University of Sofia “St. Kliment Ohridsky”
Faculty of Physics, Sofia, Bulgaria

4th International Workshop and
Summer School on Plasma Physics, Kiten Bulgaria
5 – 10 July, 2010

Microwave Measurements of Electrical Fields in Different Media –

Principles, Methods and Instrumentation

by Plamen I. Dankov

Outline

1. Electric-field measurements.

- E-field sensors – dipoles and monopoles. E-field dosimetry. Wide-band sensors, sensors for circular-polarized fields; frequency-independent, miniature, fractal, reconfigurable sensors, radiating aperture, active sensors (rectenas), etc.
- Typical EMC/EMI measurements. Safety exposure standards.
- Popular example: determination of safety rates around urban GSM base station.

2. Antenna, antenna arrays and basic antenna measurements.

- Antenna as transducer, transformer, radiator and energy converter. Main antenna parameters – radiation pattern, directivity, efficiency, polarization, etc.
- Main types of antennas. Antenna arrays. Steerable antennas.
- Far-field antenna measurements. Near-field antenna measurement. Near-field scanners. THz spectroscopy. Basic equipment for field/power/signal measurements.
- Electromagnetic simulators, applied to antennas and propagation media.

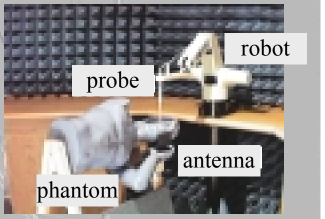
3. Characterization of dielectric materials and propagation media.

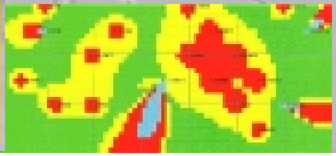
- Resonance, transmission-line and free-space methods for material characterization.
- Measurement specificity in the case of liquids, powder, absorbers, thin films, etc.
- Determination of the dielectric anisotropy of materials. “Two-resonator” method.
- Hairpin-resonator probe for characterization of electron density in plasmas.

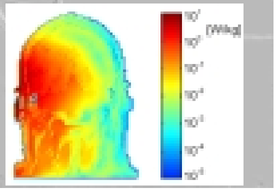
1st Part: E-field measurements

1. Electric-field measurements.

- E-field sensors – dipoles and monopoles. E-field dosimetry.
- Wide-band sensors, sensors for circular-polarized fields; frequency-independent, miniature, fractal, reconfigurable sensors, radiating aperture, active sensors (rectenas), etc.
- Typical EMC/EMI measurements. Safety exposure standards.
- Popular example: determination of safety rates around urban GSM base station.

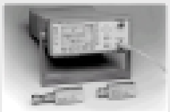




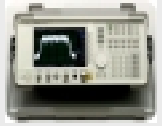


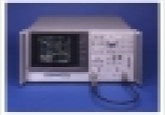
Main microwave measurements. E-field measurements

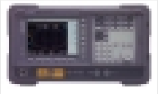
5 main types of measurements in the microwave range


Power !
(power meters)

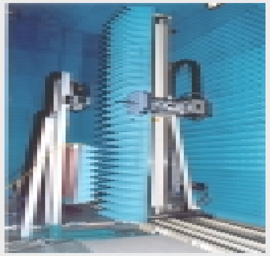

Frequency ⋆
(frequency counters)


Spectrum !
(spectrum analyzers)


S-parameters ⋆
(network analyzers)


Noise ⋆
(noise-figure meters)

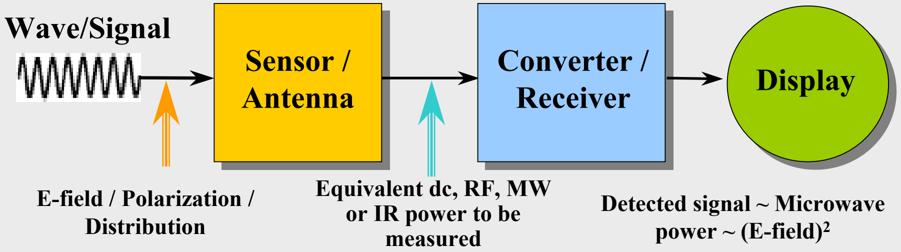

EMC/EMI measurements


Antenna measurements


Materials’ and media characterization

The E-field characterizations in the MW range are possible mainly by *power* and *spectrum* measurements. A necessity for actual information about the E fields *intensity*, *distribution* and *orientation* takes place in three main groups of measurements: 1) EMC/EMI measurements; 2) antenna measurements and 3) characterization of different materials and media (crystals, reinforced substrates, liquids, powders, absorbers, thin films, etc.)

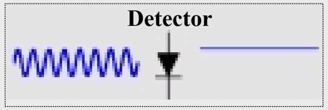
Principles for E-field measurements

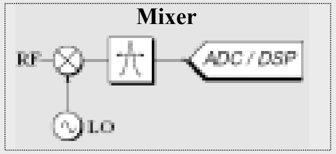


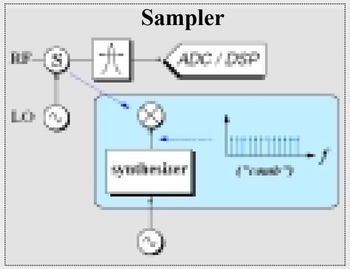
E-field / Polarization / Distribution

Equivalent dc, RF, MW or IR power to be measured

Detected signal ~ Microwave power ~ (E-field)²

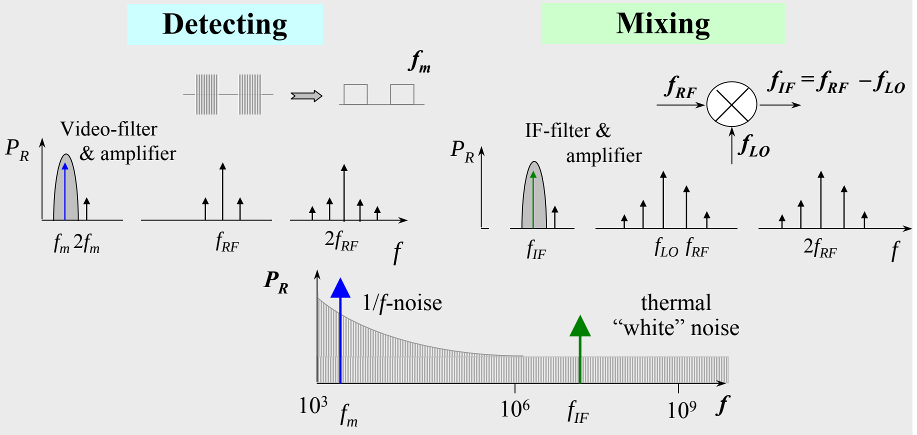






Three types of detectors/converters/receivers in the MW range

Spectrum of the received signals



Characteristics (detectors):

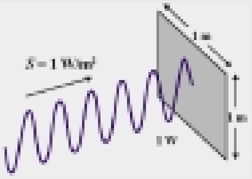
- Sensitivity ~ 1-10 μA/μW
- Frequency of detection: typically 1 kHz, 27.8 kHz (*hp*, Agilent); max to 100 kHz
- P_{min} ~10^{-7} mW (~ –70 dBm)
- Dynamic range D ~30-40 dB up to 70 dB

Characteristics (mixers):

- Intermediate frequency: ~ MHz up to 2 GHz
- P_{min} ~10^{-12} mW (or –120 dBm); due to the higher intermediate frequency IF
- Dynamic range D ~100-110 dB up to 140 dB

Relations between the fields and power flux density

S **– Average power-flux density:**



$$\bar{S} = \tfrac{1}{2}\mathrm{Re}(\mathbf{n}.\vec{\mathbf{S}}) = \tfrac{1}{2}\mathrm{Re}(E_p \times H_p^*)_z = \mathrm{Re}(\bar{E}_{RMS} \times \bar{H}_{RMS}^*)_z$$

$$\bar{S} = \mathrm{W/m^2}, \mathrm{mW/cm^2}, \mu\mathrm{W/cm^2}$$

Relation for plane waves:

$$\bar{E} = 19\sqrt{S}, \ \mathrm{V/m};$$

$$\bar{H} = 4.8\times10^4\sqrt{S}, \ \mathrm{A/m};$$

$$\bar{S} = [\mathrm{W/m^2}]$$

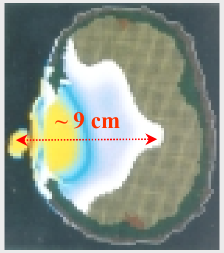
Denotations: *E*, H_p – "peak" amplitude values; *E*, H_{RMS} – Root Mean Squares values; average/effective/"measurable" fields

Important fact: *S* is the main "measurable" power quantity in the MW range; if *S* is known (measured), the fields *E* and *H* can be easy expressed through *S* for plane waves.

SAR **– Specific Absorption Rate:**

$$SAR, \ \mathrm{W/kg} = P_{abs} = \frac{\sigma|E_{local}|^2}{\rho} = \frac{\mathrm{d}}{\mathrm{dt}}\left(\frac{\mathrm{d}W_{abs}}{\rho \mathrm{d}V}\right)$$

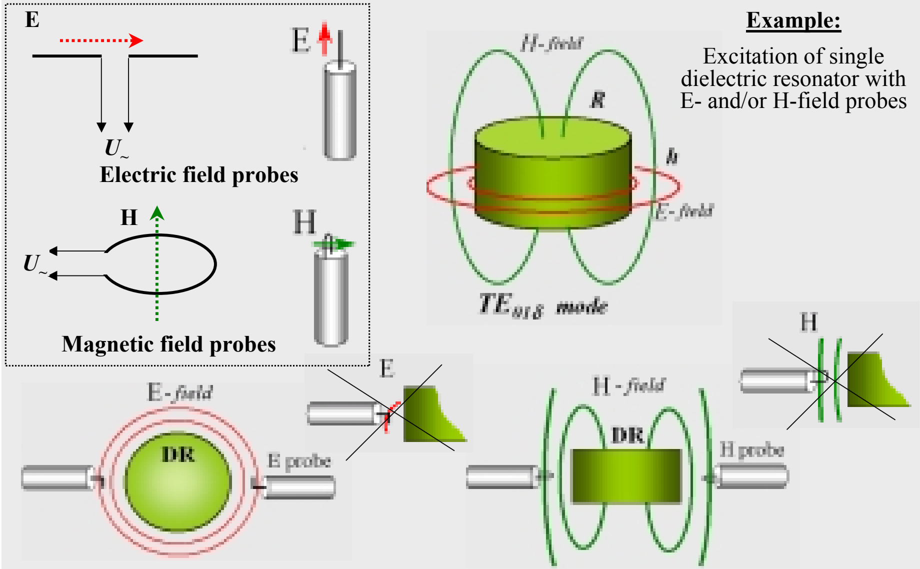
$$\frac{\mathrm{dT}}{\mathrm{dt}}, \mathrm{K/s} = \frac{\mathrm{SAR}}{C_p}$$



Denotations: σ – tissue conductivity; ρ – tissue density; $|E_{local}|$ – mean local E-field; *T* – absolute temperature; C_p – tissue thermal capacity;

Important fact: *SAR* is an important dosimetry quantity for biological tissues. It is a measure of the local absorbed energy W_{abs} in a given tissue "in-vivo" and also a measure of local heating of the tissues. Equal *S*, mW/cm² can "induce" different *SAR*, mW/g in different tissues!

Simplest field sensors – dipole and monopole probes



Electric field probes

Magnetic field probes

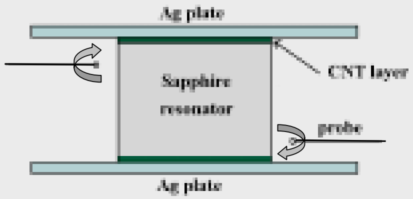
Example:

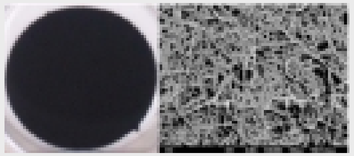
Excitation of single dielectric resonator with E- and/or H-field probes

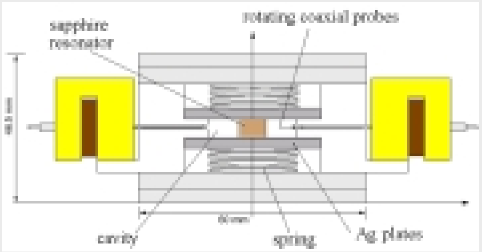
Examples for using of E-type and H-type probes for excitation of the TE_{011} mode in a cylindrical dielectric resonator (or for its suppression)

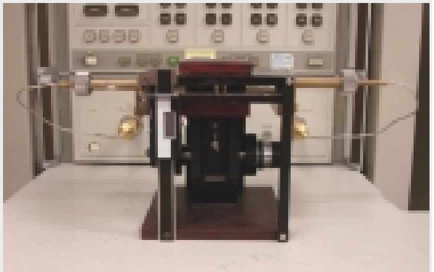
Example: Excitation in measurement dielectric resonator

Example: rotating electric or magnetic type field probes allow ensuring the best condition for excitation of a given modes – TE_{011} in this case. This is important for the considered case – measurement of the dielectric properties of CNT thin layer.





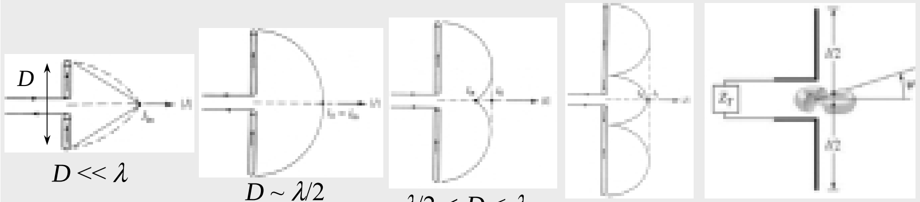




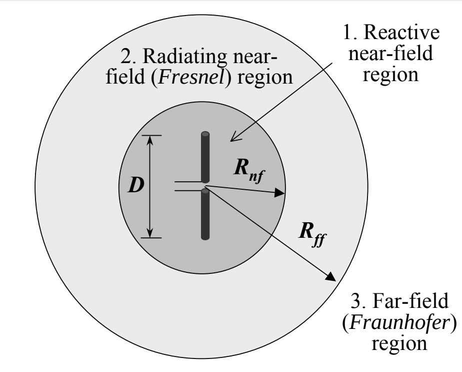
Measurement set-up for resonance characterization of CNT thin layers

---

Length of the E-field probe (electrical dipole)



$D << \lambda$ | $D \sim \lambda/2$ resonance | $\lambda/2 < D < \lambda$ | $\lambda < D < 3\lambda/2$ | Radiation pattern



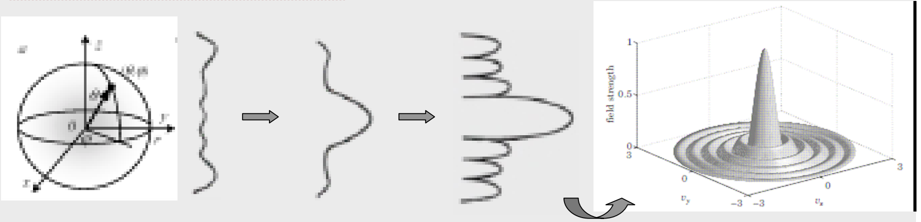
⇐ Conditionally, there exist three zones around each EM radiator, depending on the field distribution. The zones are divided by two radii:

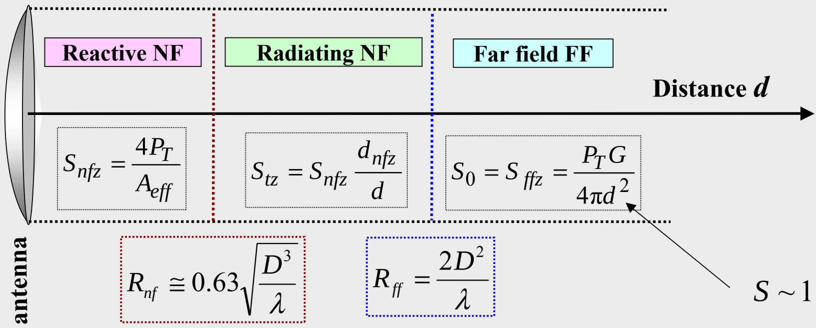
Near-field radius $$R_{nf} \cong 0.63\sqrt{\frac{D^3}{\lambda}}$$

Far-field radius $$R_{ff} = \frac{2D^2}{\lambda}$$

E-field radiation pattern

$$F(\theta,\varphi) = E(\theta,\varphi) / E_{\max}(\theta,\varphi)$$





Reactive NF | **Radiating NF** | **Far field FF**

Distance *d*

$$S_{nfz} = \frac{4P_T}{A_{eff}}$$

$$S_{tz} = S_{nfz}\frac{d_{nfz}}{d}$$

$$S_0 = S_{ffz} = \frac{P_T G}{4\pi d^2}$$

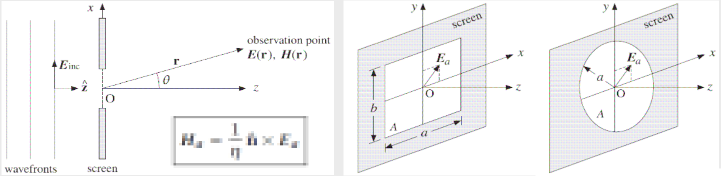
antenna

$$R_{nf} \cong 0.63\sqrt{\frac{D^3}{\lambda}}$$

$$R_{ff} = \frac{2D^2}{\lambda}$$

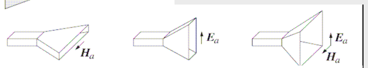
$$S \sim 1/d^2$$

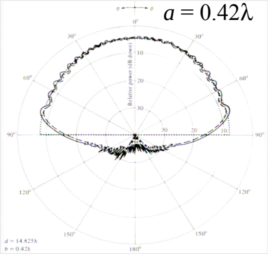
Radiating apertures as EM field sensors

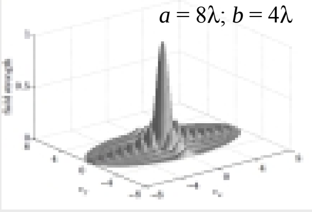


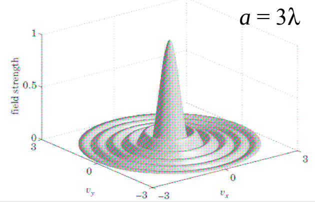
Aperture horn antennas

Huygens elementary apertures ($\Delta A << \lambda^2$)

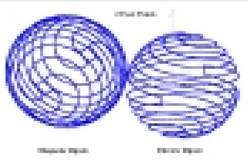


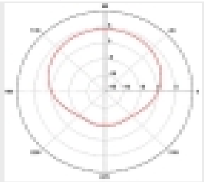




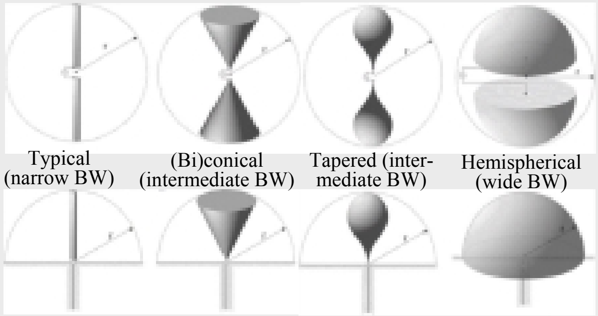


Imitation of reduced-size Huygens source at low frequency by pair of magnetic and electric dipoles and its radiation pattern



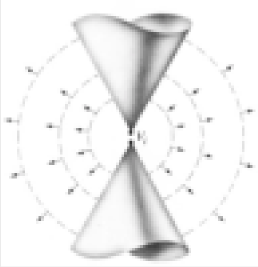


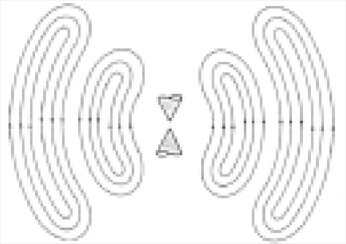
Broad-band E-field sensors

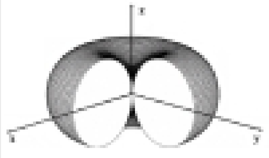

Typical (narrow BW)
(Bi)conical (intermediate BW)
Tapered (intermediate BW)
Hemispherical (wide BW)

Broad-band dipoles
(BW – bandwidth)

Broad-band monopoles



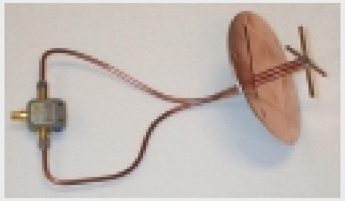


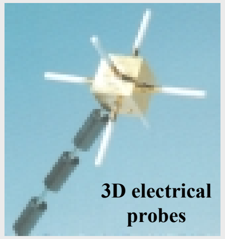


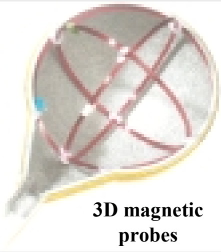
Omni-directional radiation pattern

3D sensors

$$E_\Sigma = \sqrt{E_x^2 + E_y^2 + E_z^2}$$



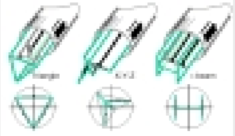

3D electrical probes


3D magnetic probes

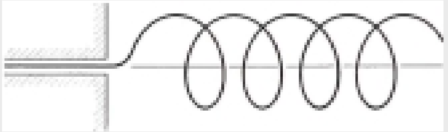
Several 3D electrical and magnetic types of sensors, usually at low-frequency range

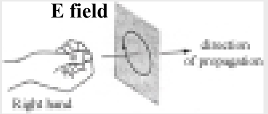

ELT-400

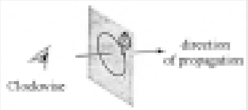
Low-frequency field meter for *E* (V/m) and *H* (A/m)

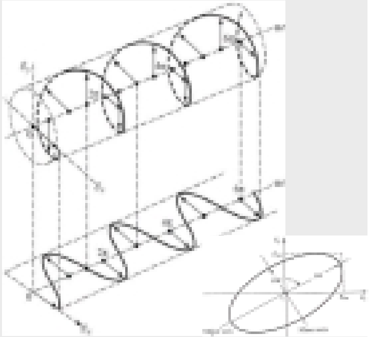


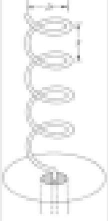
Circular polarized E-field sensors - helix

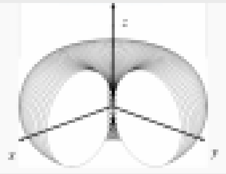




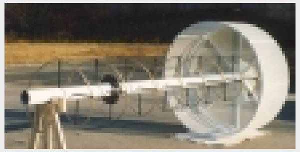






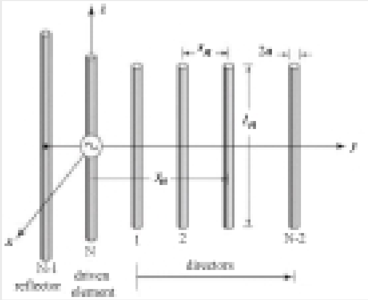


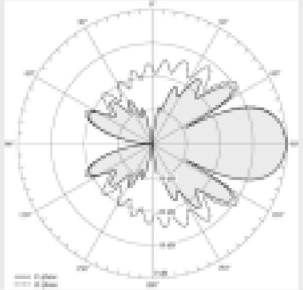
Simple helix and its radiation pattern


Helix for very low frequency: 100-160 MHz

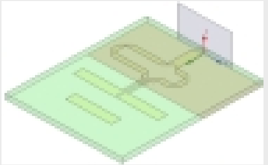

GPS helix array

Traveling-wave E-field sensors – Yagi-Uda antenna



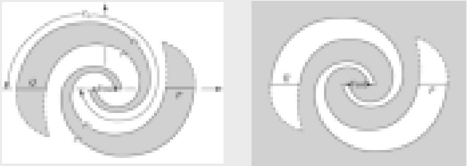

Radiation pattern


Typical TV Yagi-Uda antenna

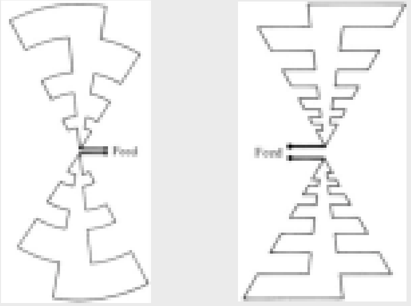

Planar quasi-Yagi antenna for 9-10 GHz (surface-wave antenna – application in RFID smart card, excitation of waveguides, etc.)

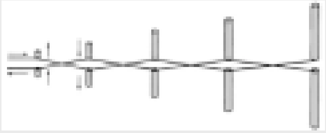
Ultra wide-band and log-periodic antennas

Frequency-independent sensors – two or multiple spirals



Spiral plate and spiral slot – for total arm length > λ the radiation pattern and impedance are f-independent

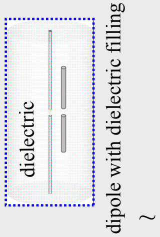




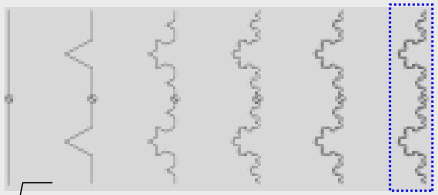
Log-periodical dipoles – crisscross connection

Log-periodical antennas – the frequency independence occurs for a certain low-frequency cut-off (longest tooth length = λ/4)

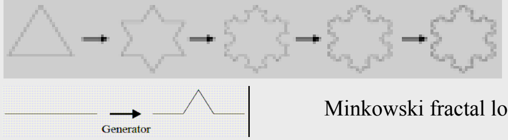
Miniaturized and multi-band fractal antenna sensors



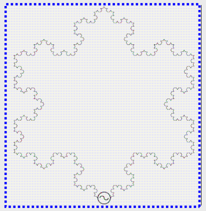
$\sim 1/\sqrt{\varepsilon_r}$

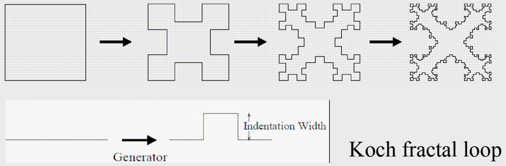


Minkowski fractal dipole

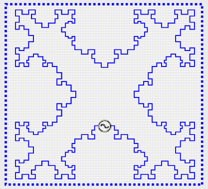


Minkowski fractal loop

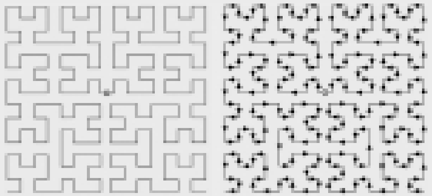




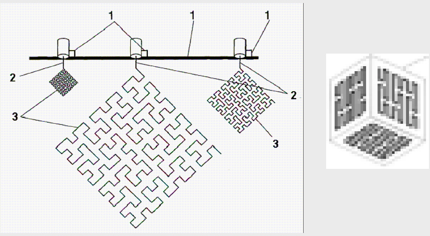
Koch fractal loop



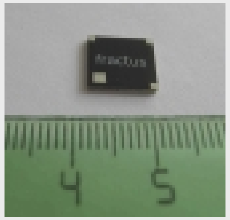
Miniature fractal antenna (for GPS applications)

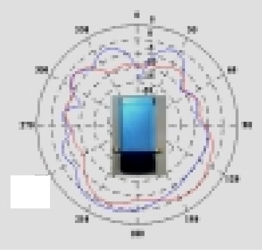


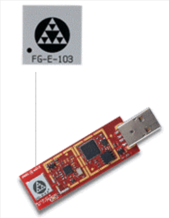
Depiction of the Hilbert curve fractal dipole and the current vector alignment



Hilbert curve fractal monopole; 3D fractal sensors



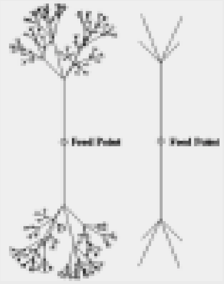




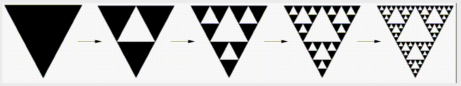
Sub-miniature, but “workable” GPS antenna receiver for small phones and USB devices

---

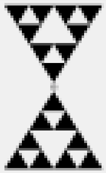
Multi-band fractal “trees” and “carpets”

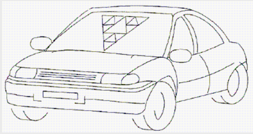


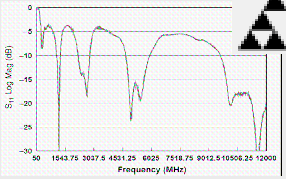
Fractal-tree dipole

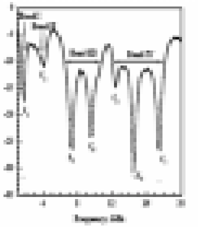


Sierpinski fractal multi-band monopole and dipole

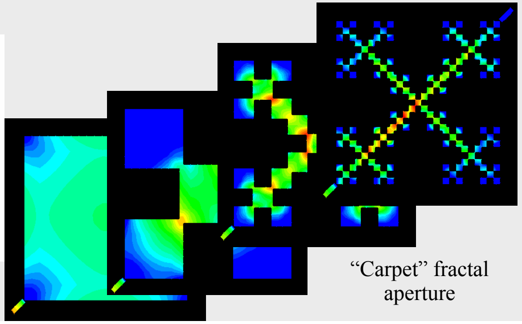






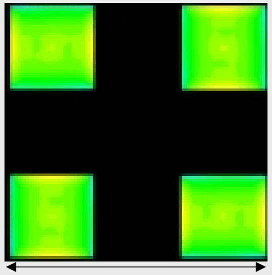


Exotic fractal tree 2-18 GHz

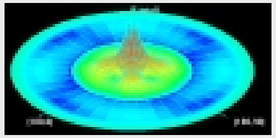


“Carpet” fractal aperture

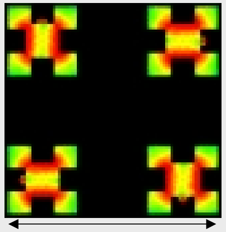
Example for miniature fractal antenna arrays



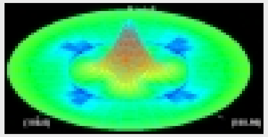
251.3 mm



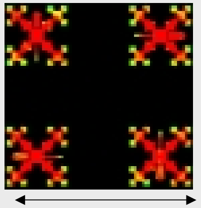
3-dB width = 31 degree
Directivity = 13.0 dBi
Efficiency = 82 %
Frequency = 1500 MHz



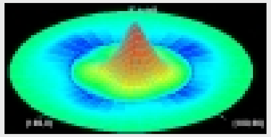
167.7 mm (67-% reduction)



3-dB width = 30 degree
Directivity = 11.8 dBi
Efficiency = 29 %
Frequency = 1500 MHz

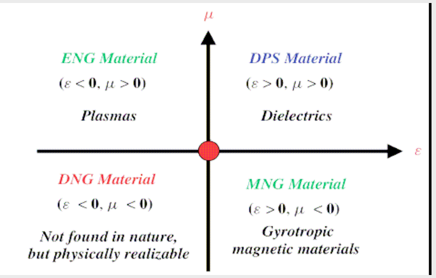


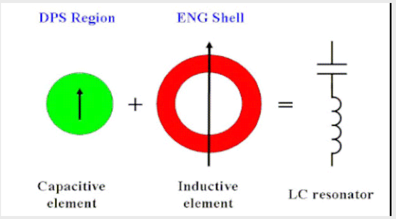
133.8 mm (53 %)



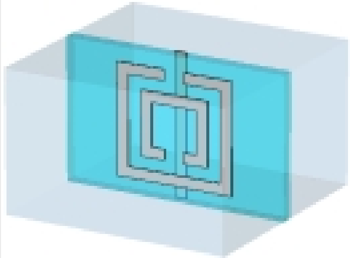
3-dB width = 30 degree
Directivity = 10.7 dBi
Efficiency = 26 %
Frequency = 1500 MHz

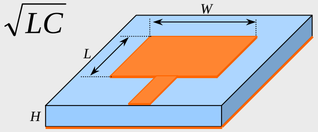
Miniature radiators based on metamaterials - principles

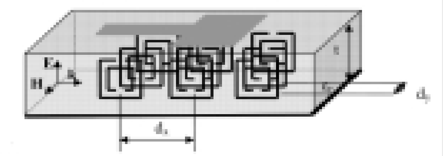




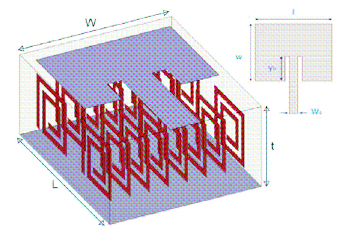
$$f \sim 1/\sqrt{LC}$$

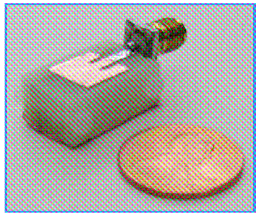


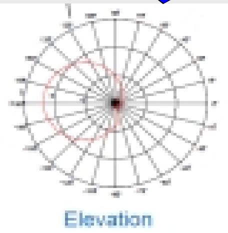


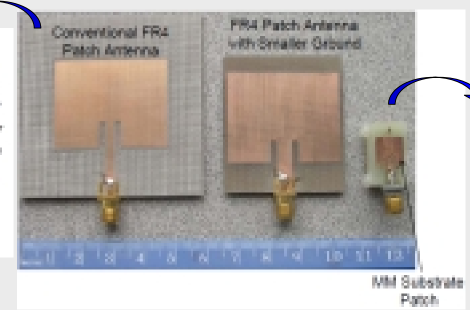


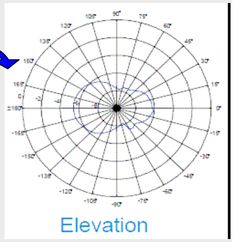
Miniature radiators, based on metamaterials



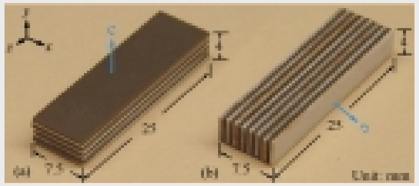


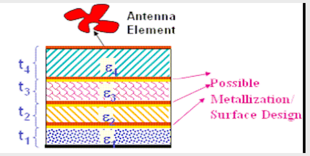


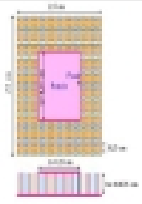


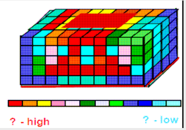


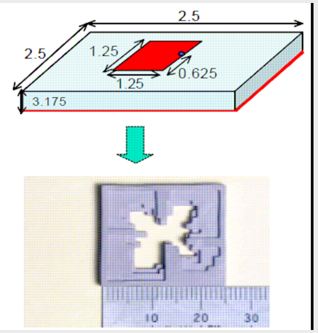
Miniature radiators based on composite metamaterials

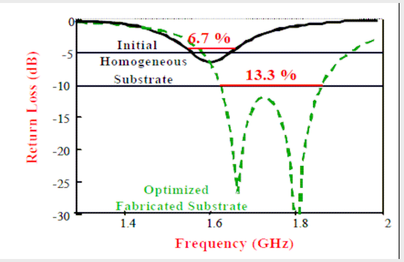




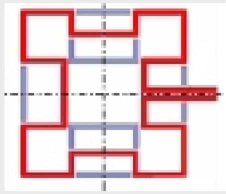


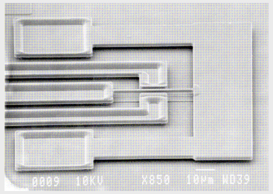




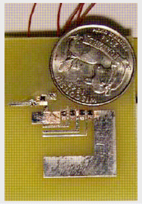


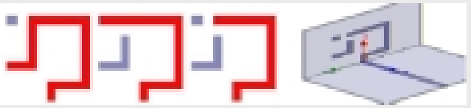
Reconfigurable dipoles using MEMS switches

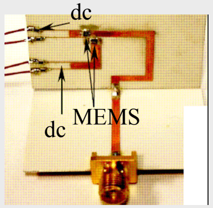

Reconfigurable dipole

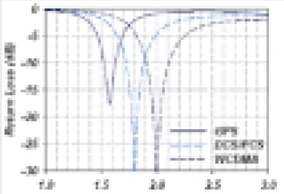


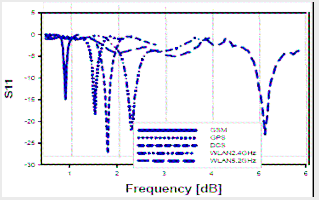
MEMS (Micro Electro-Mechanical Systems) – miniature fast "on/off" switches, tunable with dc voltage




Example: part of planar dipole with 2 MEMS, which demonstrates how can "cover" 3 frequency bands

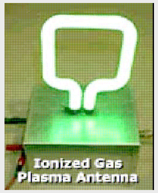


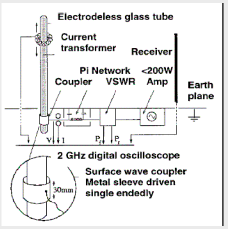


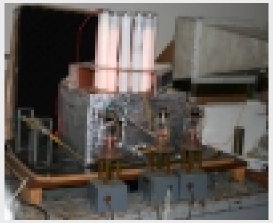


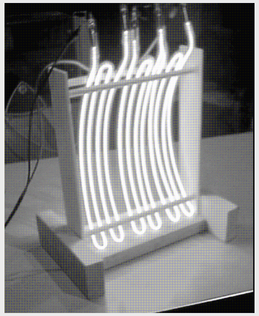
(above) Workable communication antenna with 4 MEMS's – "covers" GSM900, GPS, GSM1800, WLAN2.4GHz; WLAN5.2GHz

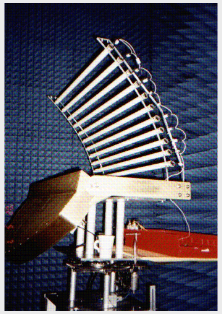
Plasma dipoles and reflector antennas

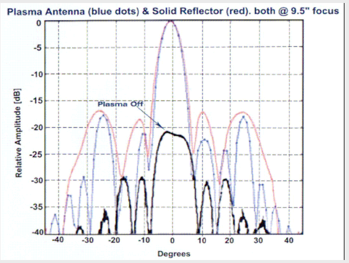




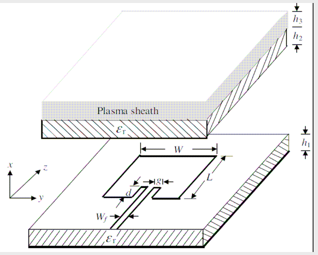


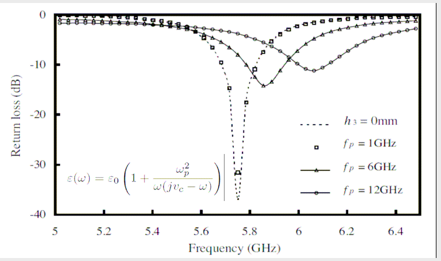




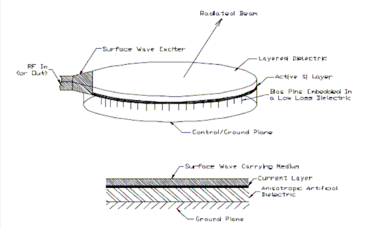


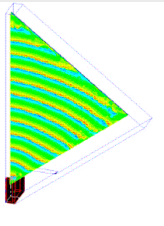
Plasma patches

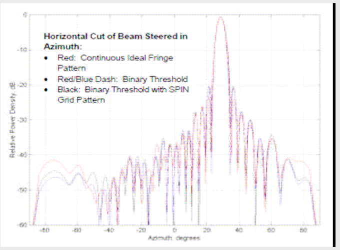




$$\varepsilon(\omega) = \varepsilon_0 \left(1 + \frac{\omega_p^2}{\omega(jv_c - \omega)}\right)$$



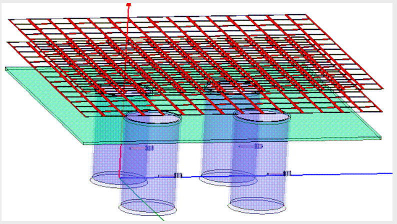


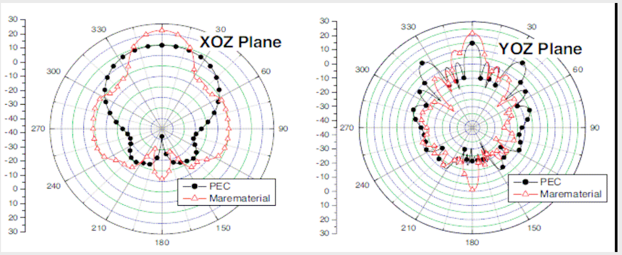


Horizontal Cut of Beam Steered in Azimuth:

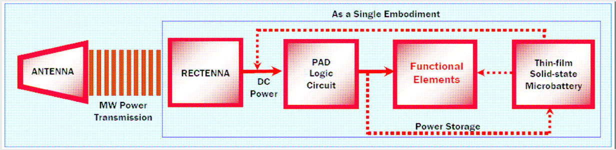
- Red: Continuous Ideal Fringe Pattern
- Red/Blue Dash: Binary Threshold
- Black: Binary Threshold with SPIN Grid Pattern

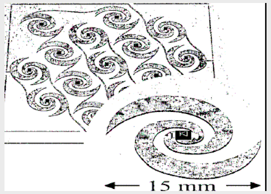
Plasma arrays

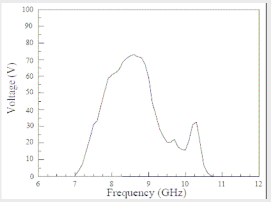


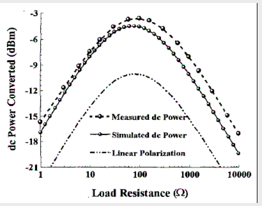


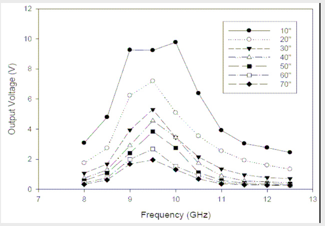
Active EM field sensors – “rectennas”

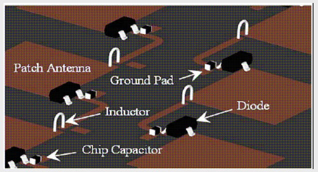


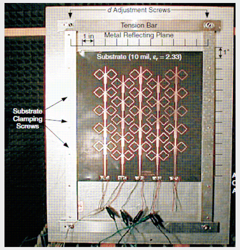




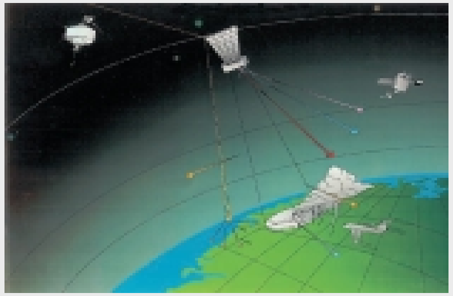


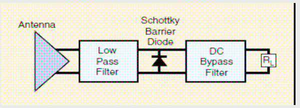


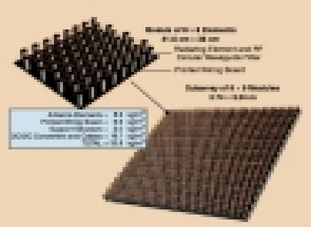


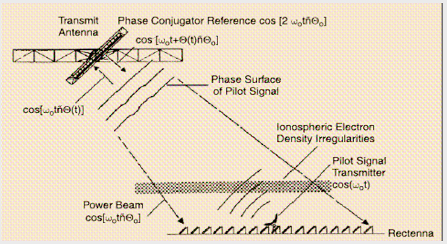


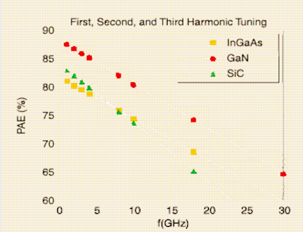
SPS (Solar Power Satellites) and microwave wireless power transmission technology







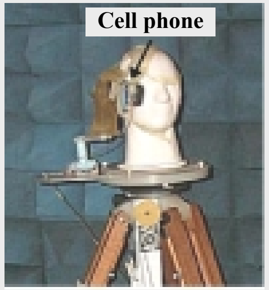




Examples for EMC measurements

Popular examples for EMC/EMI measurements

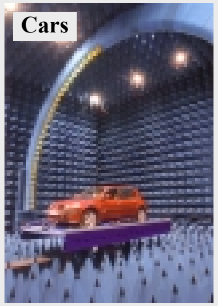

GSM base stations


Cell phone

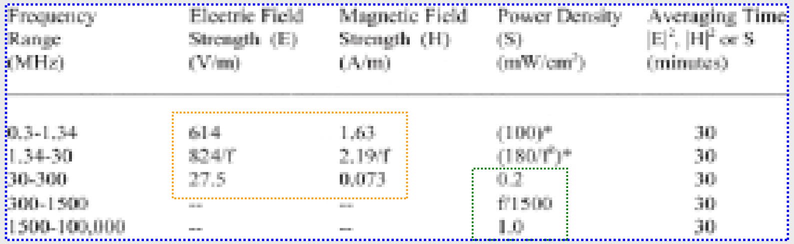

Cell phone


Satellites

Video displays

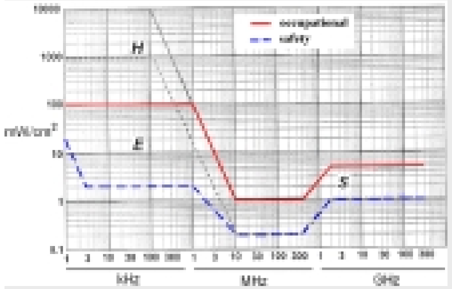

Cars

Example for EM dosimetry: EMI/EMC standards

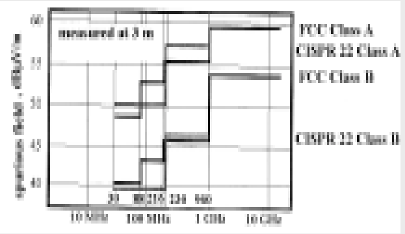


Frequency Range (MHz)	Electric Field Strength (E) (V/m)	Magnetic Field Strength (H) (A/m)	Power Density (S) (mW/cm^2)	Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes)
0.3-1.34	614	1.63	(100)*	30
1.34-30	824/f	2.19/f	(180/f^2)*	30
30-300	27.5	0.073	0.2	30
300-1500	--	--	f/1500	30
1500-100,000	--	--	1.0	30

Safety standards of FCC (USA) for *E* or *H* field strength and for power-flux density *S*



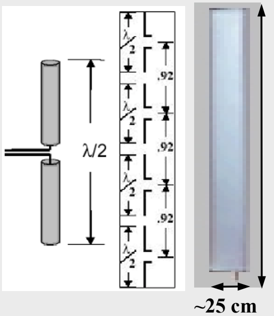
Graphical safety standards for *S*

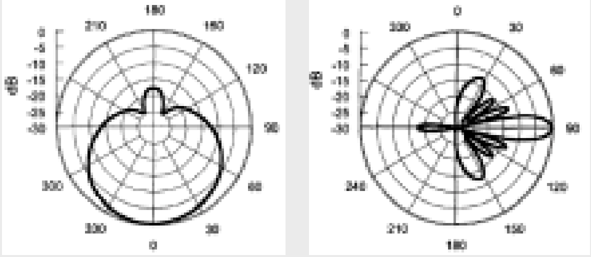


Standards for admissible wireless disturbance of equipment

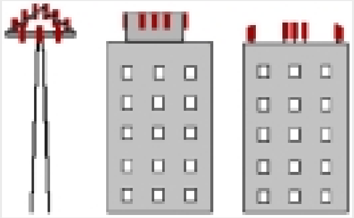
Antennas for GSM base stations

Antenna panel

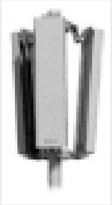




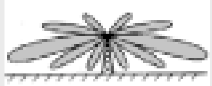
Single panel radiation pattern

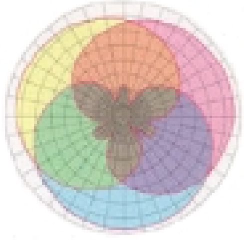


Typical mounting of the panels



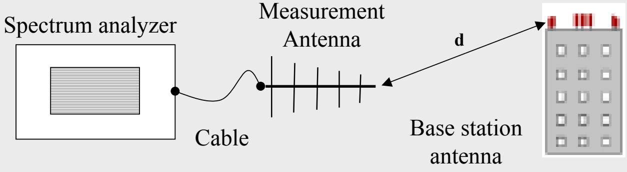
Triade the panels with 4-15^{O} tilt





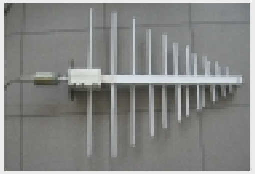
Three 120^{O} panels cover the whole BTS cell

Antennas for GSM base stations



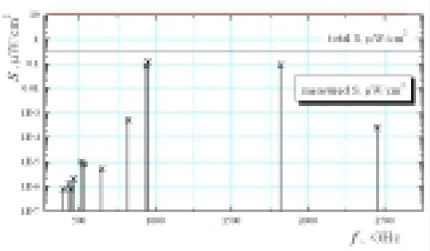
$$E_{local}\,,\mathrm{V/m} = AF\,,1/\mathrm{m}\times V_{meas}\,,\ \mathrm{V}$$

$$S,\ \ \mathrm{W/m}^2 = 2.77.10^{-3}\times E^2\ ,\mathrm{V/m}$$



Measurement scheme with the best equipment for this purpose

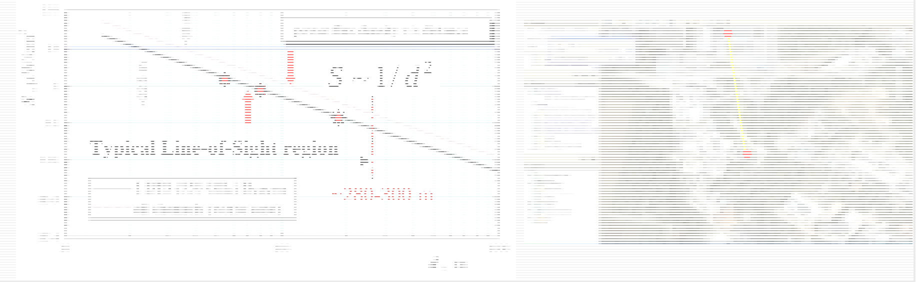
Results for the safety rates around typical urban BTS



$$E_{local}\,,\mathrm{V/m} = AF\,,1/\mathrm{m}\times V_{meas}\,,\ \mathrm{V}$$

$$S,\ \ \mathrm{W/m}^2 = 2.77.10^{-3}\times E^2\ ,\mathrm{V/m}$$

Measured power-flux density at a fixed point in the frequency range 100-2500 MHz by spectrum analyzer



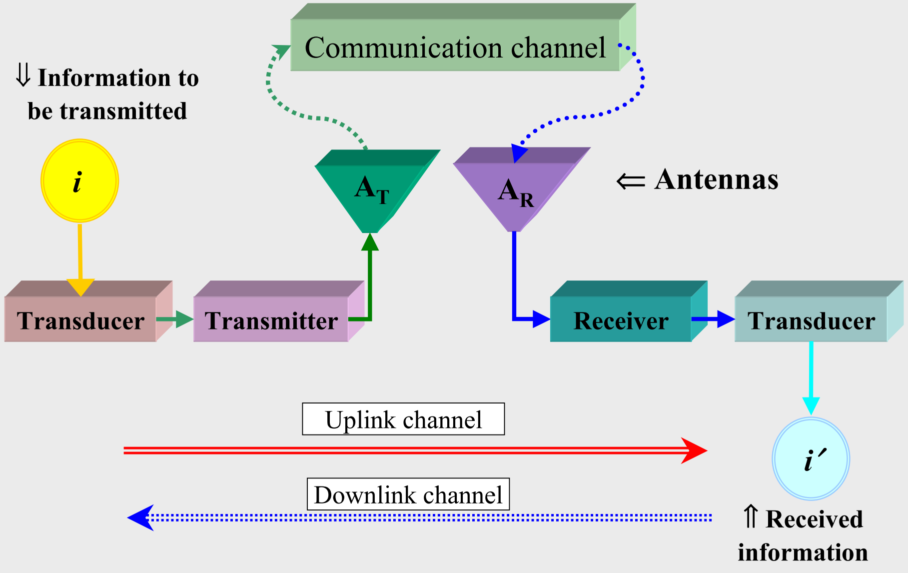
Measured power-flux density before the main lobe of GSM BTS panel

2nd Part: Antennas and antenna measurements

2. Antenna, antenna arrays and basic antenna measurements.

- Antenna as transducer, transformer, radiator and energy converter. Main antenna parameters – radiation pattern, directivity, efficiency, polarization, etc.
- Main types of antennas. Antenna arrays. Steerable antennas.
- Far-field antenna measurements. Near-field antenna measurement. Near-field scanners. THz spectroscopy. Basic equipment for field/power/signal measurements.
- Electromagnetic simulators, applied to antennas and propagation media.

The antennas are very important in the communication process



⇓ Information to be transmitted

i

Transducer → Transmitter → A_T

Communication channel

A_R → Receiver → Transducer

⇐ Antennas

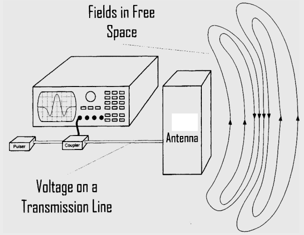
Uplink channel

Downlink channel

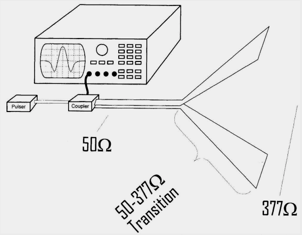
i′

⇑ Received information

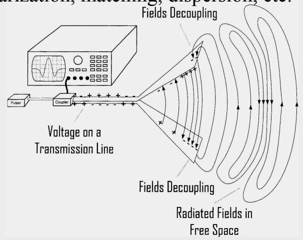
Antenna as transducer, impedance transformer, radiators and energy converter



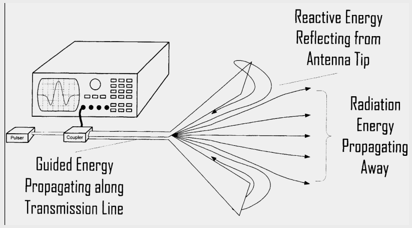
Transducer: communication device as a "*black box*" with appropriate parameters: gain, radiation pattern, BW, polarization, matching, dispersion, etc.



Transformer: *transformation* between the impedance of the transmission line (50Ω) and free space (377Ω)



Radiator: the classical interpretation – time-varying currents/voltages *generate* radiating EM field in the free space by "fields decoupling" in the antenna



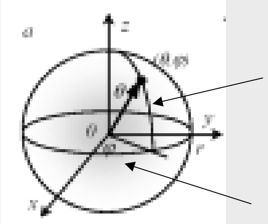
Energy converter: device, which *converts* the guided energy from the transmission line into radiation energy with a minimum of reactive energy as a by-product

---

Main antenna parameters

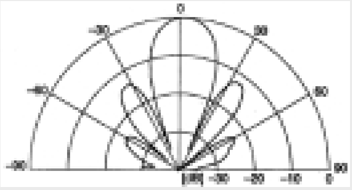
Radiation pattern

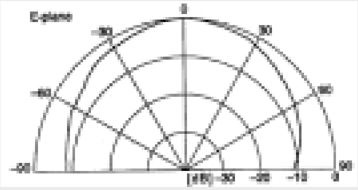
$$F(\theta,\varphi)=E(\theta,\varphi)/E_{\max}(\theta,\varphi)|_{r=const>R_{ffz}}$$

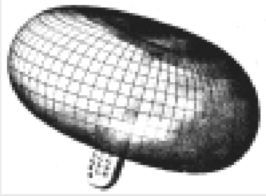


Elevation angle

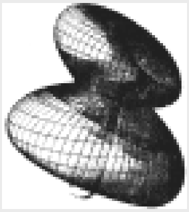
Azimuthal angle



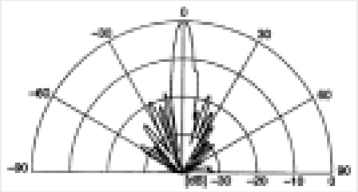




GSM 900



GSM 1800



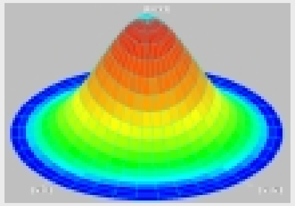
Main antenna parameters (2)

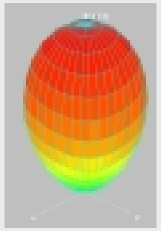
3-dB beamwidth

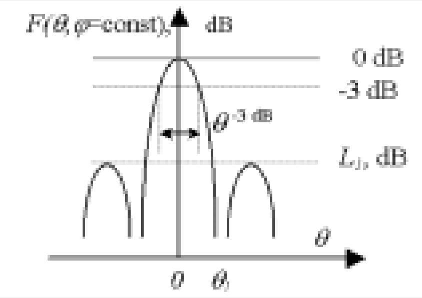
$$\theta^{-3\ dB};\quad \varphi^{-3\ dB}$$

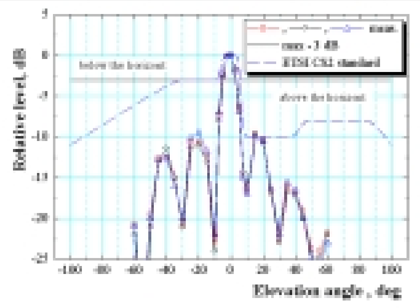
Side-lobe levels

$$L_i;\quad i=1,2,\ldots$$









Main antenna parameters (3)

Directivity *D*

The directivity present the energy benefit to use narrow-beam antenna instead isotropic antenna

$$D = S_{\max}(\theta,\varphi)/S_{isotropic}\big|_{P_T=const};\ \text{dBi}$$

$$D \cong \frac{4\pi}{\Omega_{beam}} = \frac{41253}{\Delta\theta^{-3dB}\Delta\varphi^{-3dB}},\ \deg^2$$

Gain *G = ηD*

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

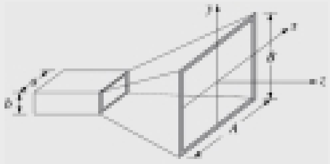
Efficiency *η*

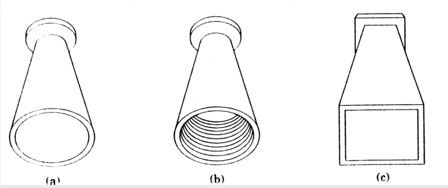
$$\eta = \frac{G}{D}$$

If the 3-dB beamwidth becomes thinner, the antenna directivity (gain) becomes bigger

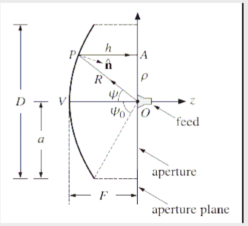
G **– Antenna gain,**
D – antenna directivity;
A_{eff} **– effective aperture;**
λ **– wavelength**

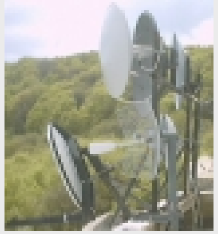
Typical aperture antennas – horns and reflectors





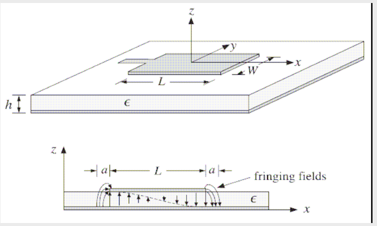
Horn antennas

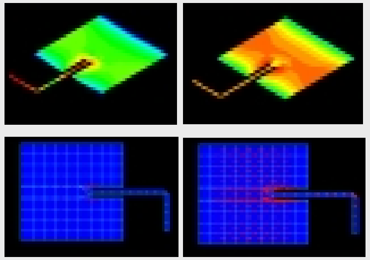


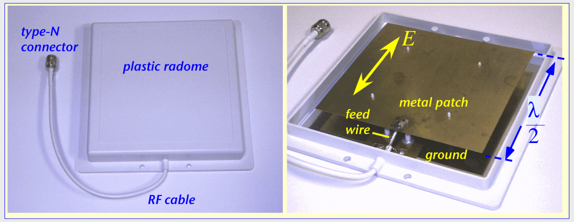


Reflector antennas (dishes)

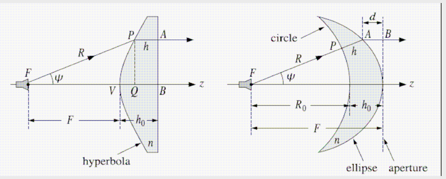
Microstrip patch antennas

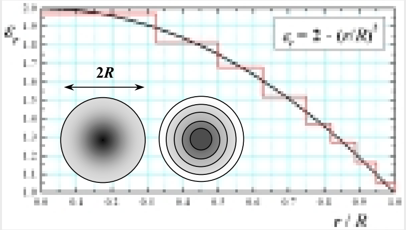


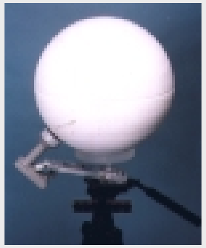


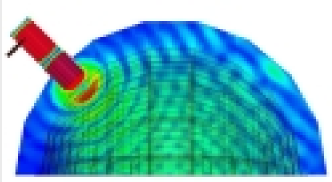


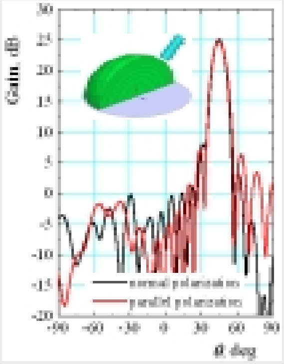
Lens antennas



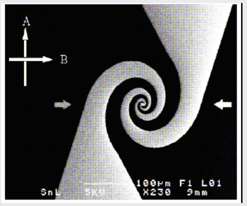


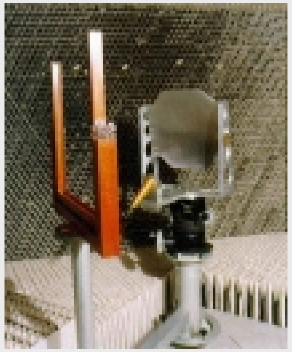


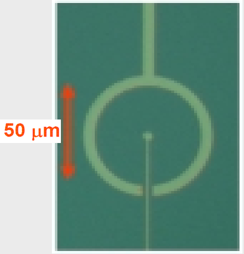


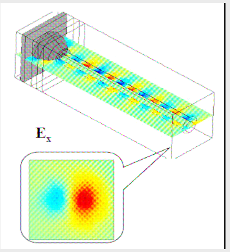


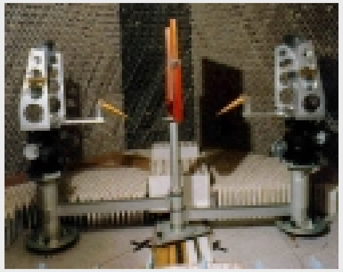
THz antennas



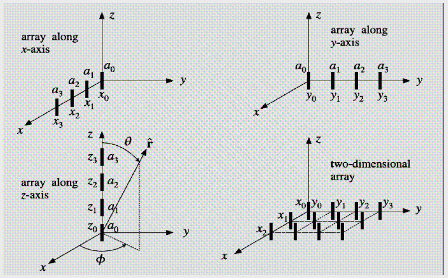


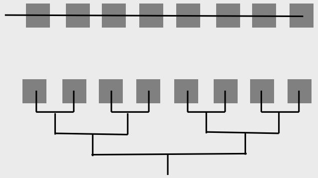




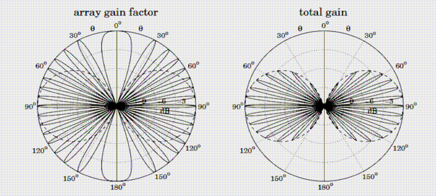


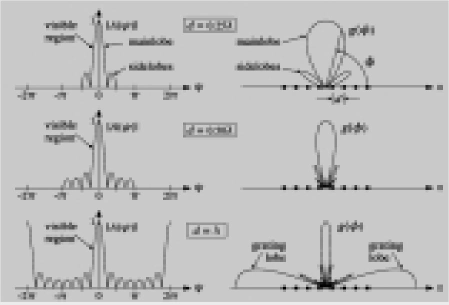
Antenna arrays



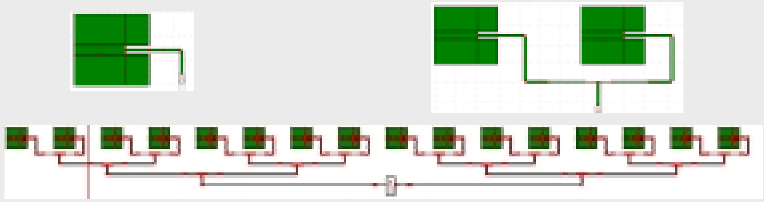


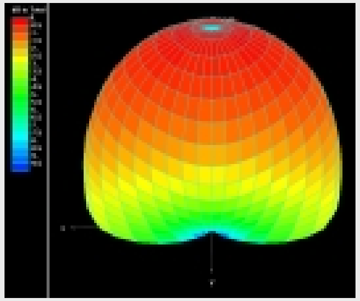
$$F_{array}(\theta,\varphi) = F_{single\ element}(\theta,\varphi).AF(\theta,\varphi)$$



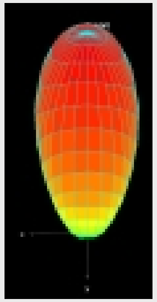


Antenna beam becomes thinner, when the element number increases

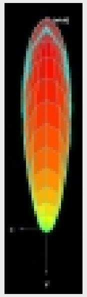




1 base element



2 elements

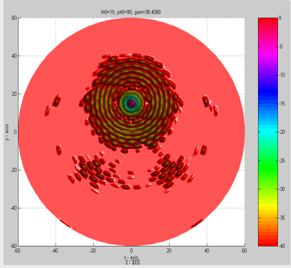


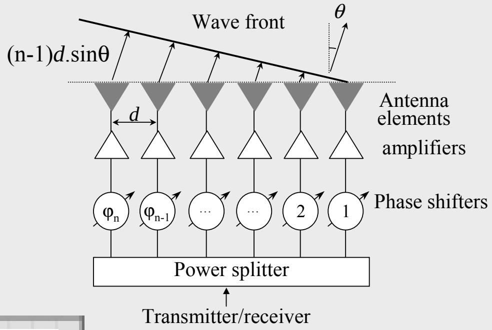
4

8

16

Antenna beamforming





Wave front

θ

(n-1)d.sinθ

d

Antenna elements

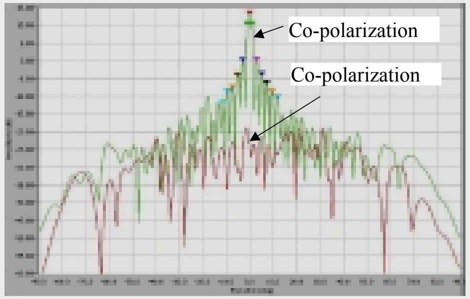
amplifiers

φ_n φ_{n-1} … … 2 1

Phase shifters

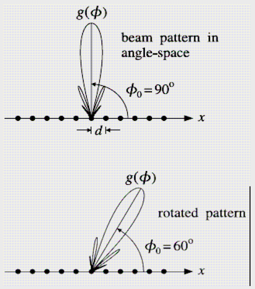
Power splitter

Transmitter/receiver



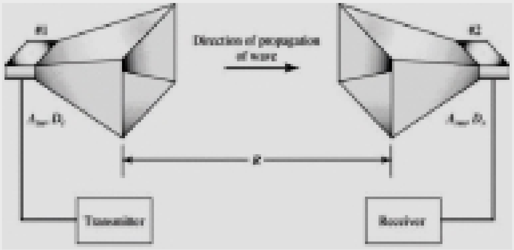
Co-polarization

Co-polarization

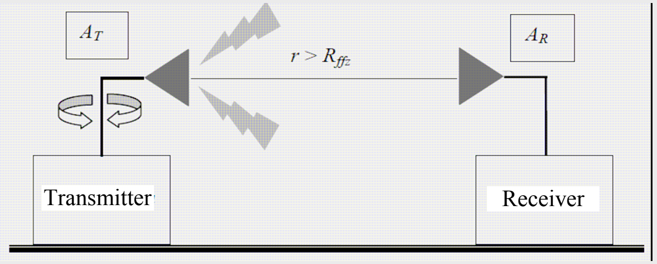


Mechanically and electronically steerable antennas

Measurement of antennas



$$\frac{P_r}{P_t} = G_{0t} G_{0r} \underbrace{\left(\frac{\lambda}{4\pi R}\right)^2}_{\text{Free space loss factor}} \left|\hat{\rho}_t \cdot \hat{\rho}_r\right|^2 \quad (2\text{-}119)$$



A_T

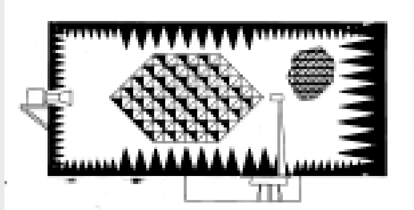
A_R

$r > R_{ffz}$

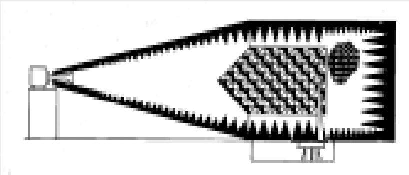
Transmitter

Receiver

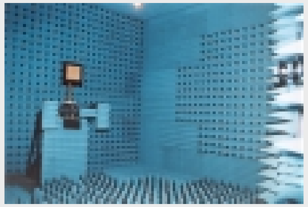
Far-field measurements

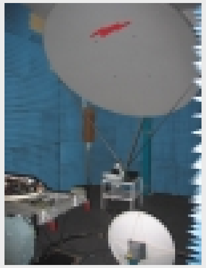


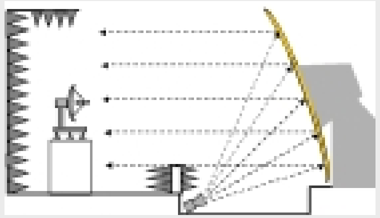
Anechoic chambers



Tapered anechoic chambers

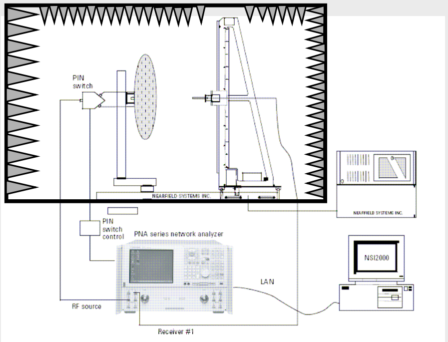




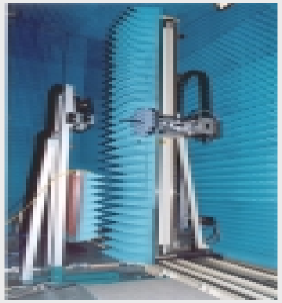


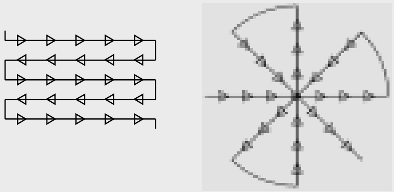
Compact test range

Near-field measurements

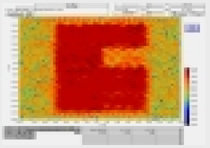


Measurement setup

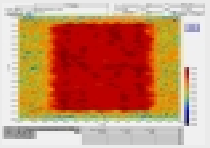




Scheme of scanning

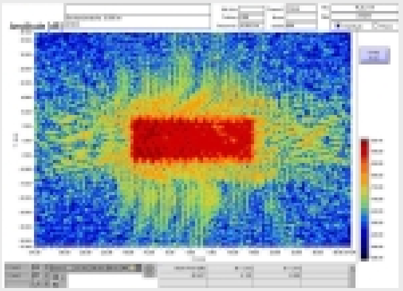


Scan of workable 8-panel antenna array

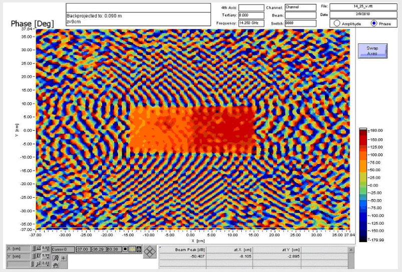


Scan of 8-panel antenna array with one bad panel

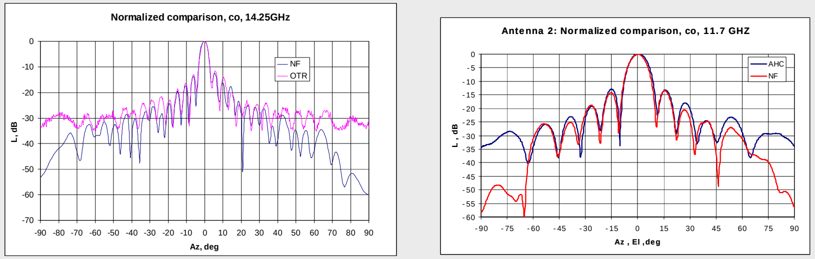
Near-field diagrams



Amplitude near-field diagram

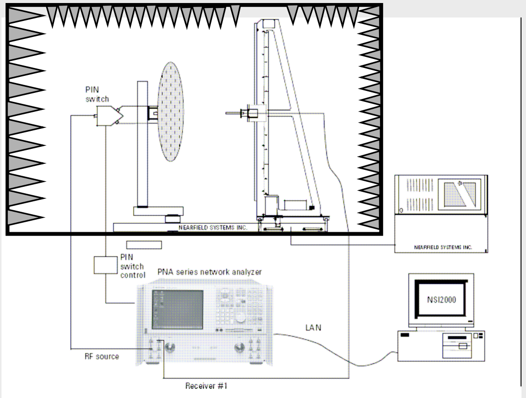


Phase near-field diagram



Conversion “near-field” to “far-field” diagram

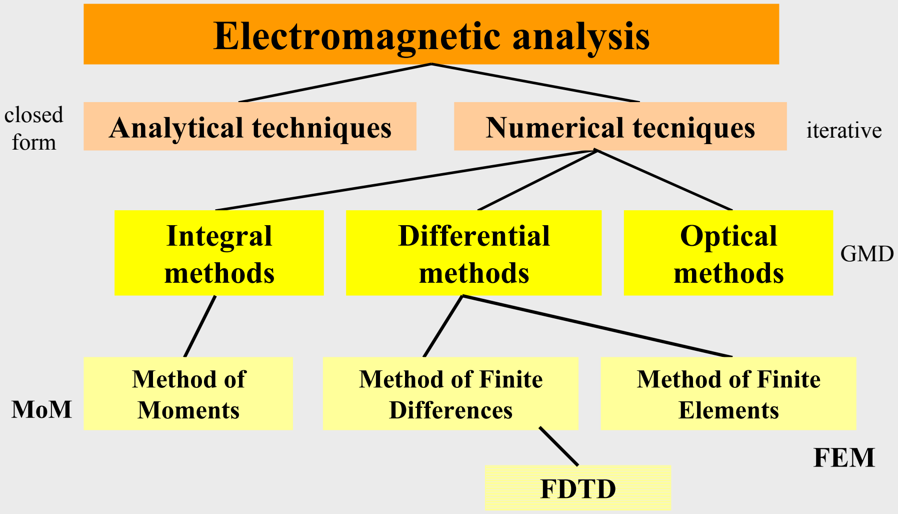
Typical measurement equipment



Vector network analyzer:
“linear impact” – ”linear response” at one swept frequency.
Includes generator and receiver

Spectrum analyzer:
“nonlinear response” – measurement of very low signal levels.
Includes sensitive receiver only

Background of the electromagnetic simulators



Electromagnetic analysis

closed form **Analytical techniques**

Numerical tecniques iterative

Integral methods

Differential methods

Optical methods GMD

MoM **Method of Moments**

Method of Finite Differences

Method of Finite Elements

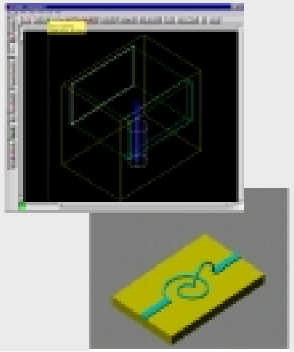
FEM

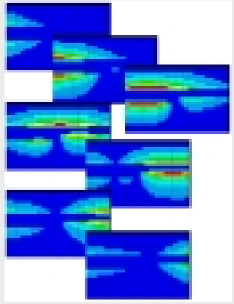
FDTD

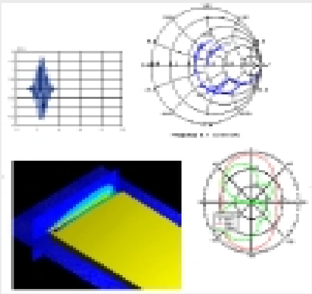
EM simulators

The modern EM 3D simulators generate own software media, where the users can relatively easy build and investigate new passive and active structure/devices. This software media includes **three main components:**

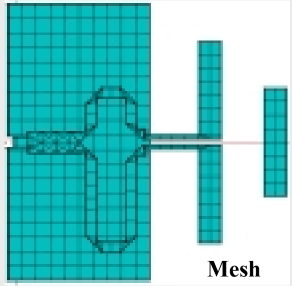
pre-processing → processing → post-processing

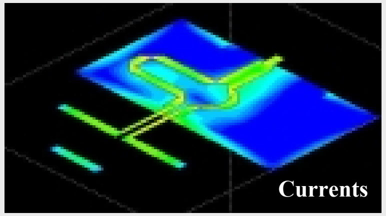


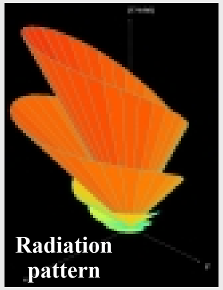


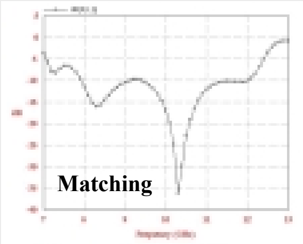


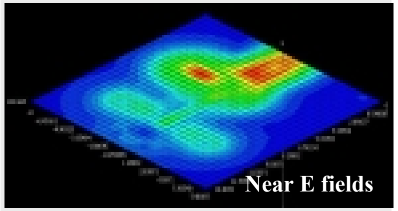
MoM examples



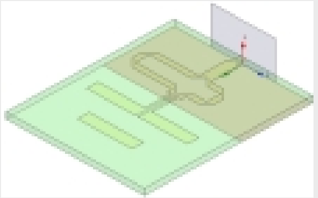


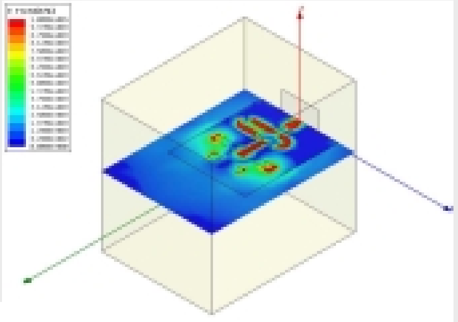


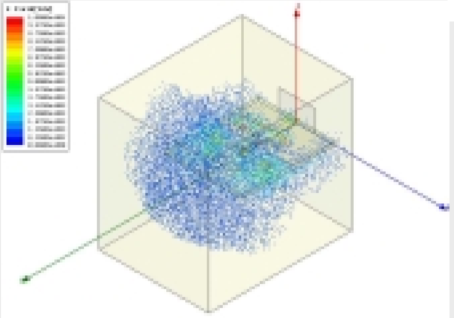


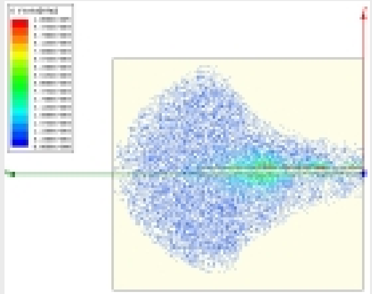


FEM examples

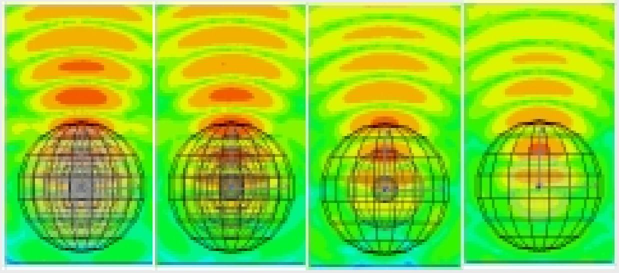


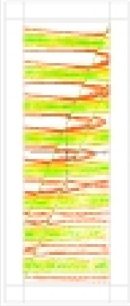


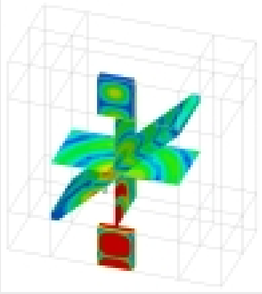




EM-field animations



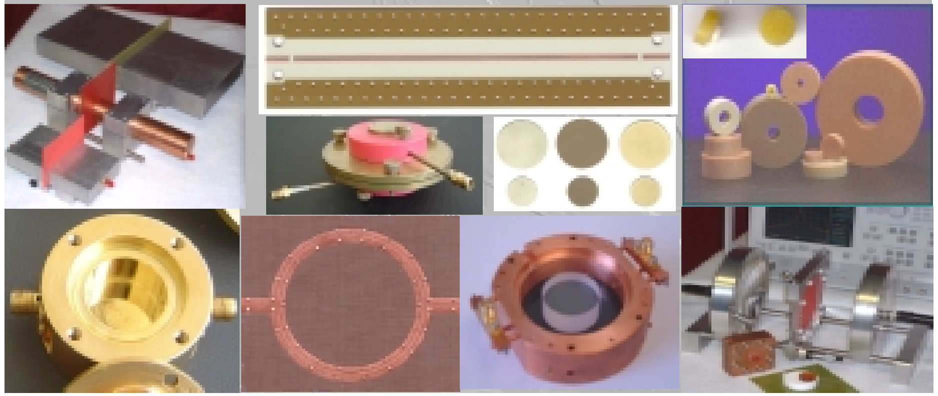




3rd Part: Measurement of materials and media

3. Characterization of dielectric materials and propagation media.

- Resonance, transmission-line and free-space methods for material characterization.
- Measurement specificity in the case of liquids, powder, absorbers, thin films, etc.
- Determination of the dielectric anisotropy of materials. “Two-resonator” method.
- Hairpin-resonator probe for characterization of electron density in plasmas.
- Conclusions.



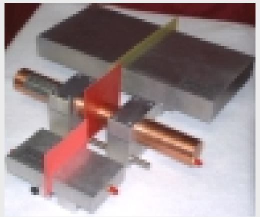
Three main types of material characterization

Resonance methods

Resonance parameters: resonance frequency f and Q-factor Q

⇩

Dielectric parameters: dielectric constant ε_r and dielectric loss tangent $\tan\delta_\varepsilon$



Transmission-line (waveguide) methods

Waveguide parameters: propagation constant (phase delay) β and attenuation α

⇩

Dielectric parameters: dielectric constant ε_r and dielectric loss tangent $\tan\delta_\varepsilon$

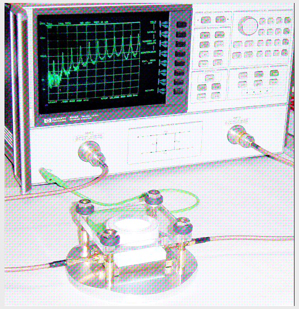
Free-space (quasi-optical) methods

Resonance parameters: free-space reflection and transmission coefficients

⇩

Dielectric parameters: dielectric constant ε_r and dielectric loss tangent $\tan\delta_\varepsilon$

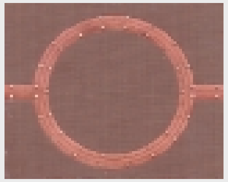
Examples for resonator methods



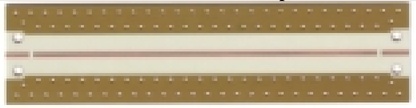
$$\varepsilon_{eff} = \left(\frac{30n}{2\,f_n[\mathrm{GHz}].L_{eff}\,[\mathrm{cm}]} \right)^2$$

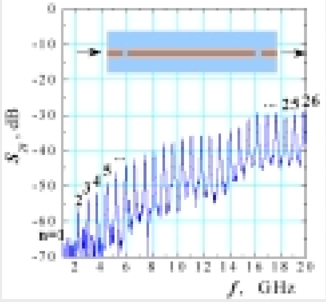
$$\varepsilon_{eff} = \left(\frac{30m}{4\,f_m[\mathrm{GHz}].\pi R_{ring}\,[\mathrm{cm}]} \right)^2$$

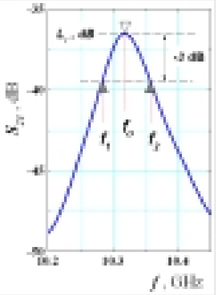
$$Q = \frac{f_{0,i}}{\Delta f}$$

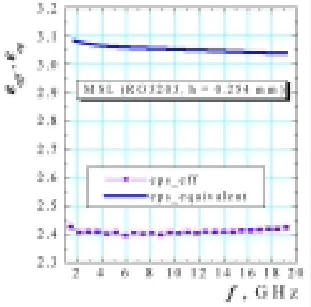


Microstrip resonators

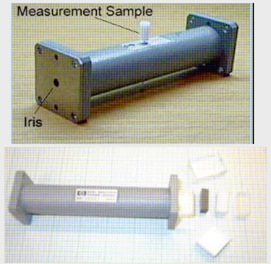




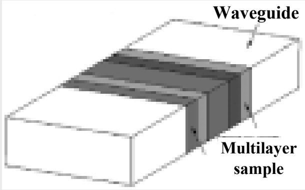




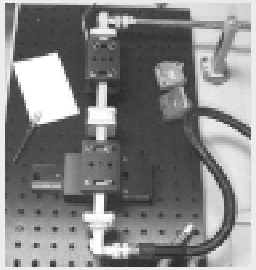
Examples for waveguide methods

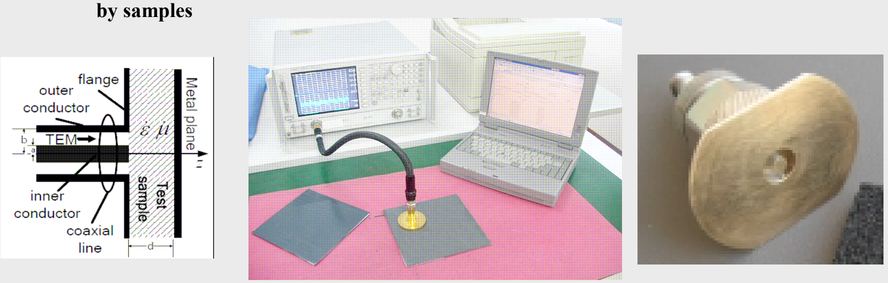


Waveguides perturbed by samples



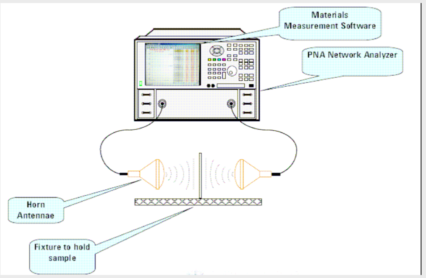
Waveguide with multilayer sample

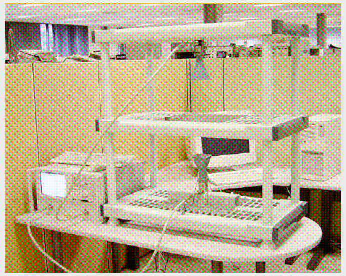




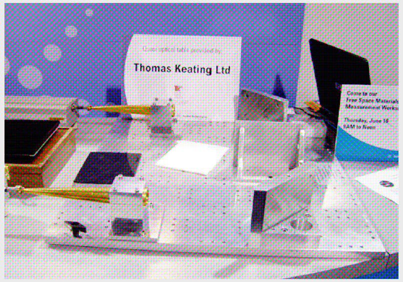
Open-ended coaxial probe

Examples for free-space methods

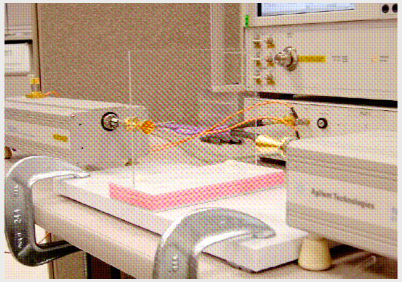




X-band setup (8-12 GHz)

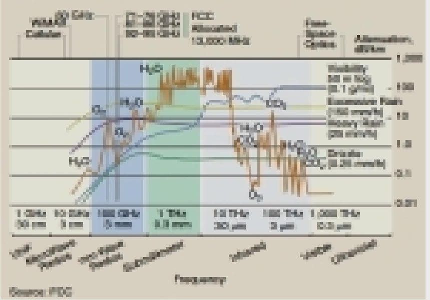


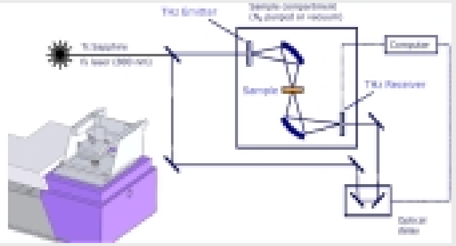
Quasi-optical free-space system



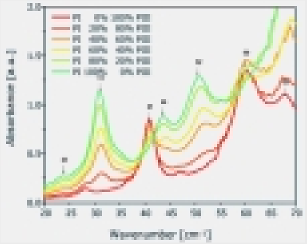
W-band setup (75-110 GHz)

THz spectroscopy

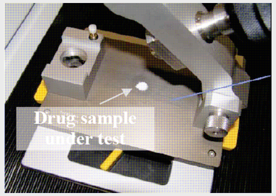




Operational scheme of the THz spectroscopy



TPS analysis of polymorphs (Carbamazine Form III/I)



Commercial spectrometer for TDR THz spectroscopy

Materials under test

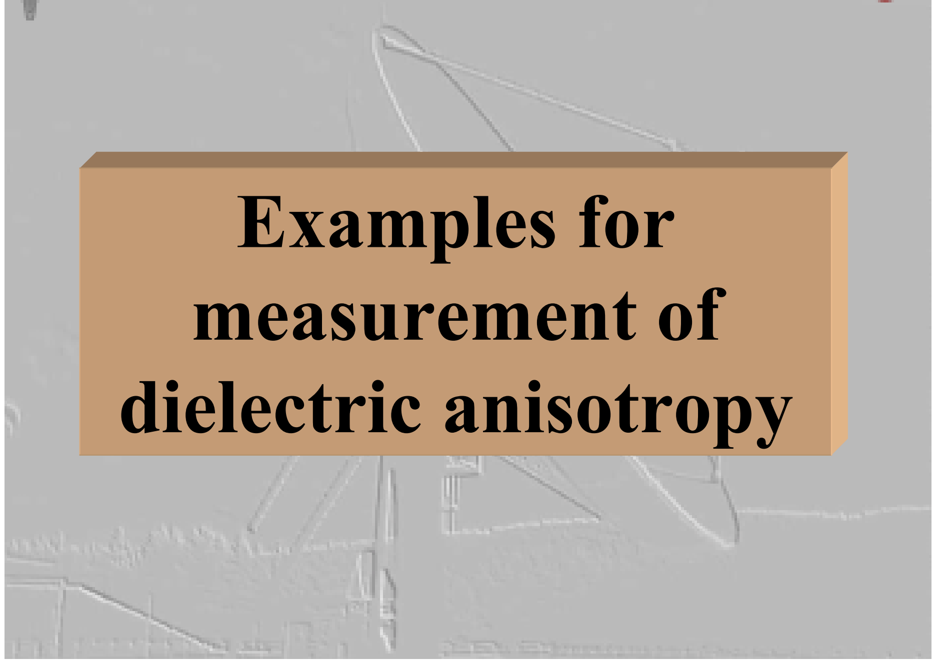
Parameters under test: dielectric constant (permittivity), dielectric loss tangent, magnetic constant (permeability), conductivity, thermal coefficients of these parameters

- **Dielectrics** (incl. ceramics, plastics, reinforced sub-strates, artificial materials, etc.)
- **Ferrites** (incl. absorbers)
- **Semiconductors**
- **Ferroelectrics**
- **Plasmas**
- **Superconductors**
- **Biological tissues**
- **Metamaterials**
- **Nanomaterials**
- **etc.**

- **Bulk materials**
- **Single-layer materials**
- **Multi-layer materials**
- **Thin-films**
- **Nanocomposite materials**
- **etc.**

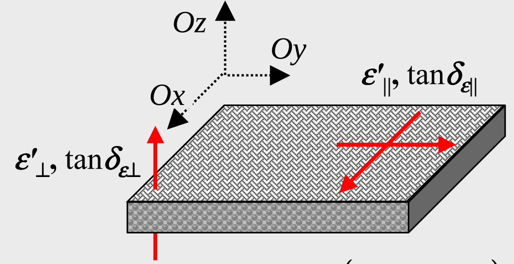
- **Plates,**
- **Disks,**
- **Prisms,**
- **Cylinders,**
- **Spheres,**
- **etc.**

- **Crystalline solids,**
- **Polycrystalline and amorphous materials,**
- **Reinforced substrates** (fiber cloths & appropriate fillers),
- **Liquid crystals,**
- **Liquids** (incl. water, petrol, milk, alcohol, etc.,
- **Absorbers,**
- **Coatings,**
- **Powder materials,**
- **etc.**



Examples for measurement of dielectric anisotropy

Dielectric anisotropy



$$\varepsilon_r = \varepsilon'_r - \mathrm{j}\varepsilon''_r = \varepsilon'_r\left(1 - \mathrm{j}\tan\delta_\varepsilon\right)$$

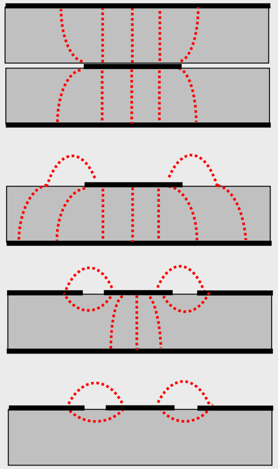
$$\left\|\varepsilon'_r\right\| = \begin{pmatrix} \varepsilon'_{||} & 0 & 0 \\ 0 & \varepsilon'_{||} & 0 \\ 0 & 0 & \varepsilon'_{\perp} \end{pmatrix} \qquad \left\|\tan\delta_\varepsilon\right\| = \begin{pmatrix} \tan\delta_{\varepsilon||} & 0 & 0 \\ 0 & \tan\delta_{\varepsilon||} & 0 \\ 0 & 0 & \tan\delta_{\varepsilon\perp} \end{pmatrix}$$

Dielectric Anisotropy:

$$\Delta A_\varepsilon = 2(\varepsilon'_{||} - \varepsilon'_{\perp})/(\varepsilon'_{||} + \varepsilon'_{\perp})$$

$$\Delta A_{\tan\delta\varepsilon} = 2(\tan\delta_{\varepsilon||} - \tan\delta_{\varepsilon\perp})/(\tan\delta_{\varepsilon||} + \tan\delta_{\varepsilon\perp})$$

Is the dielectric anisotropy important?



Two possibilities:

1. **To apply into the simulators the measured actual parameters: $\varepsilon'_{||}$; $\varepsilon'_{\perp}$; $\tan\delta_{\varepsilon||}$; $\tan\delta_{\varepsilon\perp}$**
2. **To introduce equivalent dielectric constant and loss tangent**

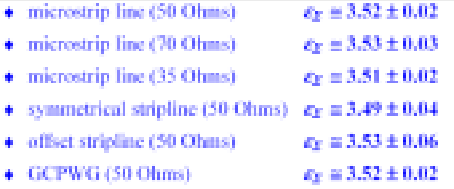
$$\varepsilon'_{\mathrm{eq}} = a\varepsilon'_{||} + b\varepsilon'_{\perp};$$

$$\tan\delta_{\varepsilon,\,\mathrm{eq}} = c\tan\delta_{\varepsilon||} + d\tan\delta_{\varepsilon\perp}$$

Example: Ro4003 substrate (1-18 GHz):

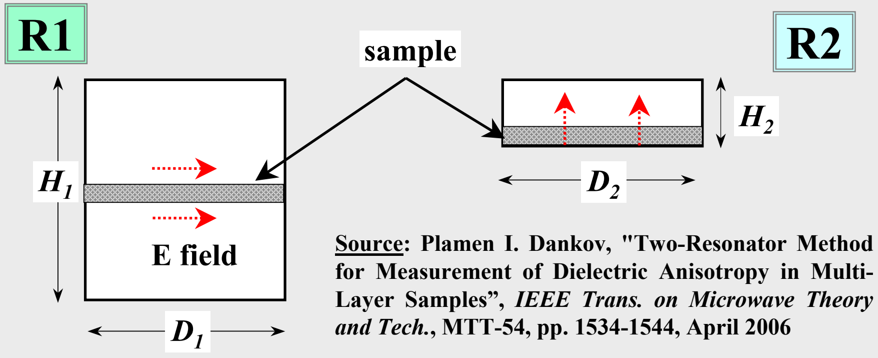
$\varepsilon'_{\mathrm{eq}} = 3.52 \pm 0.02$

$\varepsilon'_r = 3.38$ **(catalogue value)**



microstrip line (50 Ohms)	$\varepsilon_r \cong 3.52 \pm 0.02$
microstrip line (70 Ohms)	$\varepsilon_r \cong 3.53 \pm 0.03$
microstrip line (35 Ohms)	$\varepsilon_r \cong 3.51 \pm 0.02$
symmetrical stripline (50 Ohms)	$\varepsilon_r \cong 3.49 \pm 0.04$
offset stripline (50 Ohms)	$\varepsilon_r \cong 3.53 \pm 0.06$
GCPWG (50 Ohms)	$\varepsilon_r \cong 3.52 \pm 0.02$

Two-resonator method for dielectric anisotropy measurements



Source: Plamen I. Dankov, "Two-Resonator Method for Measurement of Dielectric Anisotropy in Multi-Layer Samples", *IEEE Trans. on Microwave Theory and Tech.*, MTT-54, pp. 1534-1544, April 2006

TE_{011}-mode resonator **R1**:

parallel parameters: $\varepsilon'_{||}$, $\tan\delta_{\varepsilon||}$

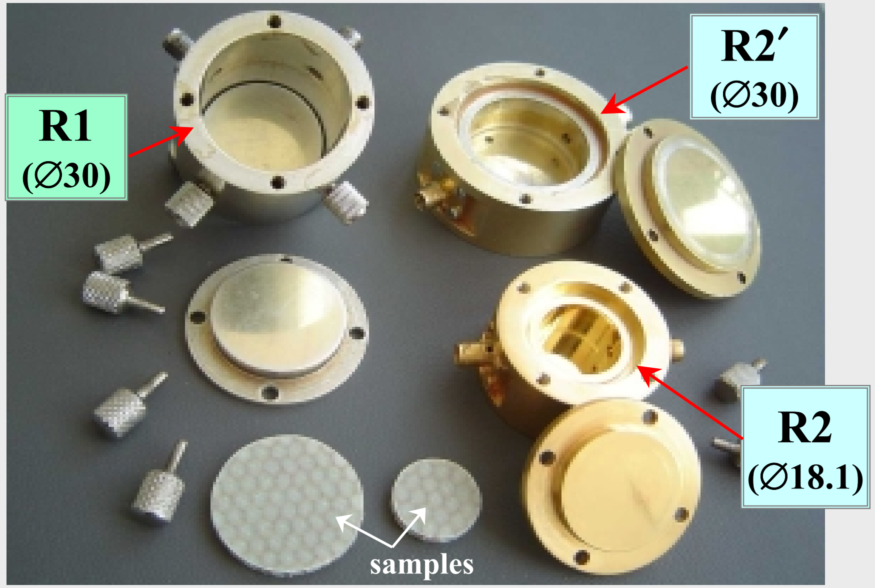
(± 1.5 %; ± 5 %)

TM_{010}-mode resonator **R2**:

normal parameters: $\varepsilon'_{\perp}$, $\tan\delta_{\varepsilon\perp}$

(± 5 %; ± 15 %)

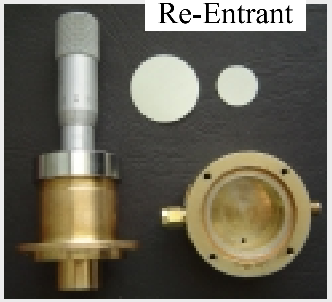
Measurement resonators



Other measurement resonators

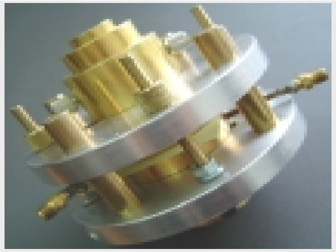
Cylinders

Re-Entrant



Split Cylinders

Split Coaxial Cylinders



Measurement procedure

1) Resonator with sample:

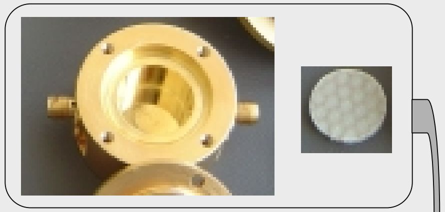
Measurement of the resonance parameters: $f_{\varepsilon\,1,2}$ and $Q_{\varepsilon\,1,2}$

2) Empty resonators

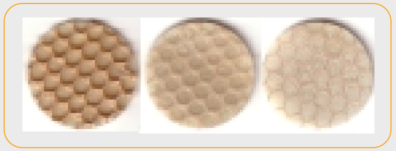
Measurement of the resonance parameters : $f_{0\,1,2}$ *and* $Q_{0\,1,2}$
(Determination of the equivalent diameters of the resonators $D_{eq\,1,2}$ and the equivalent conductivity of the walls $\sigma_{e\,1,2}$)

- **Determination of the pair of parameters: $(\varepsilon'_{\|}, \tan\delta_{\varepsilon\|})$ and $(\varepsilon'_{\perp}, \tan\delta_{\varepsilon\perp})$;**
- **Calculation of the dielectric anisotropy of the samples: ΔA_{ε}, $\Delta A_{\tan\delta\varepsilon}$**

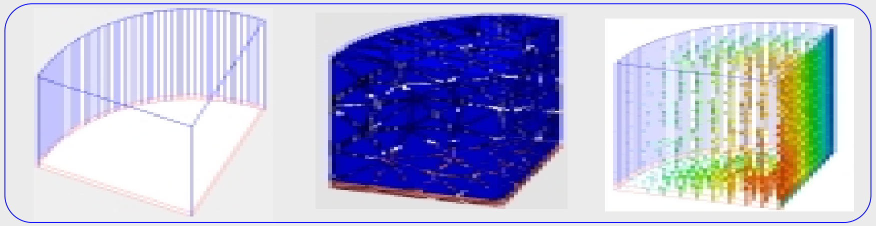
Measurement, assisted by 3D simulators



1) Resonator with sample with known dimensions and measured resonance characteristics f_{ε} and Q_{ε}

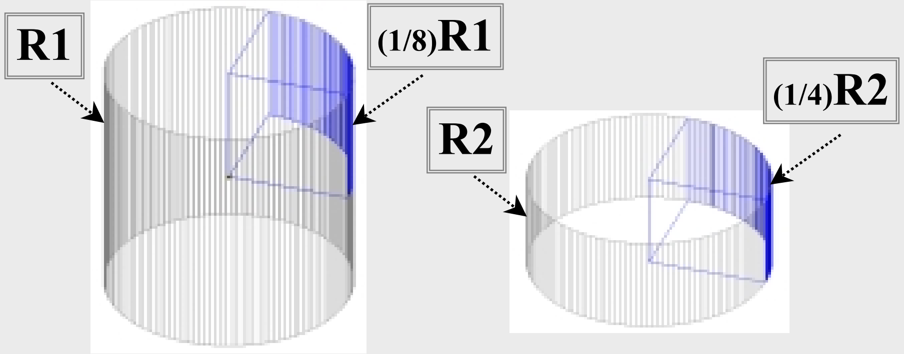


3) Determination of the full set of the dielectric parameters of materials $(\varepsilon'_{\|};\ \tan\delta_{\varepsilon\|})$ and $(\varepsilon'_{\perp};\ \tan\delta_{\varepsilon\perp})$.



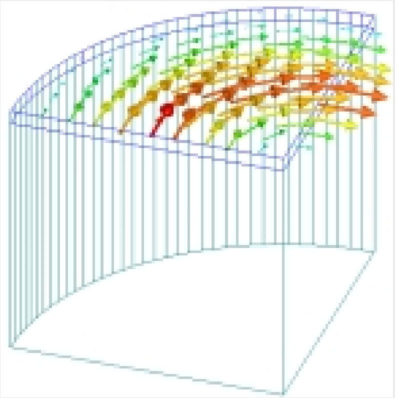
2) Introduction of 3D model of the resonator with sample, discretization (griding, meshing), field simulation and determination of the theoretical resonance characteristics f_{sim} and Q_{sim}

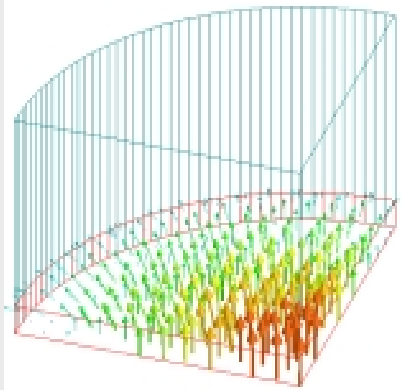
Extraction procedure



Important idea: simulation of part of the measurement resonators instead of the whole structure. The field symmetry of the excited modes (TE_{011} or TM_{010}) allows us to split the cylinders and to construct smaller 3D cavity models, which considerably decrease the computational time (50–100 times), improve accuracy and facilitate the mode identification

Electric field distribution





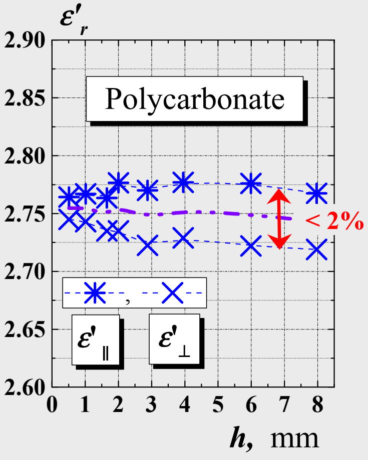
The electric fields distribution in the corresponding parts of the resonators – (1/8) R1 and (1/4) R2 fully repeat the fields distribution in the whole resonators

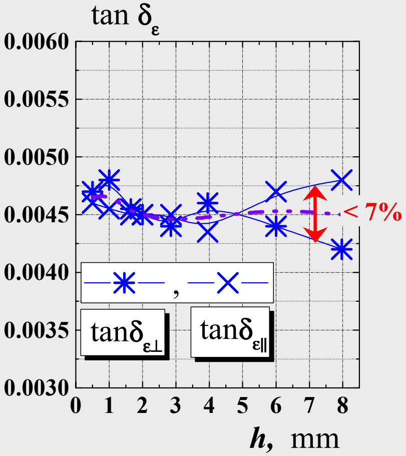
---

Substrate anisotropy of known substrates

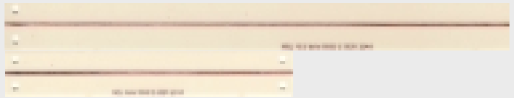
Substrates	Measured $\varepsilon'_{\parallel}$ / $\tan\delta_{\varepsilon\parallel}$	Measured $\varepsilon'_{\perp}$ / $\tan\delta_{\varepsilon\perp}$	IPC TM650 2.5.5.5 test method @ 10 GHz	Measured anisotropy ΔA_{ε} / $\Delta A_{\tan\delta\varepsilon}$ (in %)
RogersRO4003 0.5225 mm	3.605 / 0.00367	3.408 / 0.00295	3.38 ± 0.05 0.0027	6.1 / 25.2
Arlon 25N 0.520 mm	3.570 / 0.00415	3.392 / 0.00510	3.38 / 0.0027	5.8 / 21.6
Taconic RF-35 0.5125 mm	3.900 / 0.00495	3.471 / 0.00391	3.50 / 0.0033	11.5 / 26.3
Neltec NH9338 0.520 mm	4.025 / 0.00460	3.273 / 0.00277	3.38 ± 0.1 0.0025	20.6 / 52.1
ISOLA IS680 0.52 mm	3.703 / 0.00465	3.327 / 0.00300	3.38 / 0.0030	12.3 / 45.3

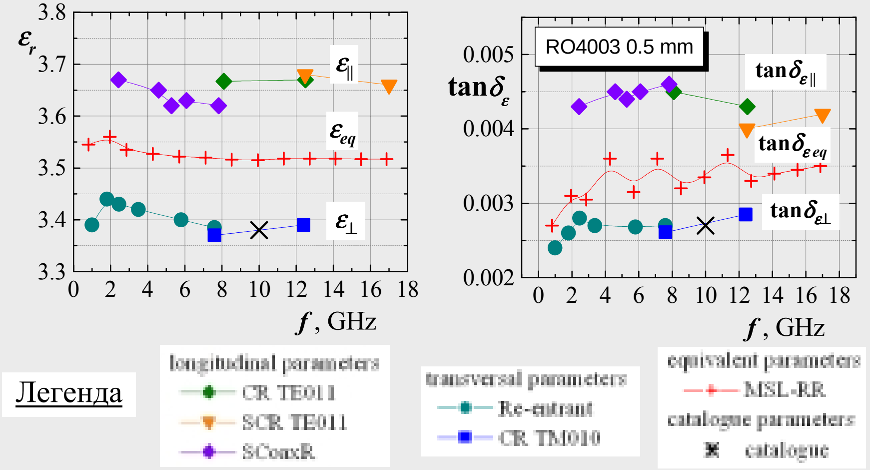
Examples for isotropic material - polycarbonate



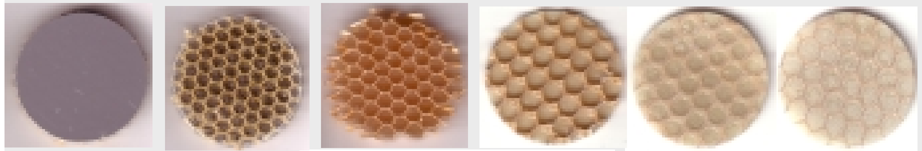


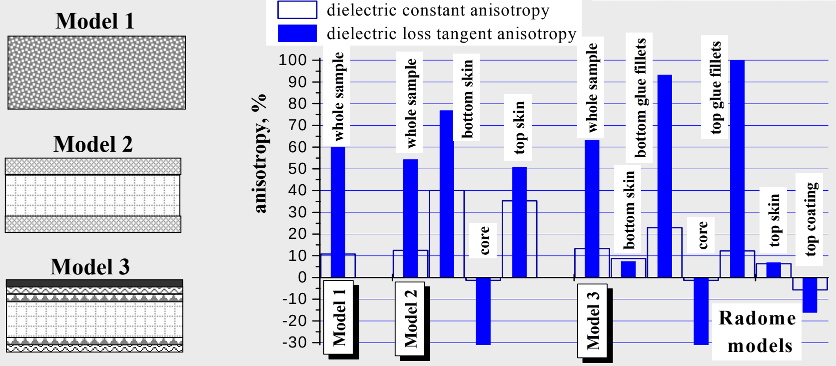
Examples for anisotropic material – Ro4003





Examples for multilayer honey-comb antenna radome



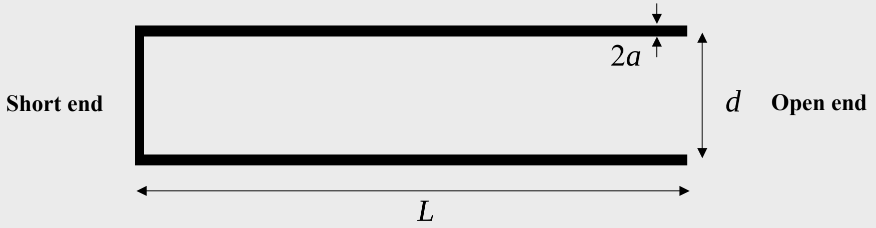


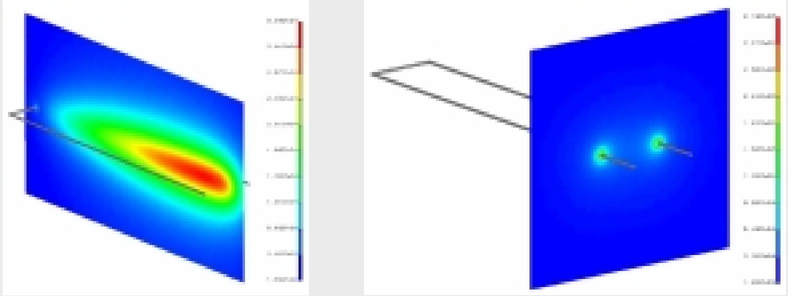
Source: Vesselin N. Peshlov, Plamen I. Dankov, Boyan Hadjistamov, "Models of Multi-layer Antenna Radomes with Anisotropic Materials", *1st European Conference on Antennas and Propagation EuCAP'2006,* France, Nice, November 2006, No. 349840PD

Example for measurement of plasma electron density by hairpin resonator probe

---

Measurement of plasma density by hairpin-resonator method

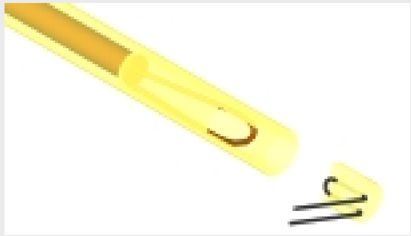


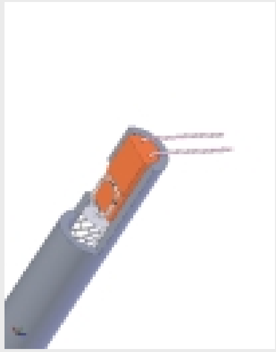


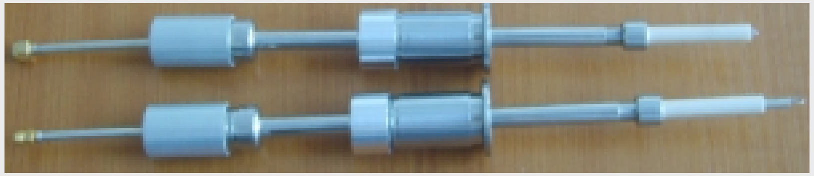
Electric field distribution in the quarter-wavelength resonator

---

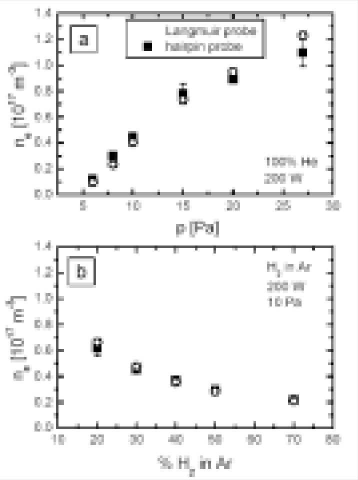
Typical construction of the hairpin measurement resonator





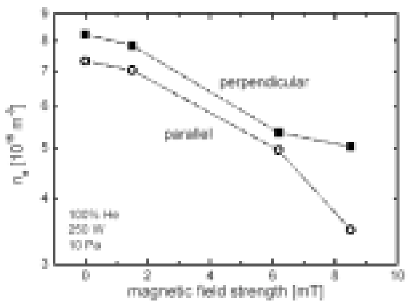


Comparison with other measurement techniques



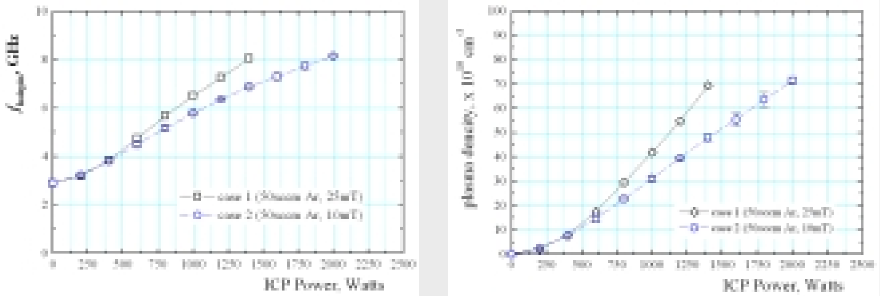
P. Starke, S. Christ-Koch, S. K. Karkari, C. Gaman, U. Fantz, A. R. Ellingboe, “Performance of a Langmuir probe and a hairpin resonance probe in inductively coupled low pressure plasmas”, *28th ICPIG*, July 15-20, 2007, Prague, Czech Republic

⇐ Fig. Comparison of the hairpin resonance probe with the Langmuir probe in Helium (a) and Argon plasmas with hydrogen admixture (b)



⇒ Fig. Electron densities in helium plasmas with increasing magnetic field strength, probe tip parallel and perpendicular to the field lines.

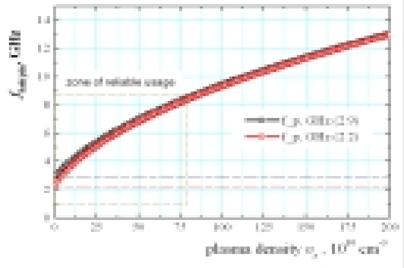
Dependences



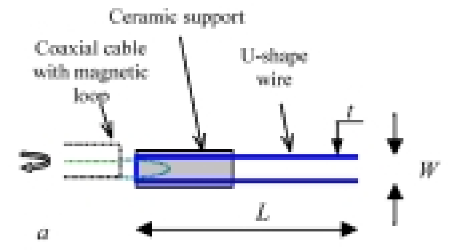
Resonance frequency and electron density vs. reactor power in Ar at different conditions

$$n_e = \frac{f^2_{p,hairpin} - f^2_{air}}{0.81}$$

$$n_e.10^{10}\,\text{cm}^{-3},\ f_{p,air},\text{GHz}$$



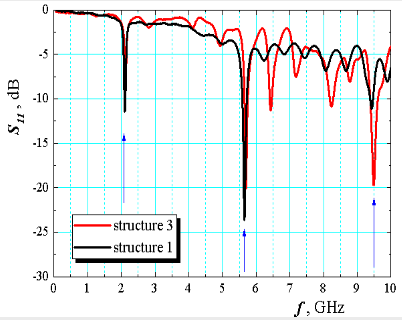
HFSS simulations



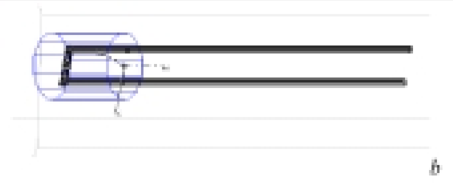
Schematic view of the reflection-type hairpin resonator with U-shape wire with length *L* and cylindrical ceramic support; *simple formula:*

$$L,\text{mm} = p\frac{300}{4f_v,\text{GHz}},$$

$$p = 1, 2, 3...$$

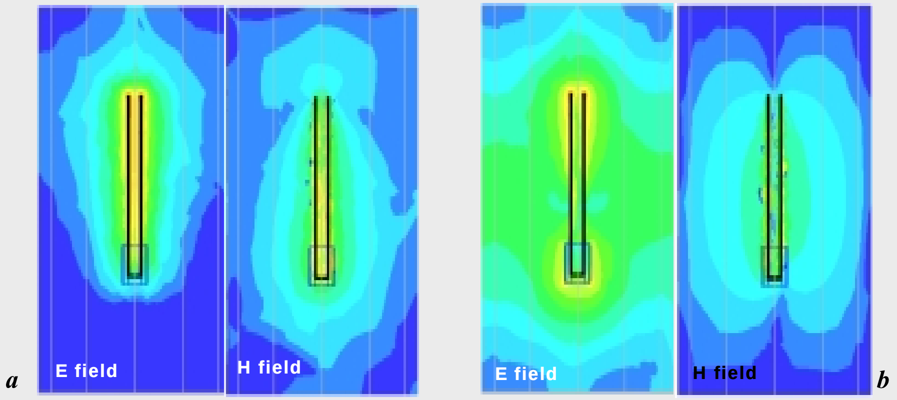


Measurement response for the first 3 resonances



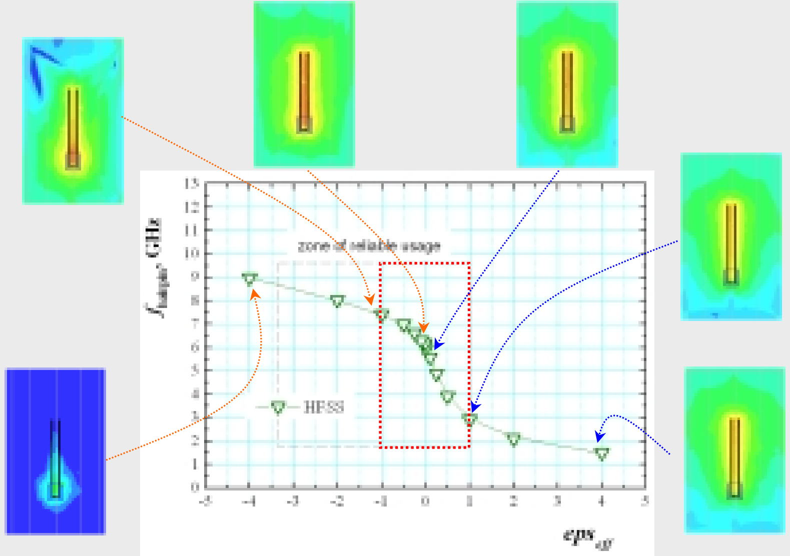
3D model of the resonator used in the Ansoft® HFSS simulator in eigen-mode option

Field distribution

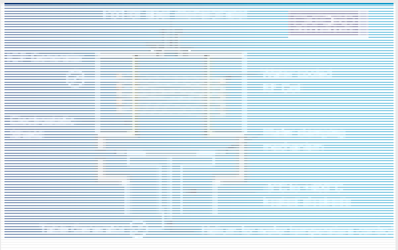


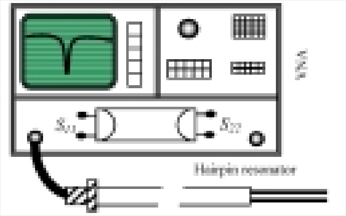
Electric-field and magnetic-field distribution of the first-order resonance TEM_{001} (*a*) and second-order resonance TEM_{002} (*b*) in the hairpin probe; obtained by HFSS-8 in eigen-mode option

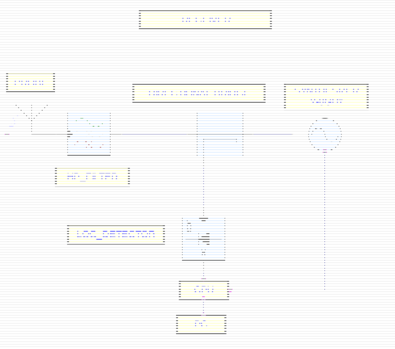
Measurement range



Measurement scheme







Thanks for your attention