Characteristic mode analysis: eigenvalue analysis of antenna structures

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October 12, 2007

Outline

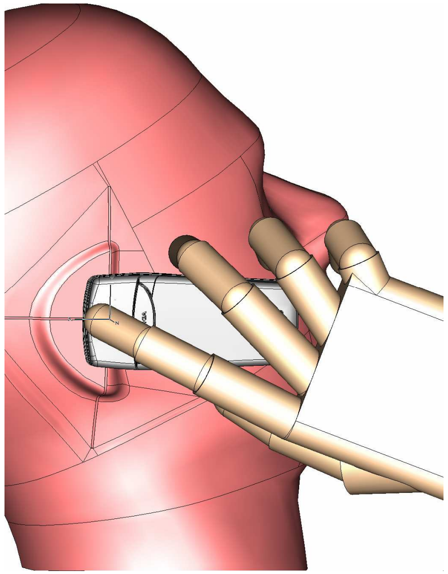
- Design challenges for mobile phones
- What can eigenvalues do for mobile phones?
    - Theory of characteristic modes
    - Ground plane resonance frequencies and resonant modes
    - How to find optimal antenna positions

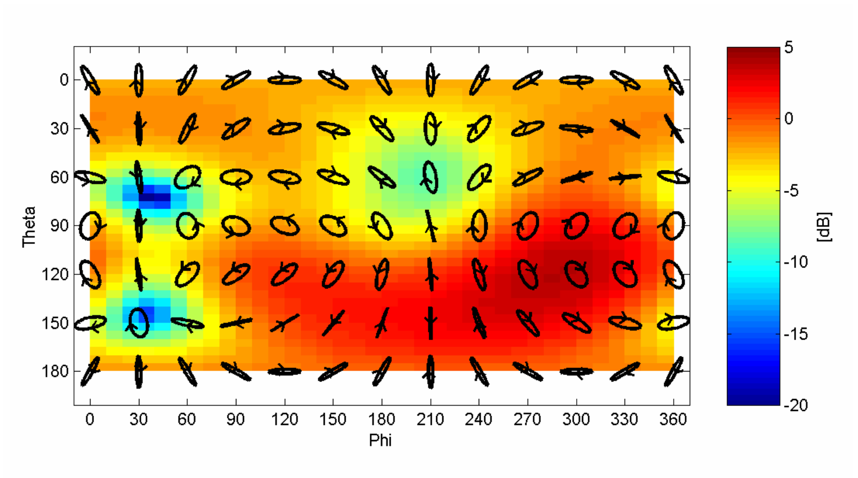
Design challenges for mobile phones

- Mobile phones have become multimedia computers incorporating the functionalities of digital cameras, video recorders, music players, internet browsers and GPS navigators
- The number of radio systems in the phone is increasing
  - Cellular radio systems: GSM, WCDMA
  - Broadband wireless systems: WLAN, WiMAX
  - Short-range systems: Bluetooth, UWB
  - Broadcast systems: FM radio, DVB-H
- Each radio system needs at least one antenna
- Antennas must have a broadband impedance match, small size and good efficiency

Research Challenges in simulations

- EM simulation of the whole mobile terminal
  - Use of mechanical CAD-models
  - Reliable estimation of the performance of antennas
  - Effect of user
  - Antenna performance evaluation in “realistic” environments
- Faster simulation methods and hardware
- Improved optimization and synthesis methods
- New understanding of antennas through simulations





Ground plane resonances

- In a mobile phone, the ground plane (i.e. the ground layers of the printed wiring board) is an important part of the antenna system
- At frequencies below 1 GHz the ground plane radiates most of the electromagnetic energy and it affects strongly the operation bandwidth and antenna performance
- The resonances of the ground plane determine much of the impedance and radiation characteristics of the antennas
- Compare with a musical instrument, e.g. a guitar: most of the sound comes from the body, the strings just excite the body to vibrate

Characteristic mode analysis

- Characteristic modes are the natural resonance modes of an open metallic structure (no antenna feed present)
- Theory developed during the 1970's by Garbacz [1], Harrington [2] et al.
- Method of moments (boundary integral) formulation of Maxwell's equations:

$$ZJ = E_{\tan}^{\mathrm{inc}}$$

where

$$Z = R + iX$$

- Characteristic modes are based on the generalized eigenvalues of the coefficient matrix

$$ZJ_n = \nu_n RJ_n \quad \Rightarrow \quad XJ_n = \lambda_n RJ_n, \quad \nu_n = 1 + i\lambda_n$$

- The matrix R appears on the right to make orthogonal radiation patterns for the modes
- The characteristic mode analysis has also been defined for dielectric and magnetic bodies that can have losses

[1] R.J. Garbacz and R.H. Turpin. A generalized expansion for radiated and scattered fields. IEEE Trans. Antennas Propagat, AP-19, pp. 348-358, 1971.

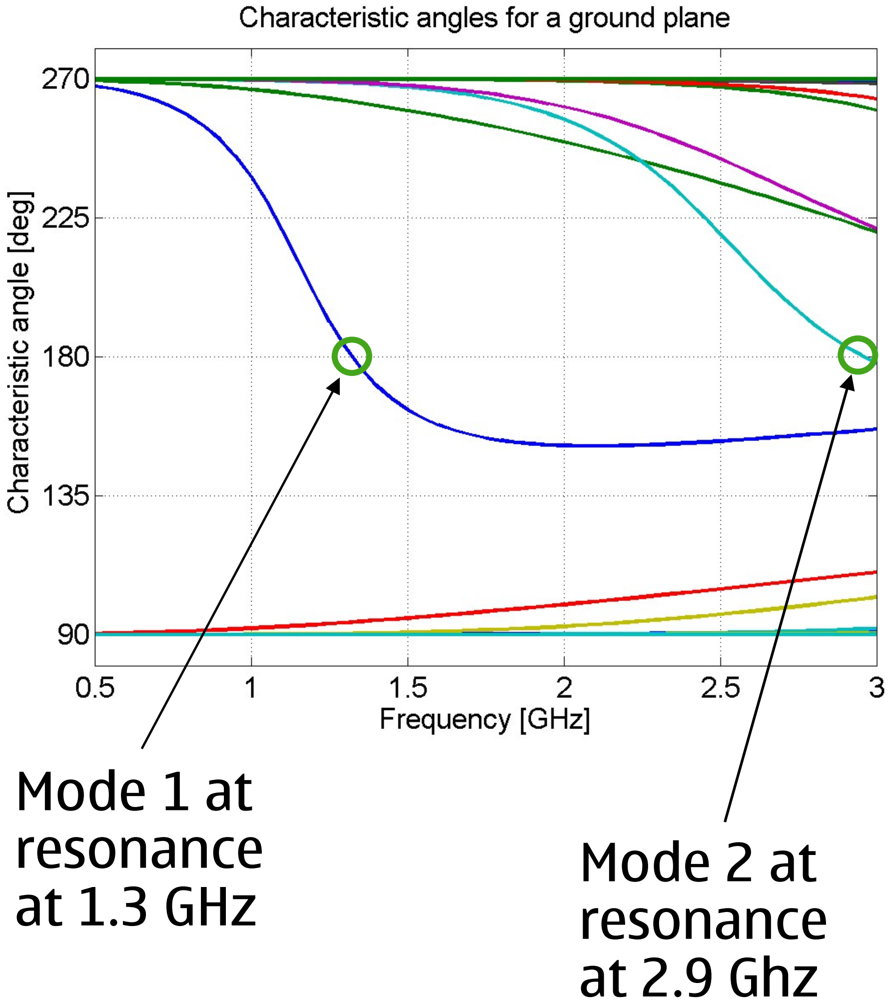
[2] R.F. Harrington and J.R. Mautz. Theory of characteristic modes for conducting bodies. IEEE Trans. Antennas Propagat, AP-19, pp. 622-628, 1971.

Characteristic values

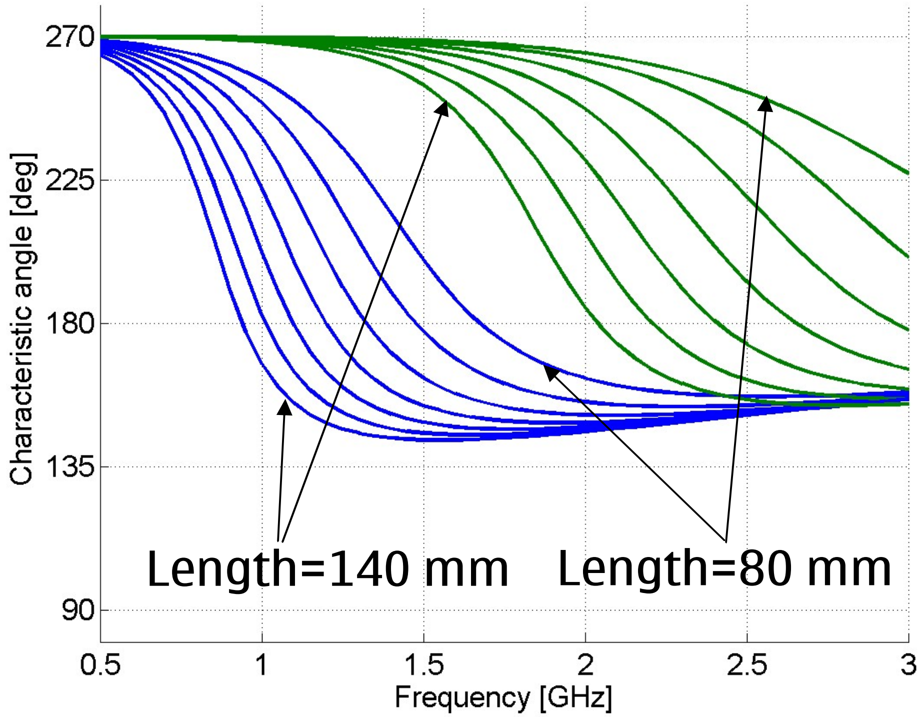
- The analysis gives the characteristic values (eigenvalues) of the resonance modes as a function of frequency
- Also the characteristic modes (current distributions derived from eigenvectors) are computed
- When the characteristic value is close to zero, the mode is at resonance and then the mode would be nicely excited by a plane wave excitation and is also a good radiating mode for antenna applications
- From the characteristic value, compute the characteristic angle $\alpha=180°+\text{atan}(-\lambda)$, at resonance the angle is close to $180°$
  - This is the argument of the complex number $-1/\nu_n$
  - It describes the phase angle between the current J_n and electric field E_n^{tan}
  - At resonance the characteristic mode radiates strongly, at 90 or 270 degrees, the mode only stores energy

Characteristic angles for a rectangular ground plane

width=40 mm, length=100 mm



width=40 mm, length varied from 80 to 140 mm



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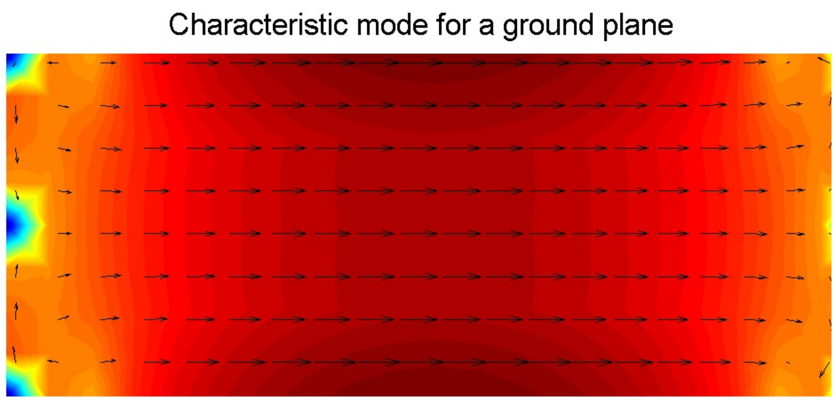
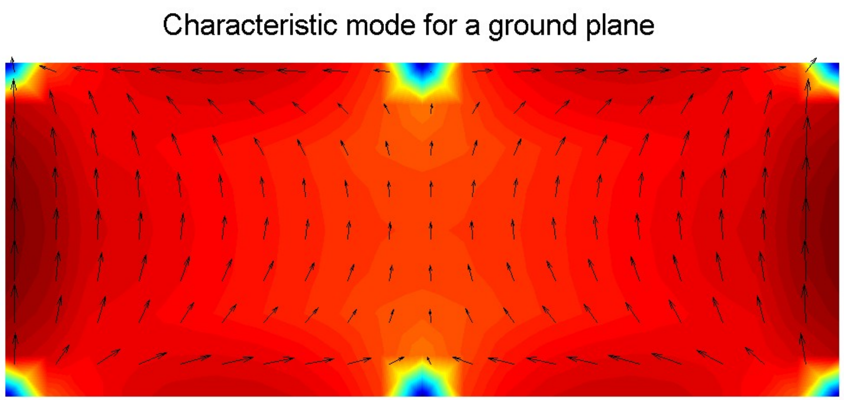
Ground plane modes of a rectangular ground plane (100 x 40 mm)

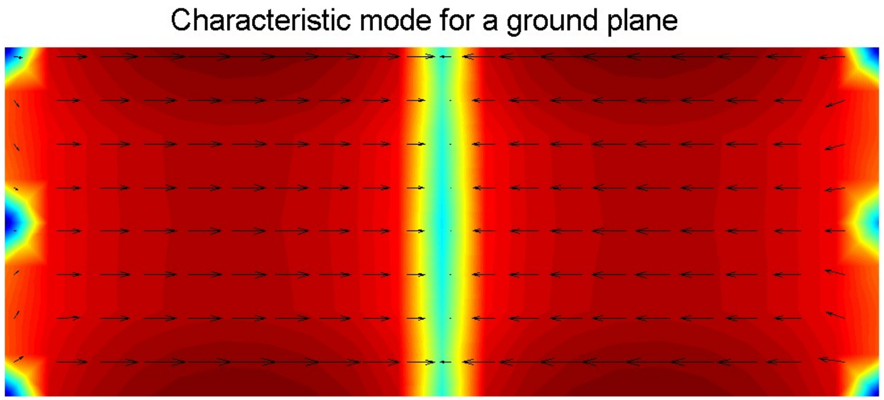
Mode 1 ($\lambda/2$ mode) resonant at 1.3 GHz



Transverse mode



Mode 2 (λ mode) resonant at 2.9 GHz

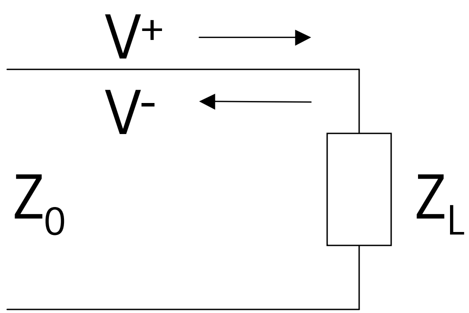


Antenna placement analysis

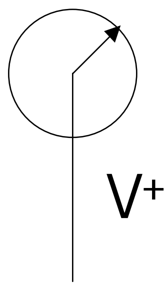
- Find the characteristic modes of the ground plane and their resonant frequencies
- Calculate the electric field of a resonant mode
- Place the (patch-type) antenna at the electric field maximum
- Try to excite multiple modes to increase the bandwidth
- At higher frequencies the antenna starts to modify the pure ground plane modes

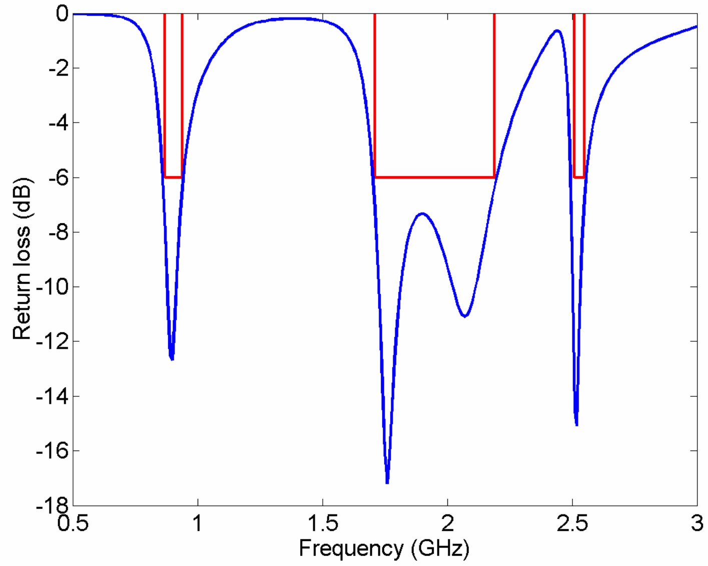
Operating bandwidth and impedance match

- The antenna is fed by a transmission line (coaxial cable, microstrip line)
- If antenna impedance differs from transmission line impedance, signal is reflected back to the amplifier and is not radiated
- Transmission line impedance is typically 50 Ω
- Reflection coefficient $\rho_L = V^- / V^+ = (Z_L - Z_0)/(Z_L + Z_0)$
- Scattering matrix element $S_{11} = \rho_L$ (in dB), also called return loss



$V^- = \rho_L V^+$





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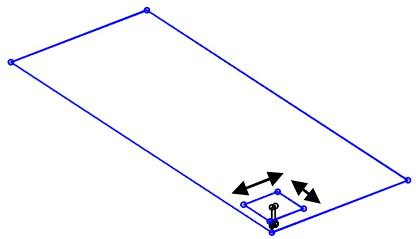
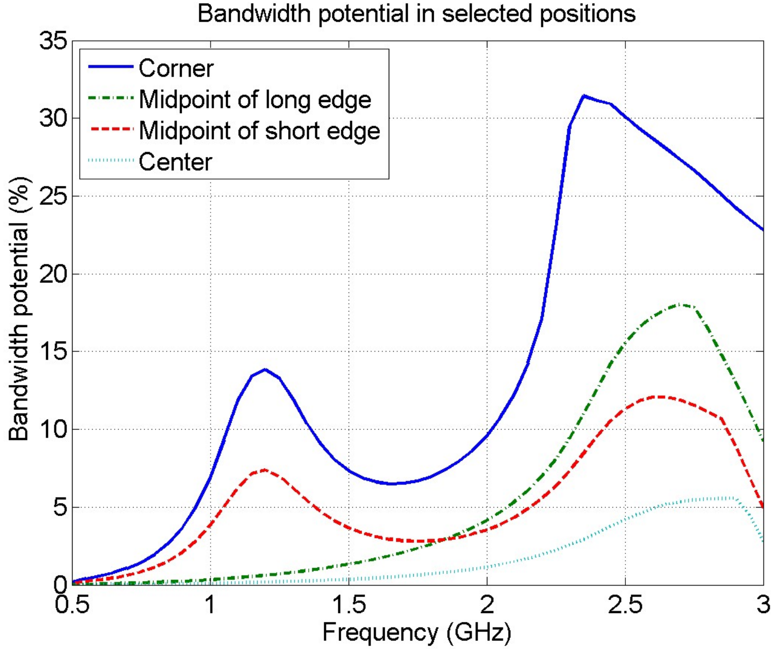
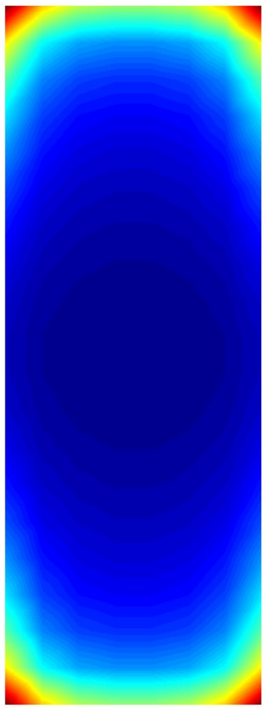
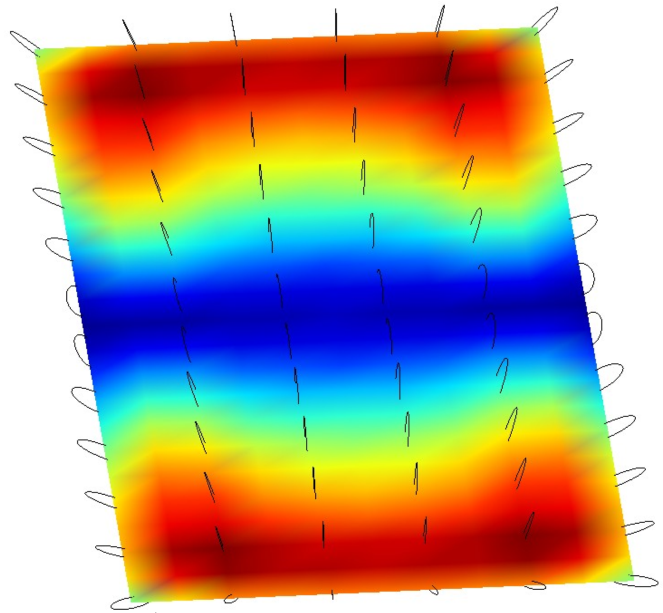
Antenna placement and obtainable bandwidth



A small patch antenna is moved over the ground plane







Electric field 5 mm above the ground plane

Both methods indicate that the best antenna positions are at the corners of the ground plane

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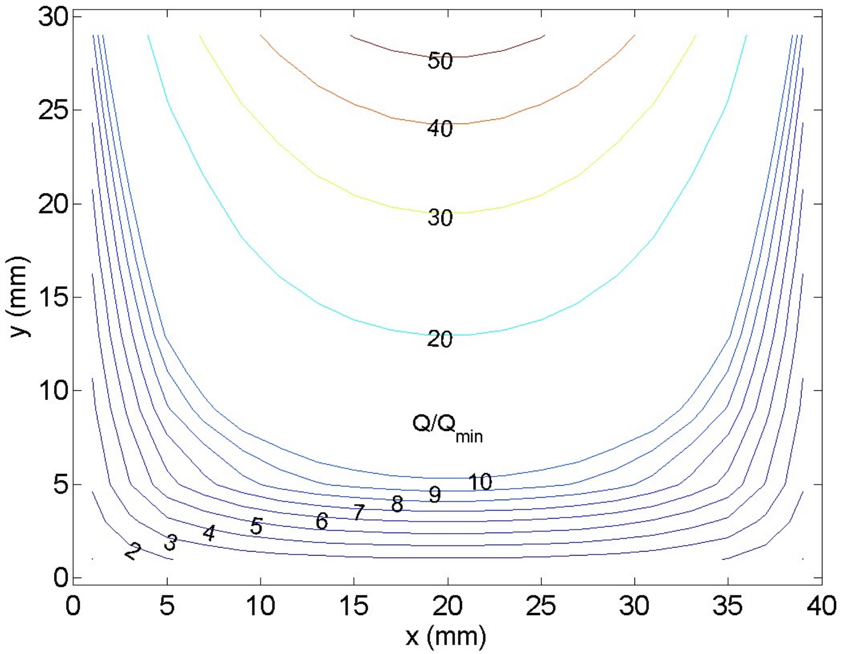
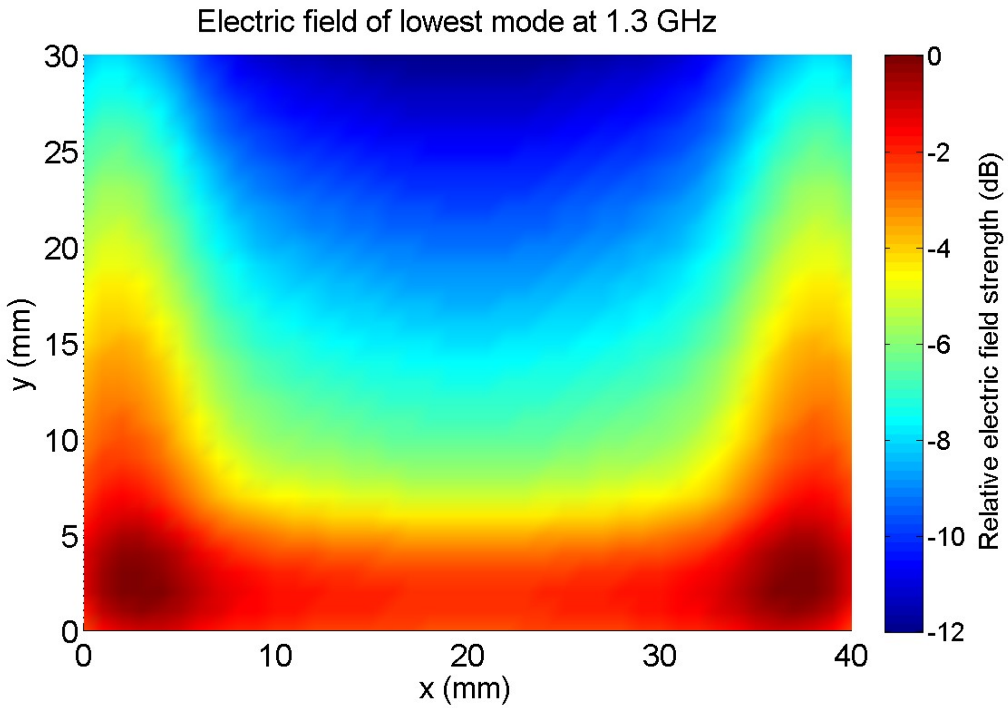
Zooming in on the lower part

- Another test: 3 mm long vertical probe antenna moved 2 mm over the ground plane. Obtainable bandwidth is given by the inverse of the quality factor Q which is computed as the ratio of susceptance to conductance





Conclusions

- Experienced antenna designers know that the best antenna positions are at the corners of a rectangular ground plane
- Characteristic mode analysis explain this as the electric field of the lowest-order characteristic mode has a maximum at the corners
- Results have been verified by computing the obtainable bandwidth of a large number of test antennas but the characteristic mode analysis is faster and gives more insight
- The technology can be used to analyze arbitrary geometries

