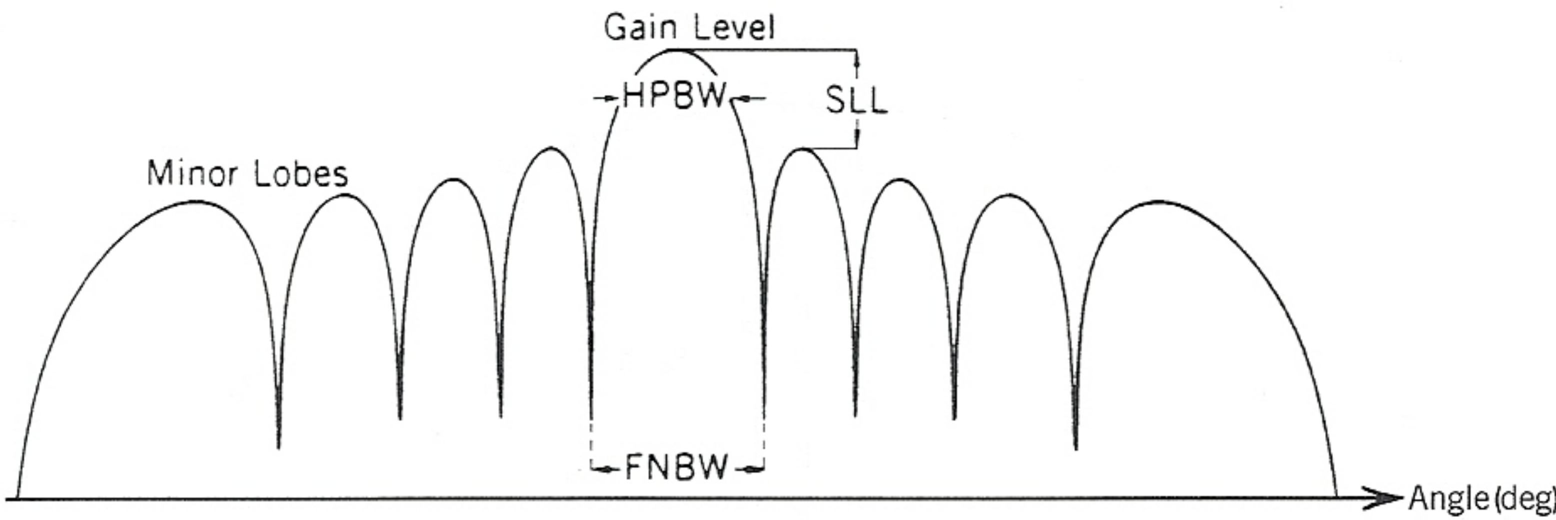


FIGURE 3.8 VSWR = 2 bandwidth [2].



Characteristics: Half-power Beamwidth and Side Lobe Level (SLL)



- HPBW: the range in degrees such that the radiation drops to one-half.
- SLL: the number of decibels below the main peak of the side peaks.

Characteristics: Directivity, Gain, Efficiency

$$\text{Poynting power density} = \vec{S}(\theta,\phi) = \frac{1}{2}\Re\left[\vec{E}\times\vec{H}^*\right],$$

$$D(\theta,\phi) = \frac{S(\theta,\phi)}{P_t/4\pi R^2},$$

$$D_{\max} = \frac{\max|\vec{S}(\theta,\phi)|}{P_t/4\pi R^2}.$$

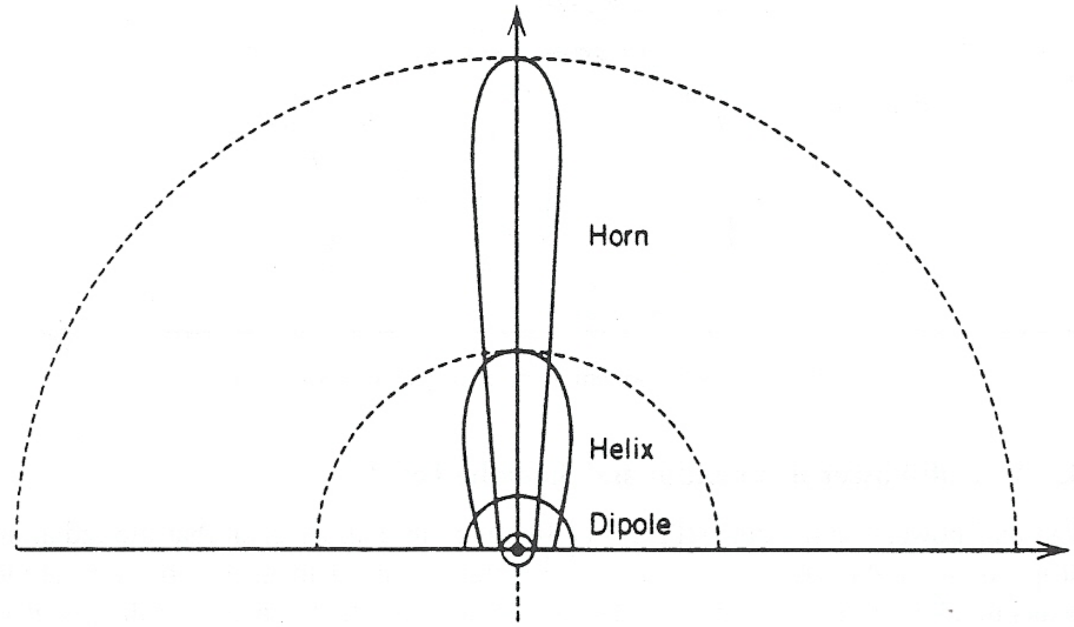
Note: $P_t = P_{rad}$

$$\text{efficiency } \eta = \frac{P_{\text{rad}}}{P_{\text{in}}} = \frac{P_{\text{rad}}}{P_{\text{rad}} + P_{\text{loss}}}.$$

$$\text{Gain } G = \eta D_{\max}.$$

- Gain and efficiency connect radiated power with ant input power.
- For example: G $P_t/4\pi R^2$ is radiated power density towards maximum radiation direction (Note: P_t is total input power $P_t = P_{rad}+P_{loss}$).
- Why don't we always maximize gain?

Characteristics: gain-bw tradeoff



- Gain-beamwidth tradeoff: maximizing one, minimizes the other.
- Gain-bandwidth tradeoff also exists (fundamental).
- Thus, maximizing ant gain comes at the cost of reduced bandwidth and increased HPBW.

Characteristics: Rough Estimation of High-Gain Ant

$$\text{HPBW} \approx K_1 \frac{\lambda_0}{\text{D}}, \qquad G \approx \frac{K_2}{\theta_1 \theta_2}$$

- $K_1 \approx 70^o$, D ant dimension at the plane of interest.
- $K_2 \approx 30{,}000$, θ_1, θ_2 are HPBW across the two orthogonal principal planes.

Characteristics: Effective Area, Polarization

- Effective area proportional, but smaller, than physical area.
- Friis Equation is derived through A_e

$$G = \frac{4\pi}{\lambda^2} A_e$$

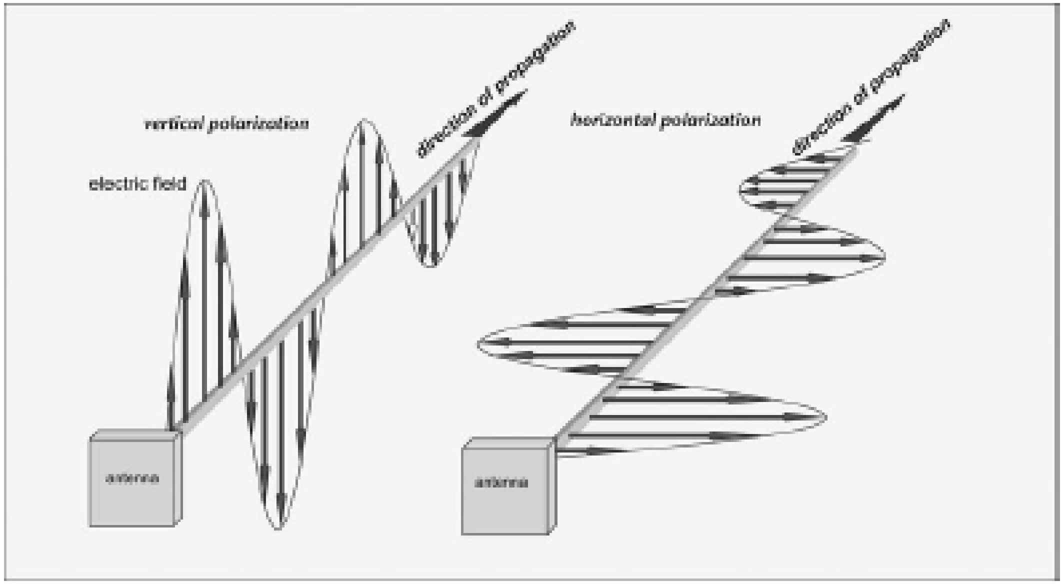
- Polarization = direction of Electric Field as a function of time:

  straight line: linear polarization,

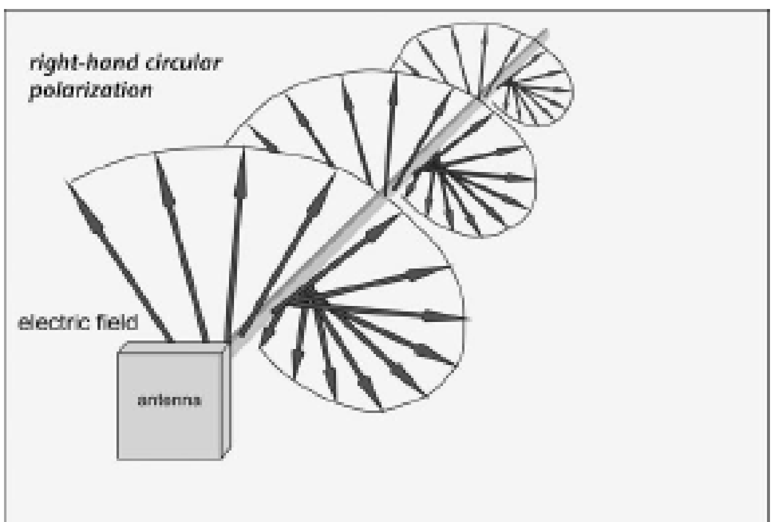
  circle: circular polarization (LH or RH),

  ellipse: eliptical polarization.

Polarization Example

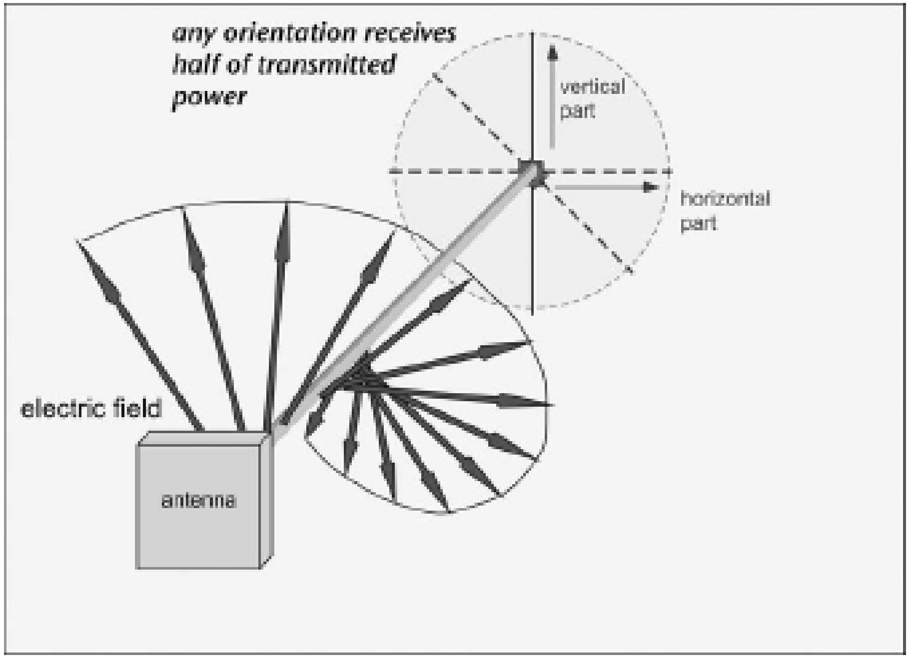


- linear…



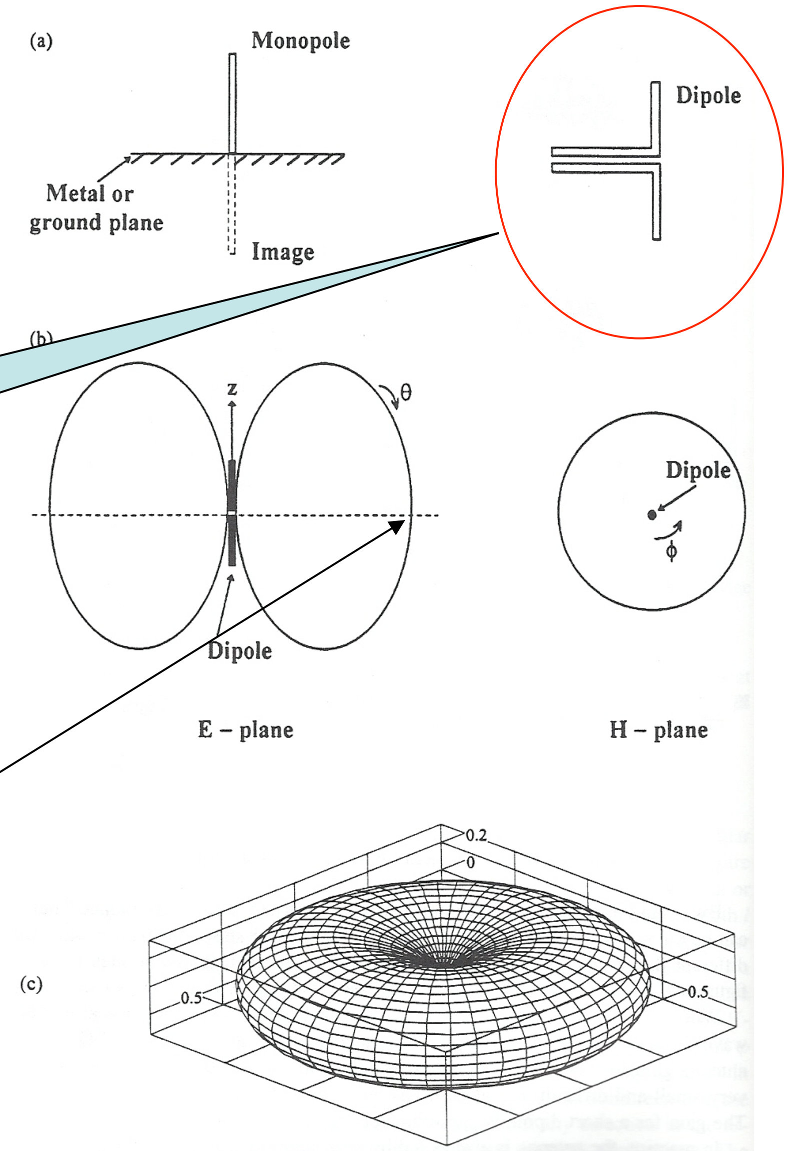
- circular…

Polarization Mismatch



- ➢ reducing received power by 3-dB

Example: Dipole



Open circuit?

- G = 1.64 => 2.15 dBi

- ERP: transmitted power referenced to dipole gain.
- EIRP: transmitted power referenced to isotropic antenna.

Βασική ερώτηση μαθήματος

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Κεραίες 2.4-2.5GHz

	Typical performance
Peak gain	2.2 dBi
Average gain	-1.0 dBi
Average efficiency	80%
Maximum Return Loss	-13 dB
Maximum VSWR	1.6:1

Frequency [GHz]	Gain [dBi]	Impedance [Nom]	VSWR	Polarization	Electrical Length	Radiation
2.4 – 2.5	2.0	50 Ω	≤ 2.0	Vertical	¼, dipole	Omni

Questions?