Microwave Circuits and Antenna Design

Antenna Design

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Notation

c = speed of light in free space

λ_0 = wavelength of free space

k_0 = wavenumber of free space

k_1 = wavenumber of substrate

η_0 = intrinsic impedance of free space

η_1 = intrinsic impedance of substrate

ε_r = relative permtitivity (dielectric constant) of substrate

ε_r^{eff} = effective relative permtitivity
(accouting for fringing of flux lines at edges)

ε_{rc}^{eff} = complex effective relative permtitivity
(used in the cavity model to account for all losses)

$$c = 2.99792458\times10^{8}\ [\mathrm{m/s}]$$

$$\lambda_0 = c / f$$

$$k_0 = \omega\sqrt{\mu_0\varepsilon_0} = 2\pi / \lambda_0$$

$$k_1 = k_0\sqrt{\varepsilon_r}$$

$$\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 376.7303\ [\Omega]$$

$$\eta_1 = \eta_0 / \sqrt{\varepsilon_r}$$

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}}$$

$$\mu_0 = 4\pi\times10^{7}\ [\mathrm{H/m}]$$

$$\varepsilon_0 = \frac{1}{\mu_0 c^2} \approx 8.854188\times10^{12}\ [\mathrm{F/m}]$$

Antenna

- Anten, hava ile elektronik cihazlar arasındaki geçiş yapısıdır. Antenler, elektrik sinyallerini havaya elektromanyetik dalga olarak ışırlar, havadaki elektromanyetik sinyalleri ise elektrik sinyaline dönüştürürler.

- A usually metallic device (as a rod or wire) is used for radiating or receiving electromagnetic waves. An antenna is a transitional structure between free-space and a guiding structure (Balanis; Antenna Theory). Ortamda ortama geçişin efekif alanı, antenin efektif ışıma alanıdır.

- Antenna is a device that converts electrons into photons or vice versa. A transmitting antenna converts electrons into photons while a receiving antenna converts photons into electrons.

- The beam width of an antenna measure at half of the maximum power received by an antenna or the 3 dB beam width of the antenna is termed as half null beam width.

- Power radiated from an antenna per unit solid angle is called radiation intensity. Unit of radiation intensity is watts per steridian or per square degree.

Antenna Performance Parameters

Antenna parameters

- Radiation resistance
- Directivity
- Antenna gain
- Beamwidth
- Effective aperture
- Friis transmission equation

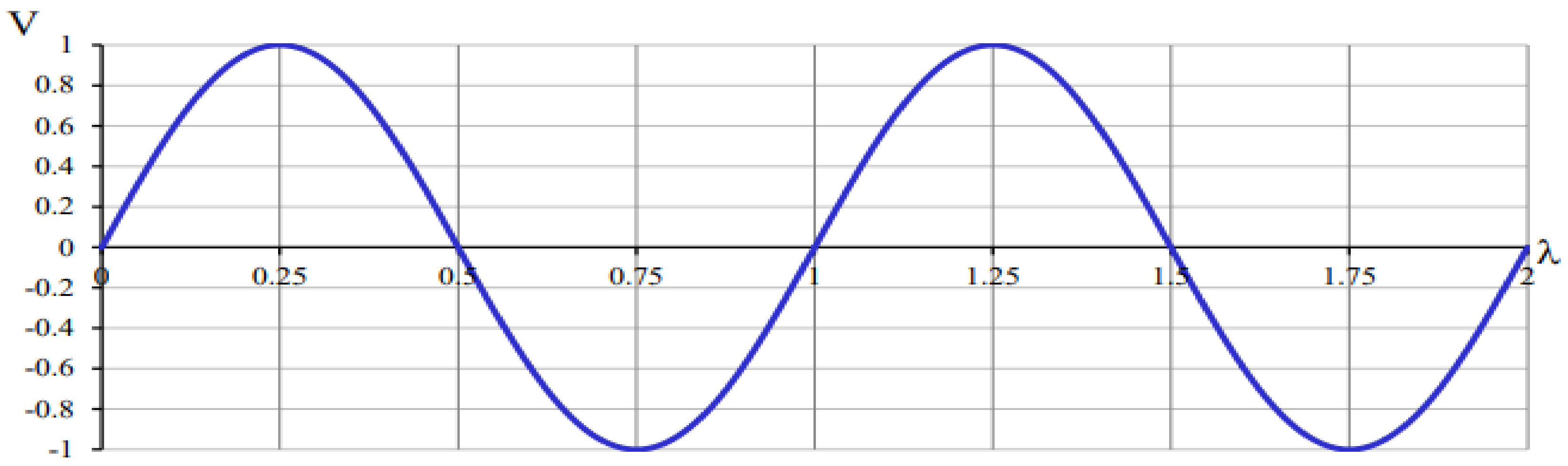
$$\frac{P_r}{P_t} = \frac{G_t G_r \lambda^2}{(4\pi R)^2} = \frac{A_{e,t} A_{e,r}}{\lambda^2 R^2}$$

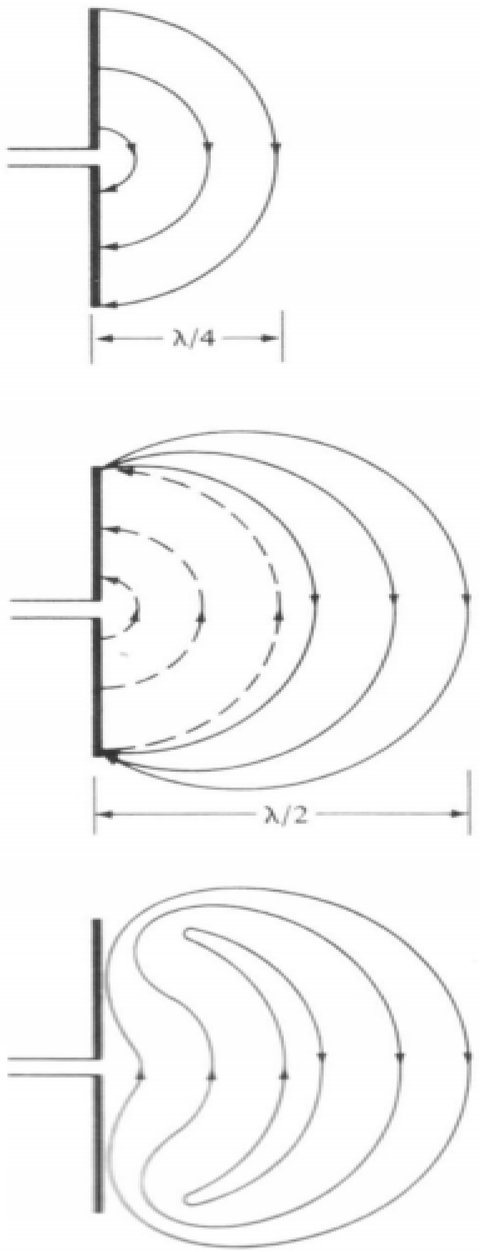
Antenna Performance Parameters

- Common antenna performance parameters include:
  - Return Loss - Impedance
  - Gain and Directivity
  - Frequency coverage
  - Bandwidth
  - Beamwidth
  - Polarization
  - Efficiency
  - Field Patterns
  - Front to Back Ratio and Side loobes

Antenna Basics

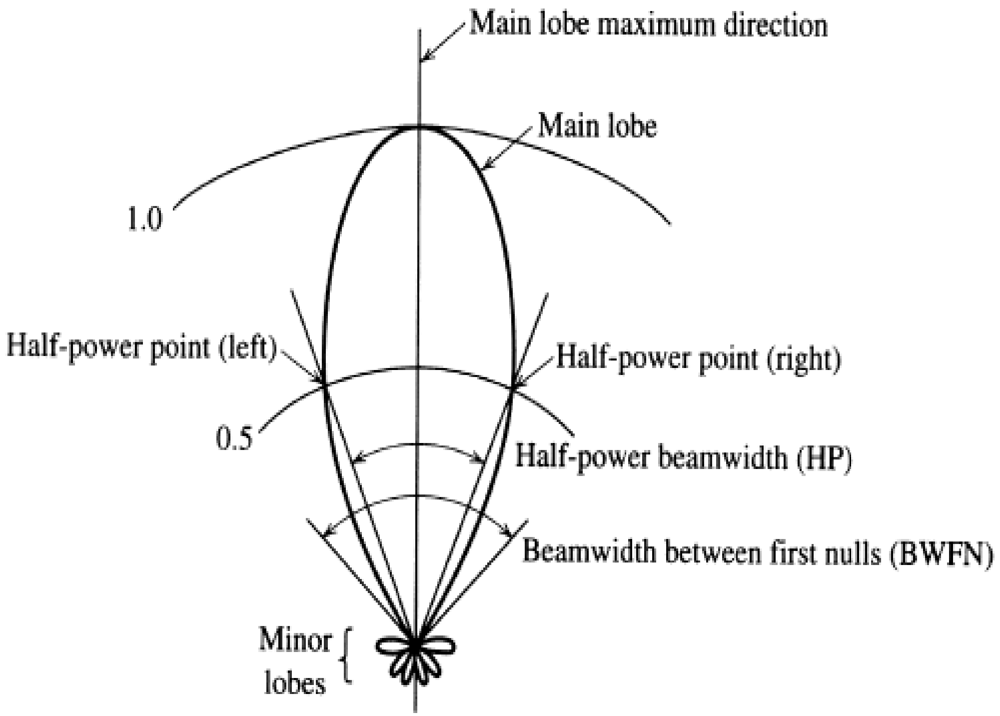
- How is radiation achieved?
- Wavelength is key: $\frac{\lambda}{2}$, $where\ \lambda = \frac{c_o}{f_r\sqrt{\epsilon_r}}$





Beamwidth (θ_B, Φ_B)

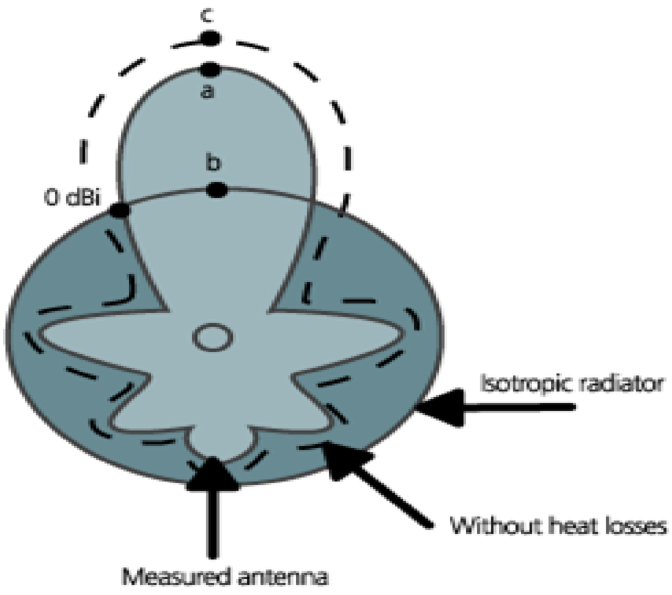
- Beamwidth (θ_B, Φ_B) of an antenna is the angle defined by the points either side of boresight at which the power is reduced by 3-dB, for a given plane.
  - For example if θ_B, represents the beamwidth in the horizontal plane, Φ_B represents the beamwidth in the orthogonal (vertical) plane.
  - The 3-dB (Gücün yarıya düştüğü) beamwidth defines the half-power beam.



dBi versus dBd

- **dBi** indicates gain vs. isotropic antenna
  - Isotropic antenna radiates equally well in all directions, spherical pattern, Gain=1, Gain(dBi))=0 dBi

- **dBd** indicates gain vs. reference half-wavelength dipole
  - Dipole has a doughnut shaped pattern with a gain of 2.15 dBi



$$dBi = dBd + 2.15\,dB$$

Antenna Gain

- Relationship between antenna gain and effective area

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

  - G = antenna gain
  - A_e = effective area
  - f = carrier frequency
  - c = speed of light (3×10^8 m/s)
  - λ = carrier wavelength

ANTENNA BASICS

1. The Gain of an antenna with losses is given by:

$$G \approx \frac{4\pi\eta A}{\lambda^2} \quad \text{Where} \quad \begin{aligned} \eta &= \text{Efficiency} \\ A &= \text{Physical aperture area} \\ \lambda &= \text{wavelength} \end{aligned}$$

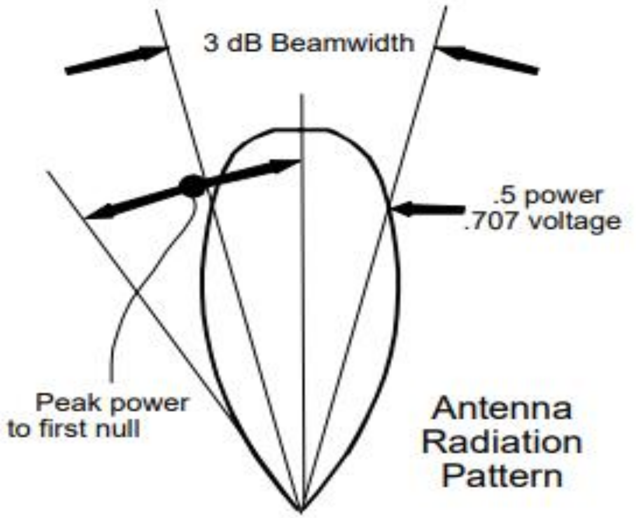
another is:

$$G = \frac{X\,\eta}{BW_\phi\; BW_\theta}$$

Where $BW_{\theta \text{ and } \phi}$ are the elev & az beamwidths in degrees.
For approximating an antenna pattern with:
(1) *A rectangle;* $X = 41253,\ \eta_{typical} = 0.7$
(2) *An ellipsoid;* $X = 52525,\ \eta_{typical} = 0.55$

2. Gain of rectangular X-Band Aperture
$G = 1.4\ LW$ Where: Length (L) and Width (W) are in cm

3. Gain of Circular X-Band Aperture
$G = d^2\eta$ Where: d = antenna diameter in cm
η = aperture efficiency



4. Gain of an isotropic antenna radiating in a uniform spherical pattern is one (0 dB).

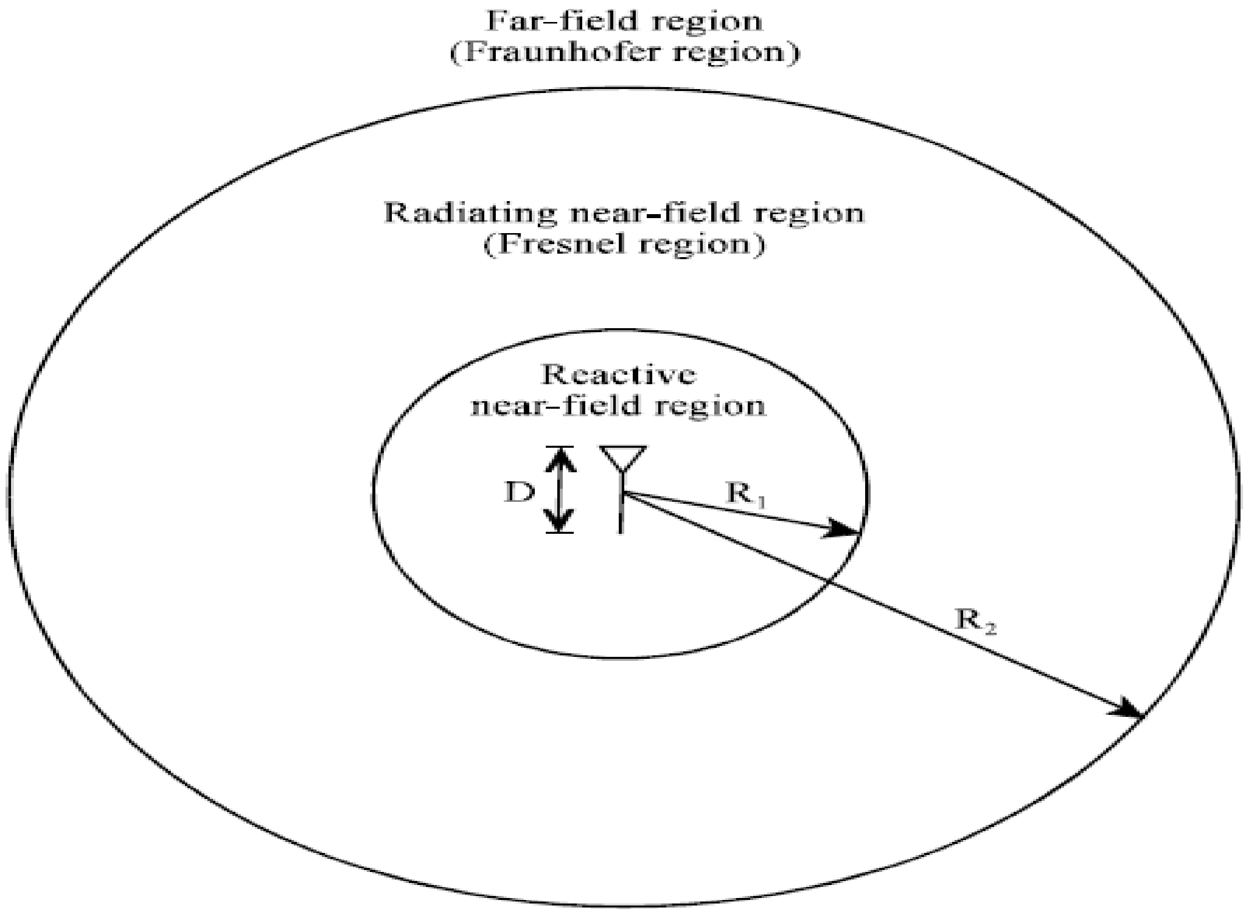
5. Antenna with a 20 degree beamwidth has a 20 dB gain.

6. 3 dB beamwidth is approximately equal to the angle from the peak of the power to the first null (see figure at right).

7. Parabolic Antenna Beamwidth: $$BW = \frac{70\lambda}{d}$$

Where: BW = antenna beamwidth; λ = wavelength; d = antenna diameter.

Antenna Field Regions

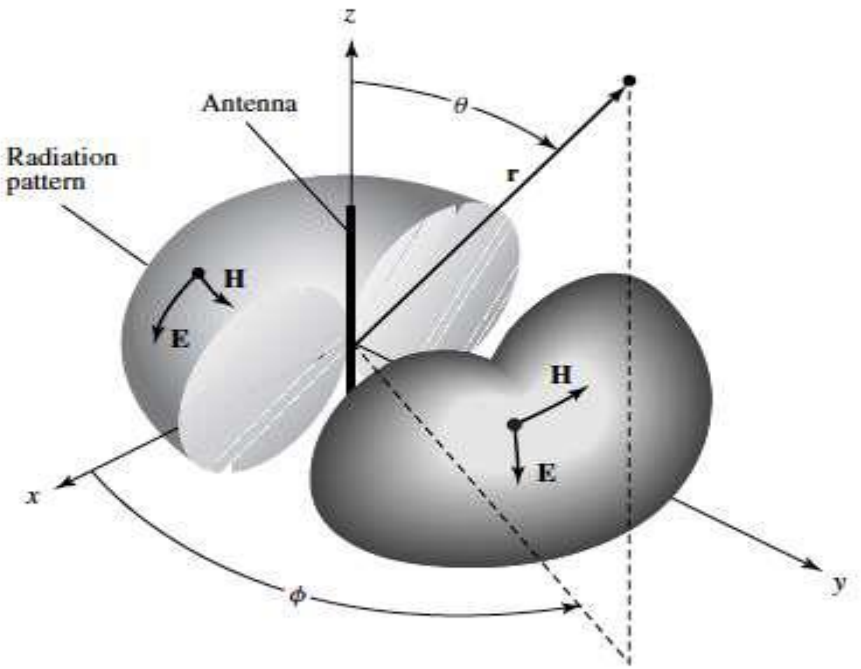


D = maximum antenna dimension

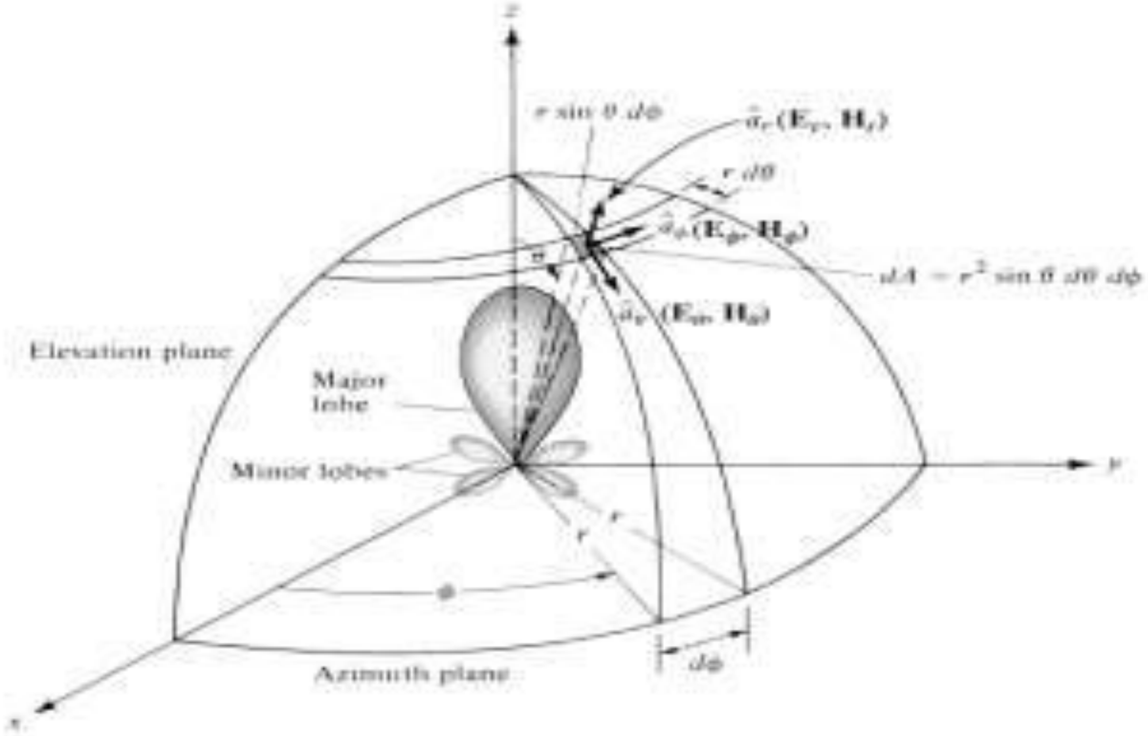
$$R_1 = 0.62\sqrt{\frac{D^3}{\lambda}}$$

$$R_2 = \frac{2D^2}{\lambda}$$

Pattern of antennas

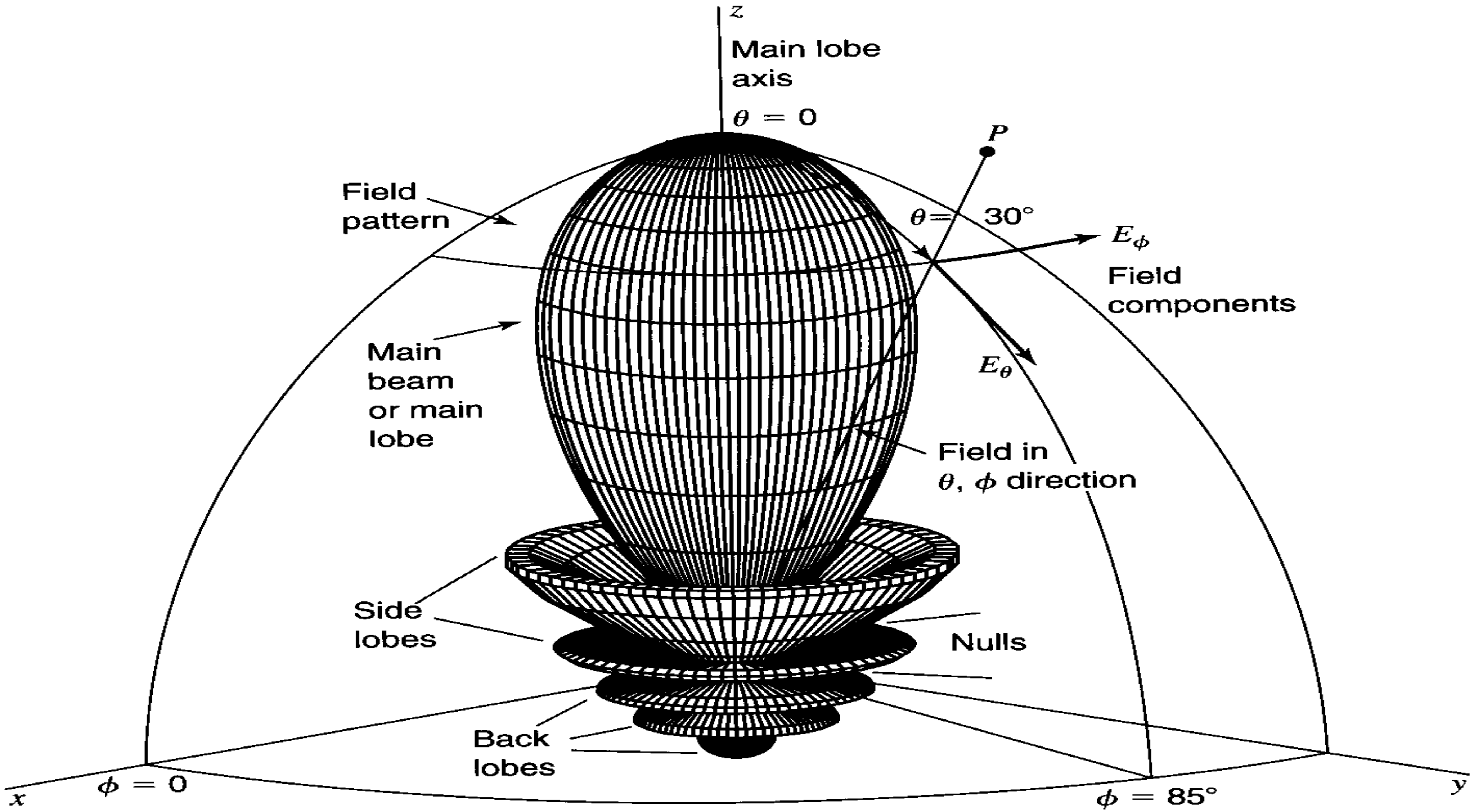


Isotropic,directional,and omnidirectional pattern

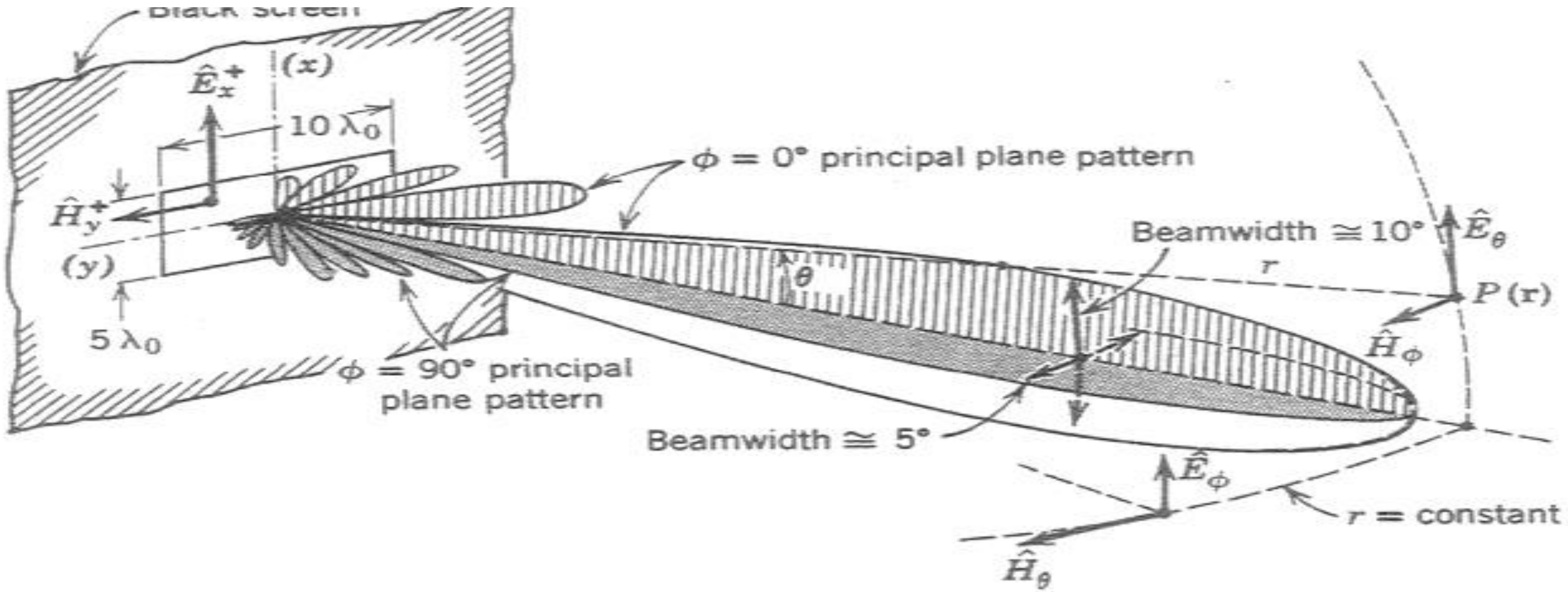


Radiation pattern

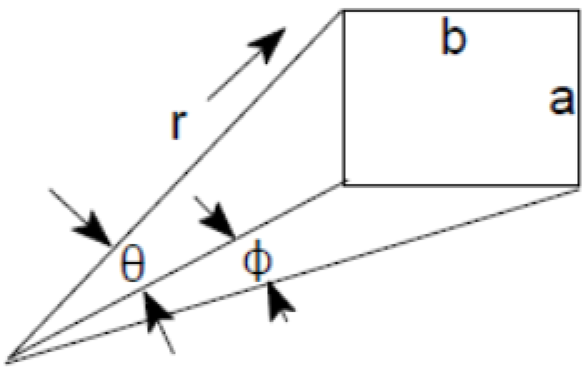
Radiation pattern



Antenna Pattern 3D



Approximating the antenna pattern as a **rectangular** area:



Where $\theta = BW_\theta$, and $\phi = BW_\phi$

$$a = r \sin\theta, \quad b = r \sin\phi, \quad \text{area} = ab = r^2 \sin\theta \sin\phi$$

$$G = \frac{\textit{Area of Sphere}}{\textit{Area of Antenna pattern}} = \frac{4\pi r^2}{r^2 \sin\theta \sin\phi} = \frac{4\pi}{\sin\theta \sin\phi}$$

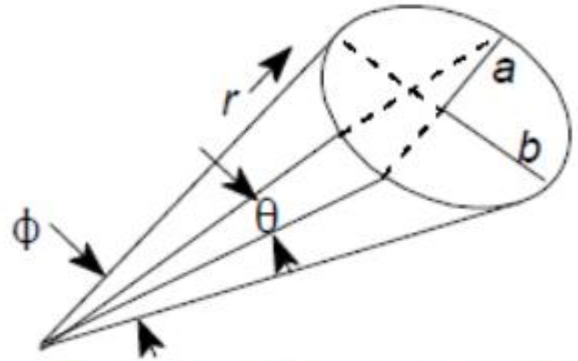
For small angles, $\sin\phi = \phi$ in radians, so:

$$G = \frac{4\pi}{\sin\phi \sin\theta} = \frac{4\pi}{\phi\ \theta\ (radians)} = \frac{4\pi}{\phi\ \theta}\left(\frac{360^\circ\ 360^\circ}{2\pi\ 2\pi}\right) = \frac{41253}{\phi\ \theta\ (degrees)}\ or\ \frac{41253}{BW_\phi\ BW_\theta\ (degrees)}$$

The second term in the equation above is identical to equation [3].

Converting to dB, $G_{max}(dB) = 10\,Log\left[\frac{41253}{BW_\phi\ BW_\theta}\right]$ *with* BW_ϕ *and* BW_θ *in degrees*

Approximating the antenna pattern as an **elliptical** area:



Where $\theta = BW_\theta$, and $\phi = BW_\phi$

Area of ellipse = $\pi a b = \pi[(r \sin\theta)/2][(r\sin\phi)/2] = (\pi r^2 \sin\theta \sin\phi)/4$

$$G = \frac{\textit{Area of Sphere}}{\textit{Area of Antenna pattern}} = (4\pi r^2)\left(\frac{4}{\pi r^2 \sin\theta \sin\phi}\right) = \frac{16}{\sin\theta \sin\phi}$$

For small angles, $\sin\phi = \phi$ in radians, so:

$$G = \frac{16}{\sin\phi \sin\theta} \approx \frac{16}{\phi\ \theta\ (radians)} = \frac{16}{\phi\ \theta}\left(\frac{360°\ 360°}{2\pi\ 2\pi}\right) = \frac{52525}{\phi\ \theta\ (degrees)}\ \text{or}\ \frac{52525}{BW_\phi\ BW_\theta\ (degrees)}$$

For a very directional radar dish with a beamwidth of 1° and an average efficiency of 55%:

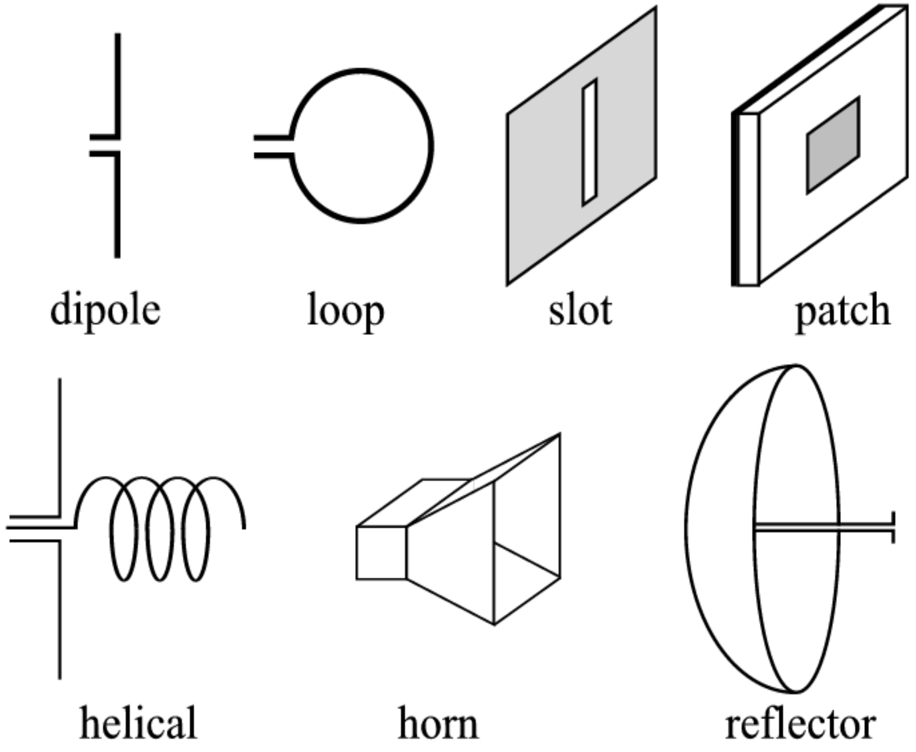
Ideally: G = 52525, or in dB form: 10 log G =10 log 52525 = 47.2 dB

With efficiency taken into account, G = 0.55(52525) = 28888, or in log form: 10 log G = 44.6 dB

Types of Antennas

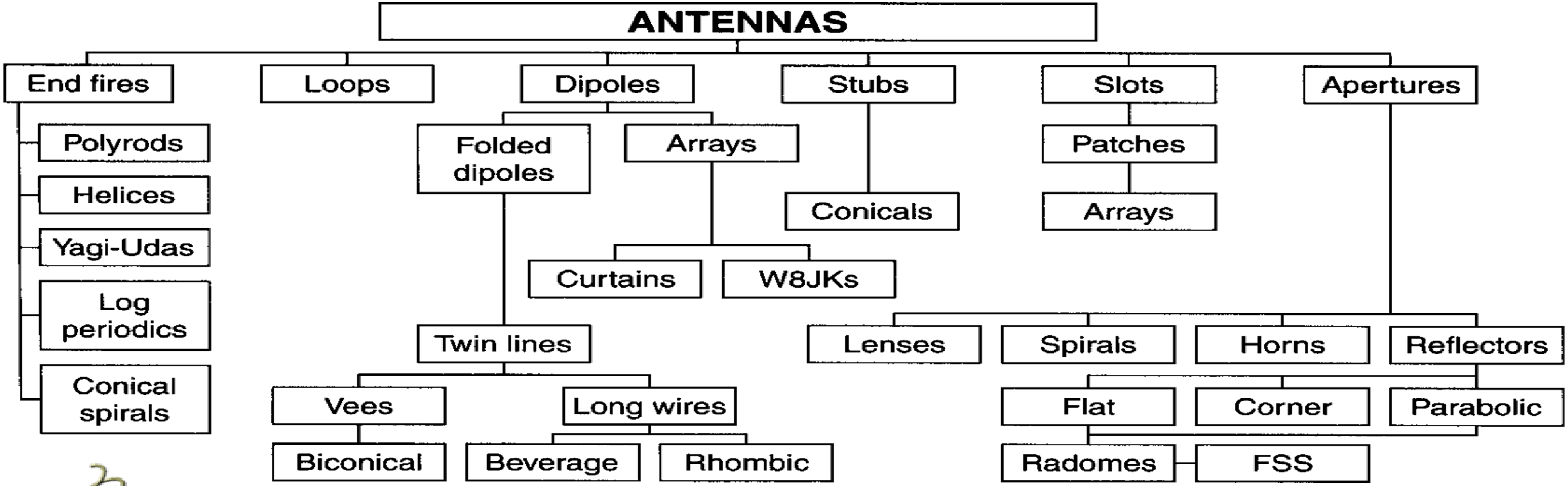
Types of Antennas

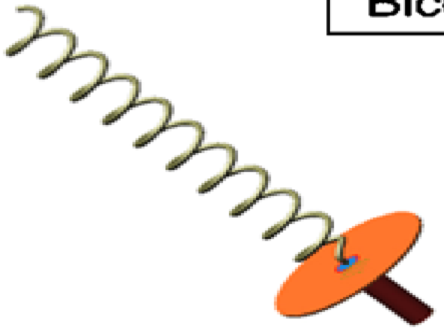
- Wire antennas
- Aperture antennas
- Array antennas
- Reflector antennas
- Lens antennas
- Patch antennas

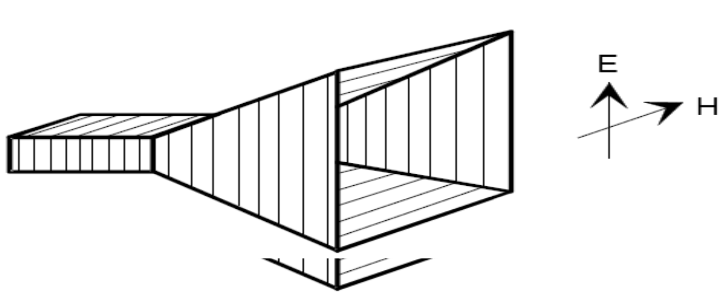


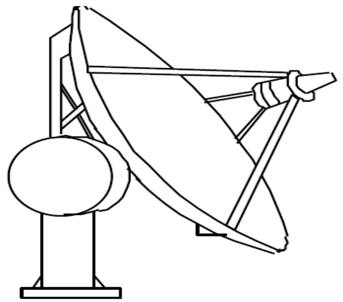
Antennas come in a wide variety of sizes and shapes

Antenna types







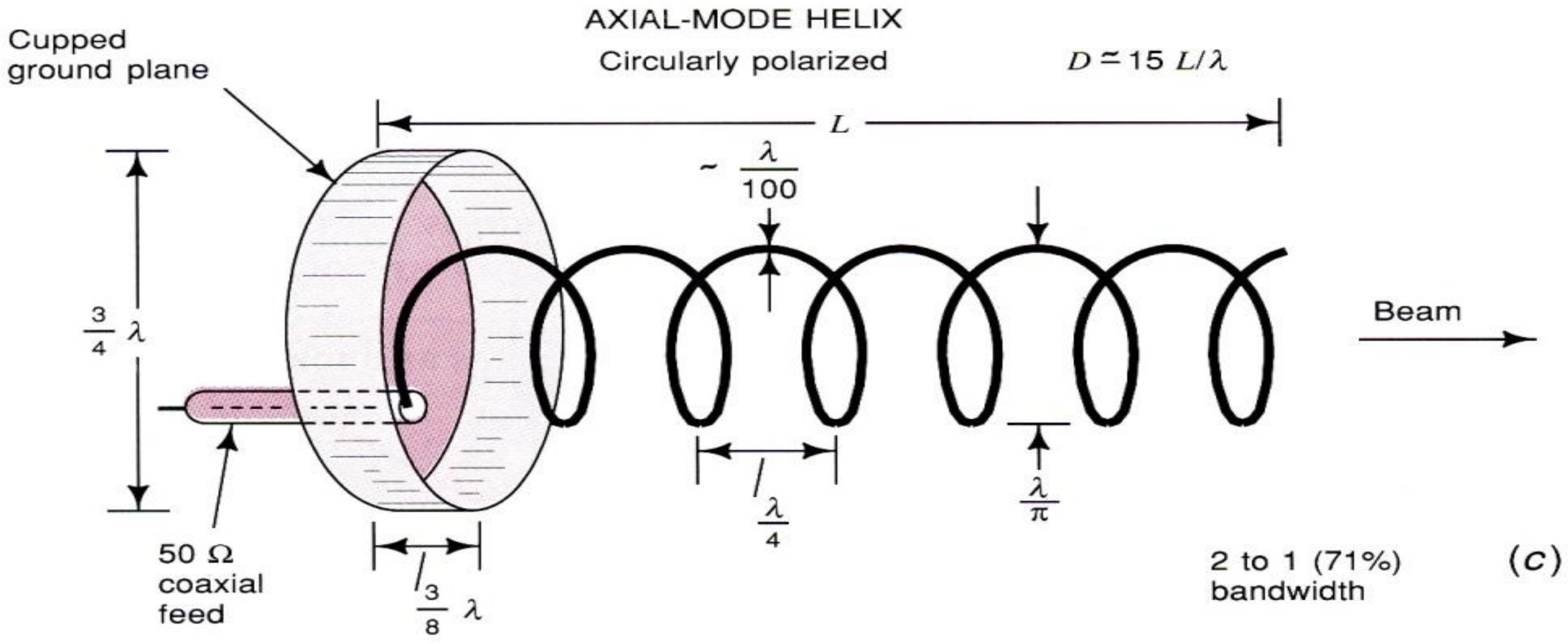


Helical antenna

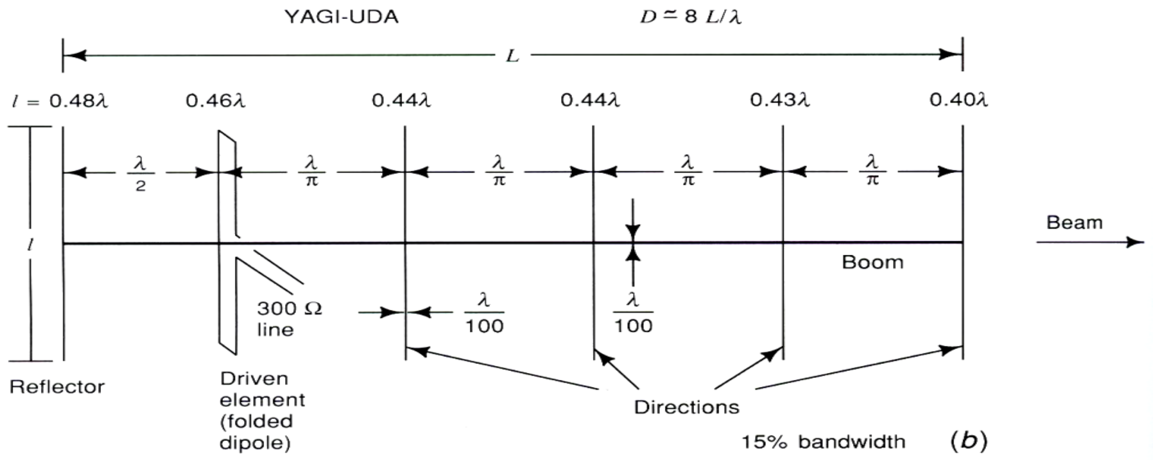
Horn antenna

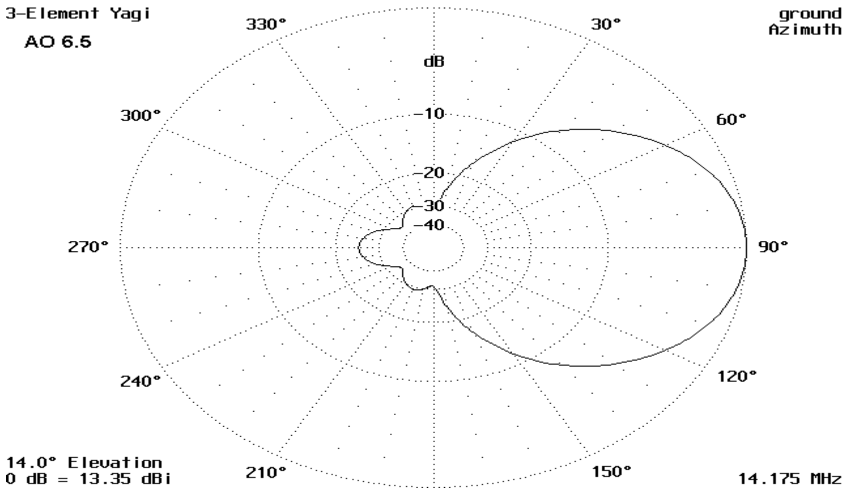
Parabolic reflector antenna

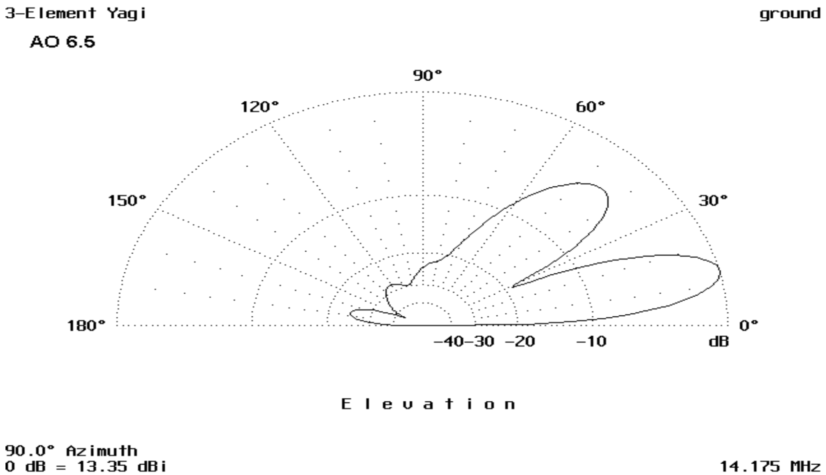
Different Antennas


AXIAL-MODE HELIX
Circularly polarized
$D \simeq 15\ L/\lambda$
Cupped ground plane
L
$\sim \frac{\lambda}{100}$
$\frac{3}{4}\lambda$
Beam
50 Ω coaxial feed
$\frac{\lambda}{4}$
$\frac{\lambda}{\pi}$
$\frac{3}{8}\lambda$
2 to 1 (71%) bandwidth
(c)

Yagi-Uda

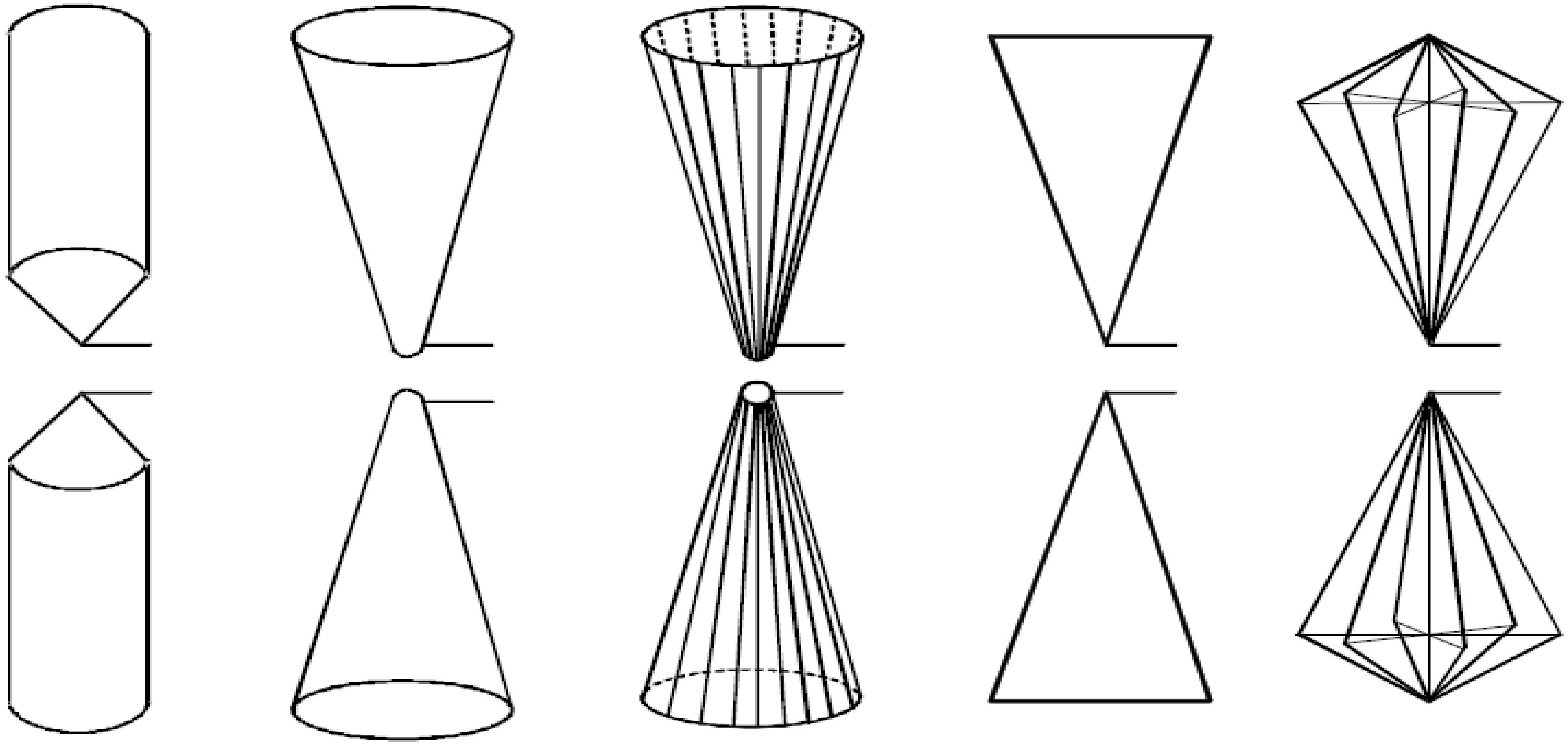






Elements	Gain dBi	Gain dBd
3	7.5	5.5
4	8.5	6.5
5	10	8
6	11.5	9.5
7	12.5	10.5
8	13.5	11.5

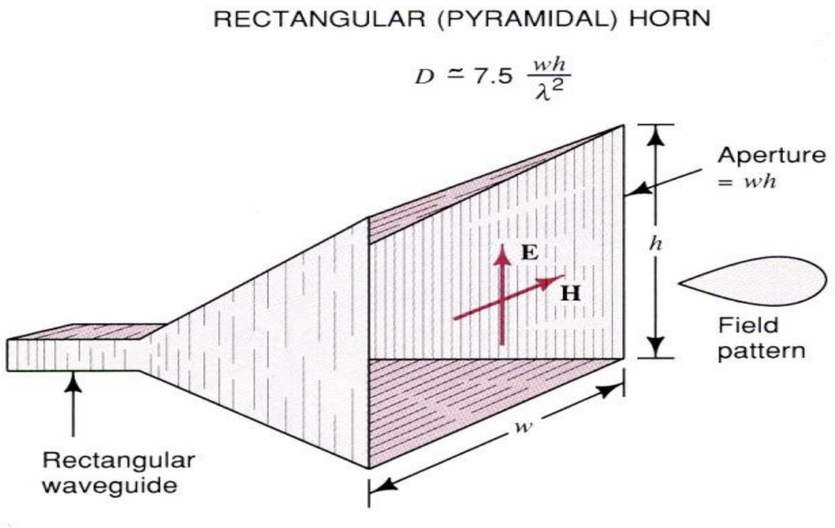
Dipole antennas

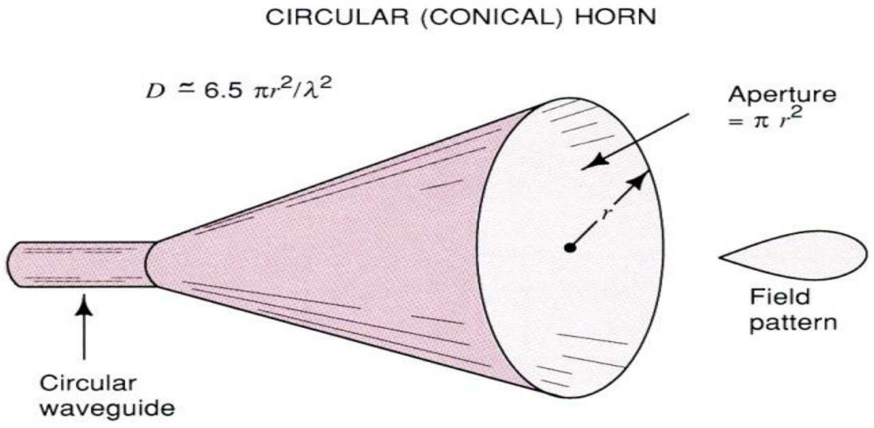


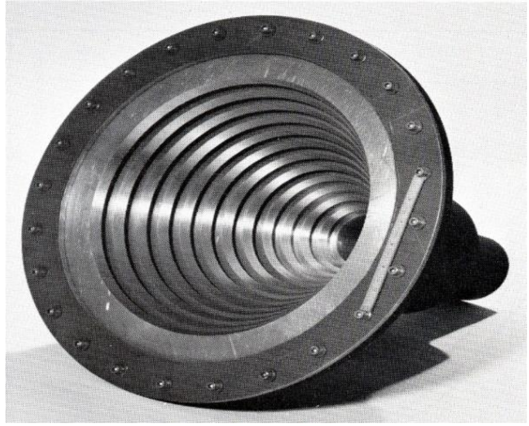
Versions of broadband dipole antennas

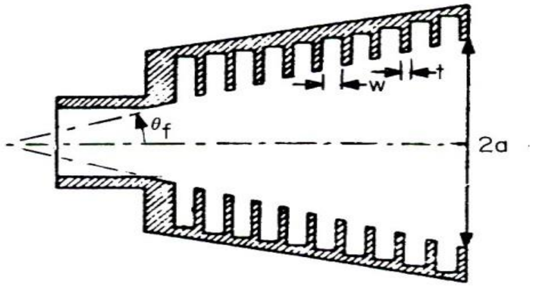
Horn antenna

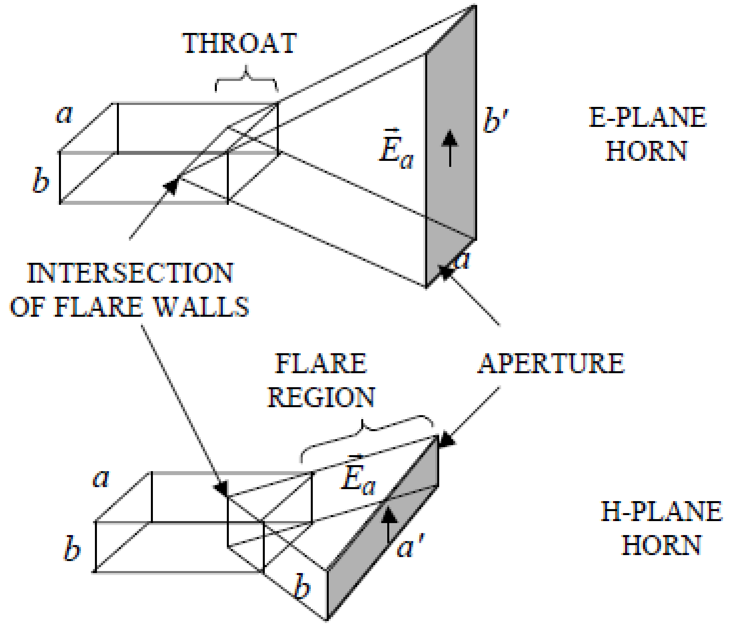
- Rectangular or circular waveguide flared up
- Spherical wave fronts from phase centre
- Flare angle and aperture determine gain
- Aperture antennas derived from waveguide technology (circular, rectangular)
- Can transfer high power (magnetrons, klystrons)
- Above few GHz
- Will be explored inprace during the school










THROAT
a
b
$\vec{E}_a$
b′
E-PLANE HORN
INTERSECTION OF FLARE WALLS
a
APERTURE
FLARE REGION
a
b
$\vec{E}_a$
a′
b
H-PLANE HORN

The aperture dimensions of a pyramidal horn are 12x6 cm and operating at a frequency of 10 GHz. Find the beam width and directivity.

Frequency = 10 GHz

$$\lambda = \frac{3\times10^{8}}{10\times10^{9}} = 3\,cm$$

$$d = 12\,cm \quad and \quad w = 6\,cm$$

$$Beamwidth: \phi_E = 56\frac{\lambda}{d} = 14^{0}$$

$$\phi_H = 67\frac{\lambda}{w} = 33.5^{0}$$

$$power\ gain = \frac{4.5wd}{\lambda^2} = 36 = 15.56dB$$

$$Directivity = \frac{7.5wd}{\lambda^2} = 60$$

Horn Example

Example: An E-plane horn has $R_1 = 20\lambda$ and $a = 0.5\lambda$.

(a) The optimum aperture dimension for maximum directivity

$$b' = \sqrt{2\lambda R_{1E}} = \lambda\sqrt{40} = 6.3\lambda$$

(b) The flare angle for the optimum directivity

$$\tan(\psi/2) = \frac{b'/2}{R_1} = \frac{6.3\lambda/2}{20\lambda} = 0.1575$$

$$\psi/2 = 8.95^\circ$$

$$\psi = 17.9^\circ$$

(c) The optimum directivity is

$$D_{\text{opt}} = 10.2\frac{(0.5\lambda)(6.3\lambda)}{\lambda^2}\left(\frac{1}{1.25}\right) = 25.7 = 14.1\text{ dB}$$

Parabolic conducting reflector Geometry and operation

For a parabolic conducting reflector surface of focal length *f* with a feed at the focus *F*.

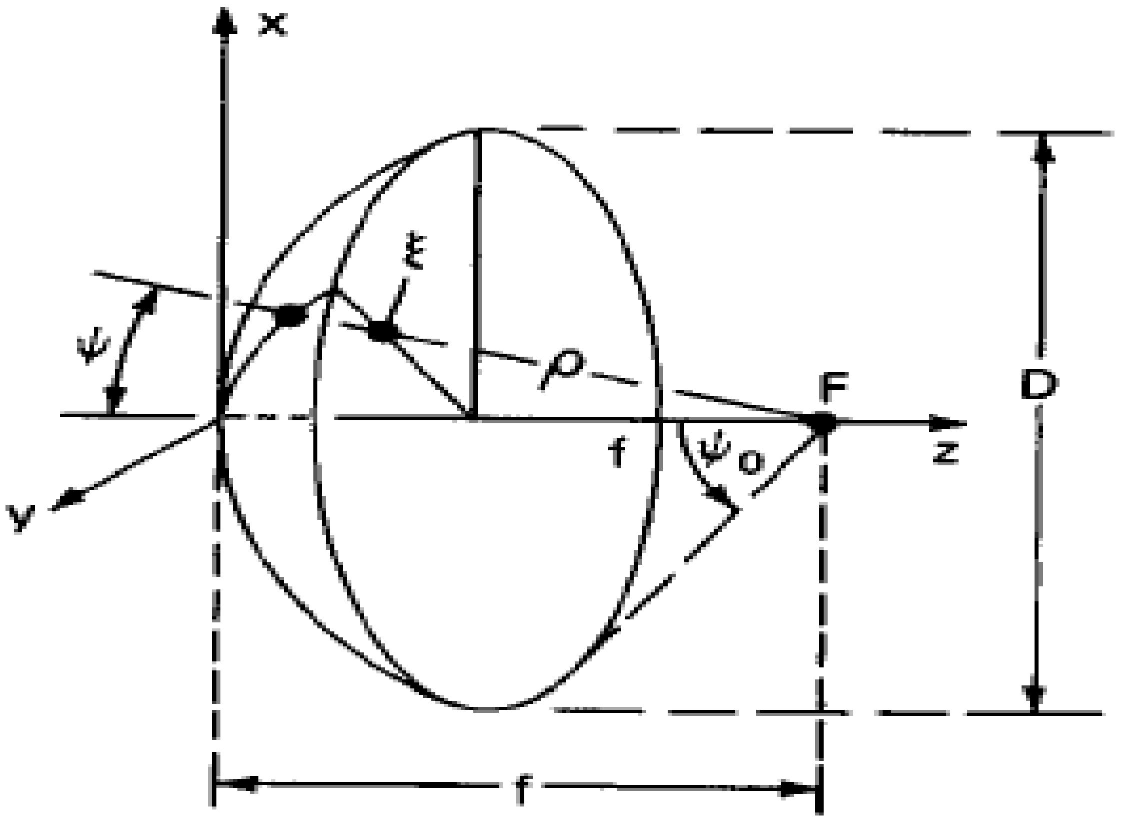
In rect. coordinates

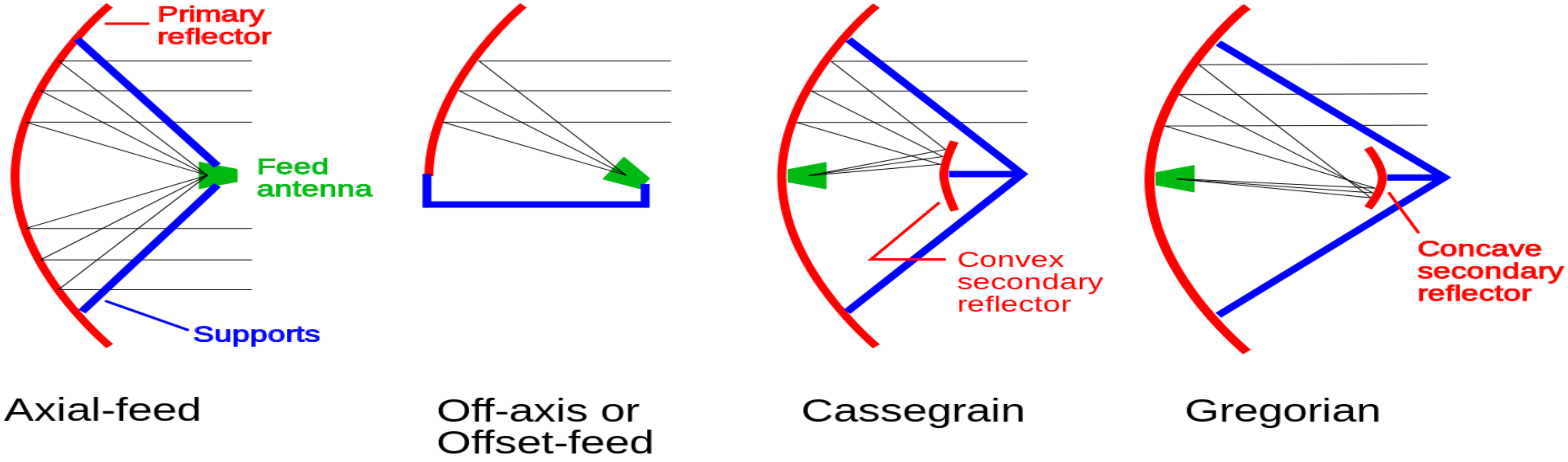
$z = (x^2 + y^2)/4f$

In spherical coordinates

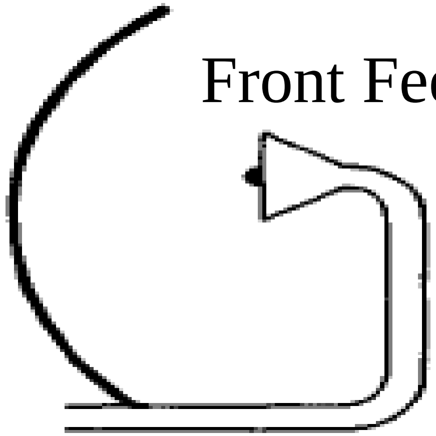
$\rho = f \sec^2 \psi/2$

$\tan \psi_o/2 = D/4f$

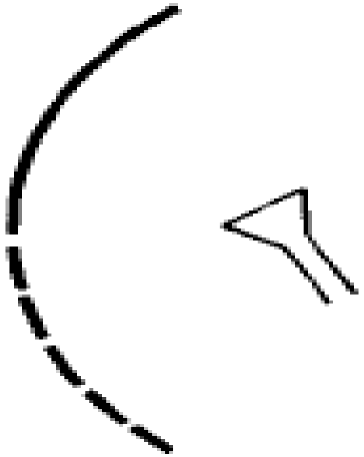



Primary
reflector
Feed
antenna
Supports
Axial-feed
Off-axis or
Offset-feed
Convex
secondary
reflector
Cassegrain
Concave
secondary
reflector
Gregorian

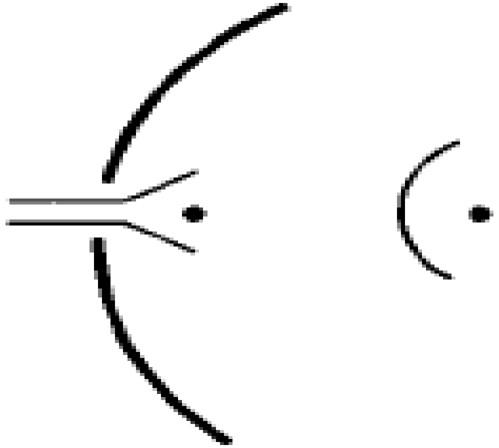
Feeds



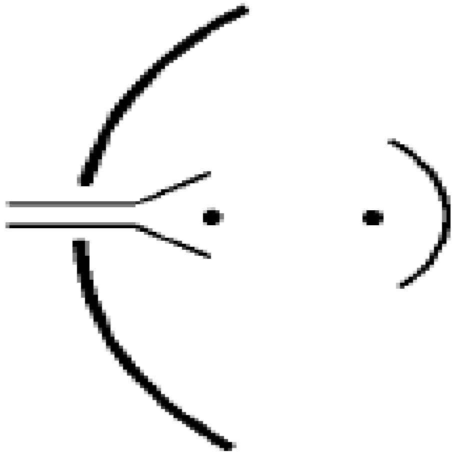
Front Feed



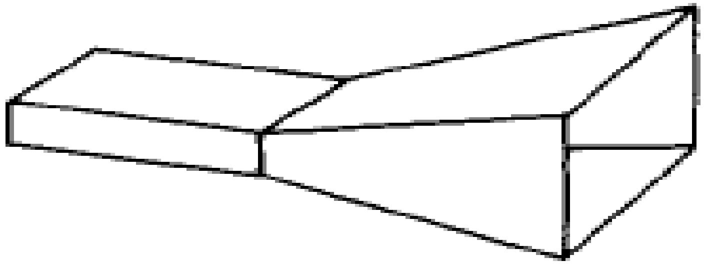
Offset Feed



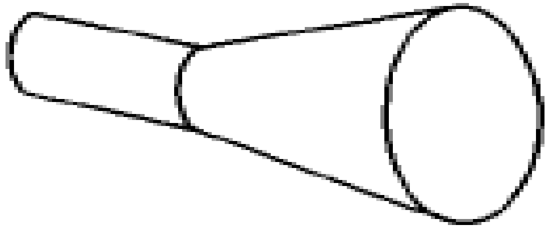
Cassegrain Feed



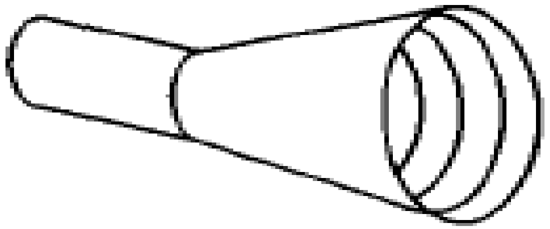
Gregorain Feed



Simple Pyramidal horn



Simple Conical

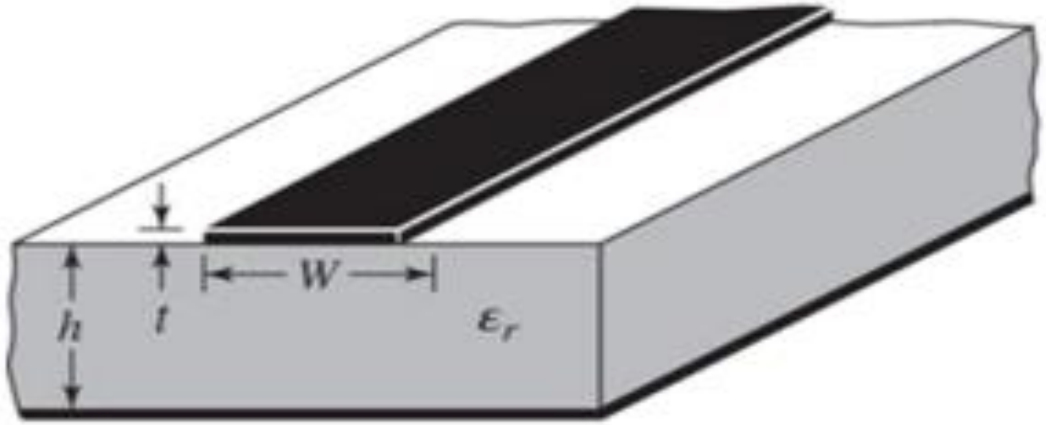


Corrugated Conical Horn

Microstrip Antenna Design

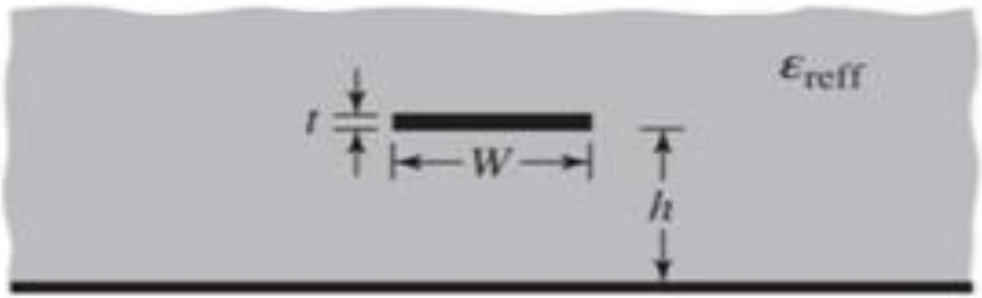
Micro-strip Antenna

- What is Micro-strip Antenna ?
- A Micro-strip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side.
- Invented by Bob Munson in 1972 (but earlier work by Dechamps goes back to1953).



(a) Microstrip line

(b) Electric field lines



(c) Effective dielectric constant

Rectangular Microstrip Feedline formul

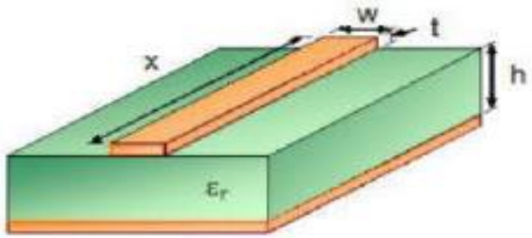
Effective Width and Height

$$W = w + \frac{t}{\pi}\left[\ln\left(\frac{2h}{t}\right) + 1\right]$$

$$H = h - 2t$$

$$\lambda = \frac{c}{f\sqrt{\varepsilon_{eff}}}$$ **Wavelength**

$$\theta = \frac{2\pi}{\lambda}$$ **Phase**



for $\frac{W}{H} < 1$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\frac{H}{W}}} + 0.04\left(1 - \frac{W}{H}\right)^2\right]$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}}\ln\left(\frac{8H}{W} + \frac{W}{4H}\right) \quad \Omega$$

for $\frac{W}{H} \geq 1$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + 12\frac{H}{W}}}$$

$$Z_0 = \frac{120\,\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{W}{H} + 1.393 + \frac{2}{3}\ln\left(\frac{W}{H} + 1.444\right)\right]} \quad \Omega$$

The characteristic impedance of the microstrip may be written as

$$Z_o = \begin{cases} \dfrac{60}{\sqrt{\varepsilon_e}} \ln\left(\dfrac{8d}{W} + \dfrac{W}{4d} \right) & W/d \le 1 \\ \dfrac{120\pi}{\sqrt{\varepsilon_e}\,[W/d + 1.393 + 0.667 \ln(W/d + 1.444)]} & W/d \ge 1 \end{cases}$$

Solving this equation for W/d yields

$$\frac{W}{d} = \begin{cases} \dfrac{8e^{A}}{e^{2A} - 2} & W/d \le 2 \\ \dfrac{2}{\pi}\left[B - 1 - \ln(2B-1) + \dfrac{\varepsilon_r - 1}{2\varepsilon_r}\left\{ \ln(B-1) + 0.39 - \dfrac{0.61}{\varepsilon_r} \right\} \right] & W/d \ge 2 \end{cases}$$

where

$$A = \frac{Z_o}{60}\sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1}\left(0.23 + \frac{0.11}{\varepsilon_r} \right)$$

$$B = \frac{377\pi}{2 Z_o \sqrt{\varepsilon_r}}$$

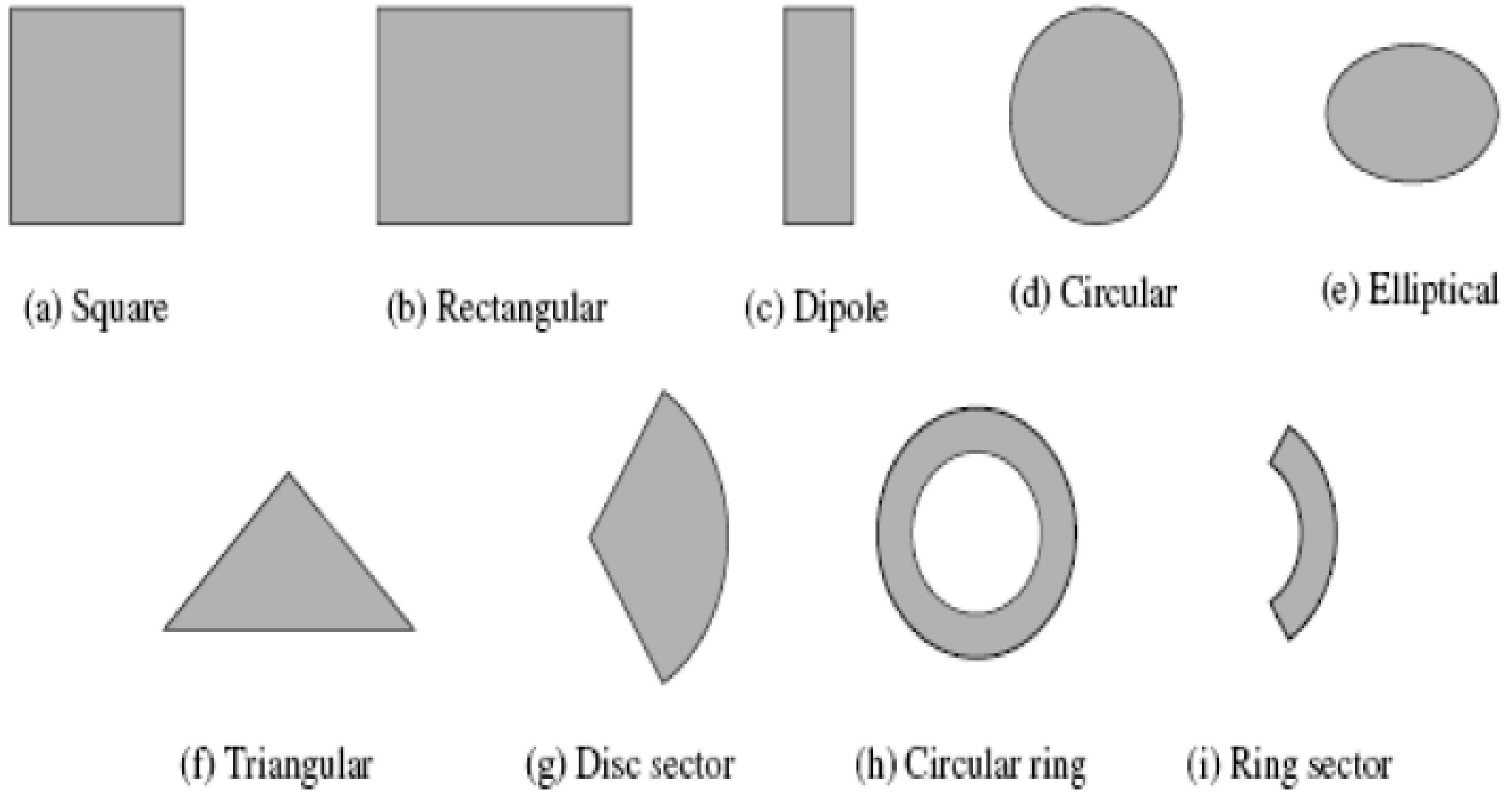
Microstrip Antenna Applications

- Used in mobile satellite communication system.
- Direct broad cast telivision(DBS).
- Wire less LAN’S.
- Feed elements in coaxial system
- GPS system.
- Missiles and telementry
- UHF Patch Antennas for Space

Why we use Microstrip Patch Antennas ?

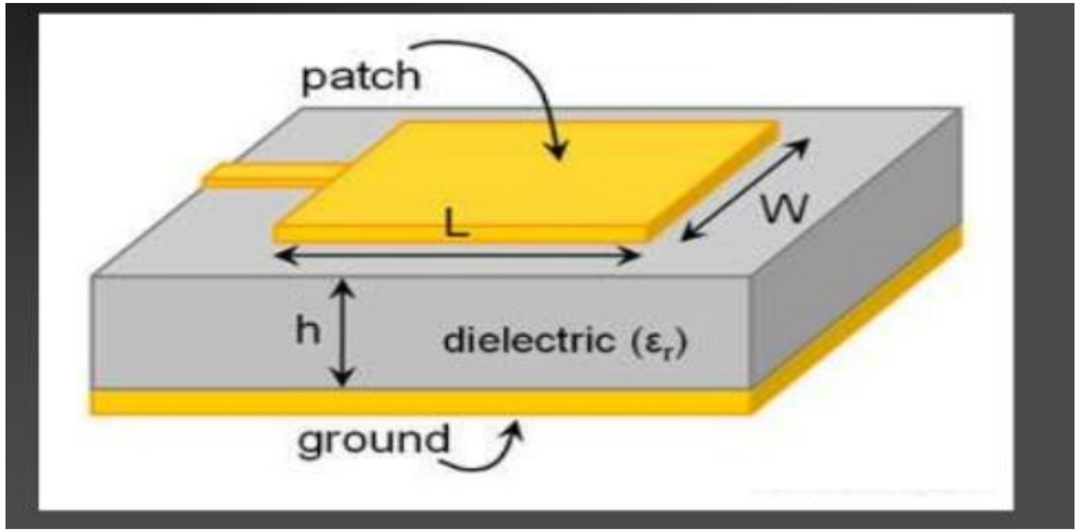
- Flat surface makes them ideal for mounting on airplane
- Impedance matching fairly simple
- Microstrip patch antennas have a very high antenna quality factor(Q).
- Q represents the losses associated with the antenna and a large Q leads to narrow bandwidth and low efficiency.
- Q can be reduced by increasing the thickness of the dielectric substrate. But as the thickness increases, an increasing fraction of the total power delivered by the source goes into a surface wave
- UHF Patch antenna
- UHF Patch Antennas for Space
- These antennas are capable of supporting high data rates to at least 10 Watts of transmitted power.

Shapes of Microstrip Patch



Feeding Techniques

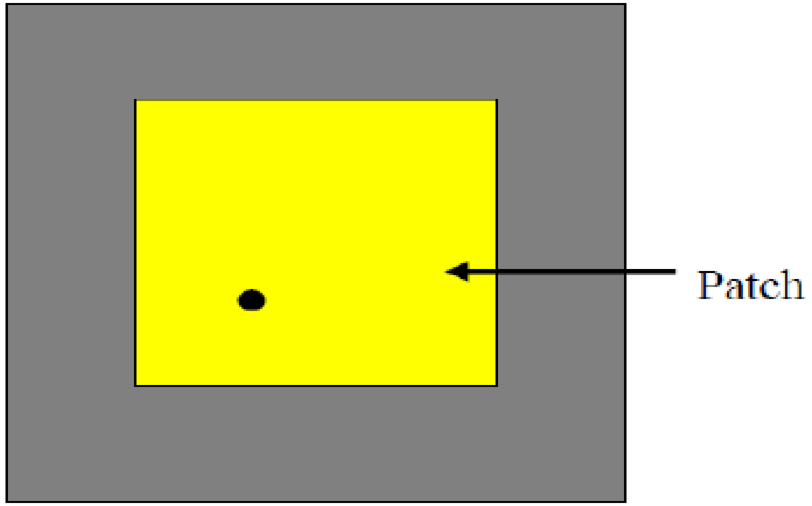
- Coaxial feed
- Microstrip feed
- Proximity coupled microstrip feed
- Aperture coupled microstrip feed
- Coplanar wave guide
- Line Feed



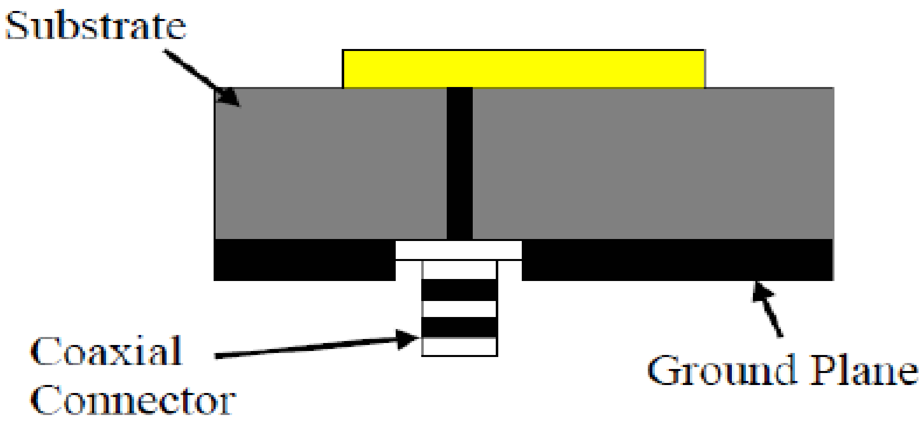
1-Microstrip Line Feed : In this type of feed technique, a conducting strip is connected directly to the edge of the microstrip patch. This kind of feed arrangement has the advantage that the feed can be etched on the same substrate to provide a planar structure.

2-Coaxial Feed

- The Coaxial feed or probe feed is a very common technique used for feeding Microstrip patch antennas.
- The main advantage of this type of feeding scheme is that the feed can be placed at any desired location inside the patch in order to match with its input impedance.
- This feed method is easy to fabricate and has low spurious radiation.
- However, its major disadvantage is that it Coaxia Ground Plane Connector Substrate Patch provides narrow bandwidth and is difficult to model since a hole has to be drilled in the substrate . and the connector protrudes outside the ground plane, thus not making it completely planar for thick substrates .



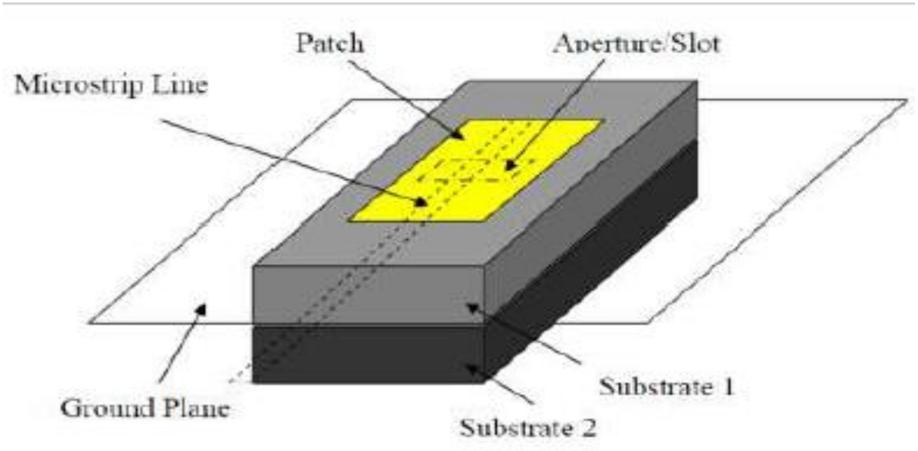
Probe fed Rectangular Microstrip Patch Antenna from top



Probe fed Rectangular Microstrip Patch Antenna from side view

3-Aperture Coupled Feed

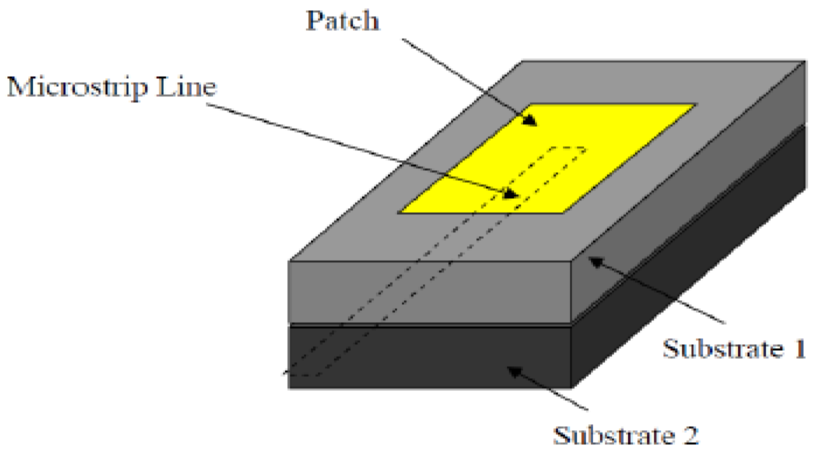
- In this type of feed technique, the radiating patch and the microstrip feed line are separated by the ground plane .
- Coupling between the patch and the feed line is made through a slot or an aperture in the ground plane.
- The coupling aperture is usually centered under the patch, leading to lower cross polarization due to symmetry of the configuration.
- The amount of coupling from the feed line to the patch is determined by the shape, size and location of the aperture.



Aperture-coupled feed

4-Proximity Coupled Feed

- This type of feed technique is also called as “the electromagnetic coupling scheme” .
- The main advantage of this feed technique is that it eliminates spurious feed radiation and provides very high bandwidth due to overall increase in the thickness of the microstrip patch antenna.
- This scheme also provides choices between two different dielectric media, one for the patch and one for the feed line to optimize the individual performances.
- Matching can be achieved by controlling the length of the feed line and the width-to-line ratio of the patch.
- The major disadvantage of this feed scheme is that it is difficult to fabricate because of the two dielectric layers which need proper alignment.
- Also, there is an increase in the overall thickness of the antenna.



Proximity-coupled Feed

Advantages

- Low fabrication cost, hence can be manufactured in large
- quantities.
- Easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.
- Supports both, linear as well as circular polarization.
- Low cost , Less size , Low Mass .
- Mechanically robust when mounted on rigid surfaces.
- High Performance
- Light weight and low volume.

Disadvantages

- Narrow bandwidth associated with tolerence problem
- Lower Gain(Nearly 6db) .
- Large ohmic losses in feed structure of arrays.
- Excitation of surface waves .
- Most microstrip antennas radiate into half-space .
- Relatively low efficiency (due to dielectric and conductor losses) .
- relatively high level of cross polarization radiation
- Spurious feed radiation (surface waves, strips, etc.)
- Inherently low impedance bandwidth.
- Low efficiency .
- Extraneous radiation from feeds and junctions .
- Low power handling capacity.

Remedies

- Low power and low gain can overcome by arrays configuration.
- Surface wave associated limitations such as poor efficiency,increased mutual coupling, reduced gain and radiation pattern can overcome.
- The band width can increase up to 60% by using some special techniques.
- In addition, as the substrate thickness increases, the radiation Q of the antenna decreases.
- Thus, impedance bandwidth increases with increasing substrate thickness.

Optimizing the Substrate Properties for Increased Bandwidth

The easiest way to increase the bandwidth of an MSA is to :

1) Print the antenna on a thicker substrate.

- However, thick substrates tend to trap surface wave modes , especially if the dielectric constant of the substrate is high .
- Finally if the substrate is very thick, radiating modes higher than the fundamental will be excited.

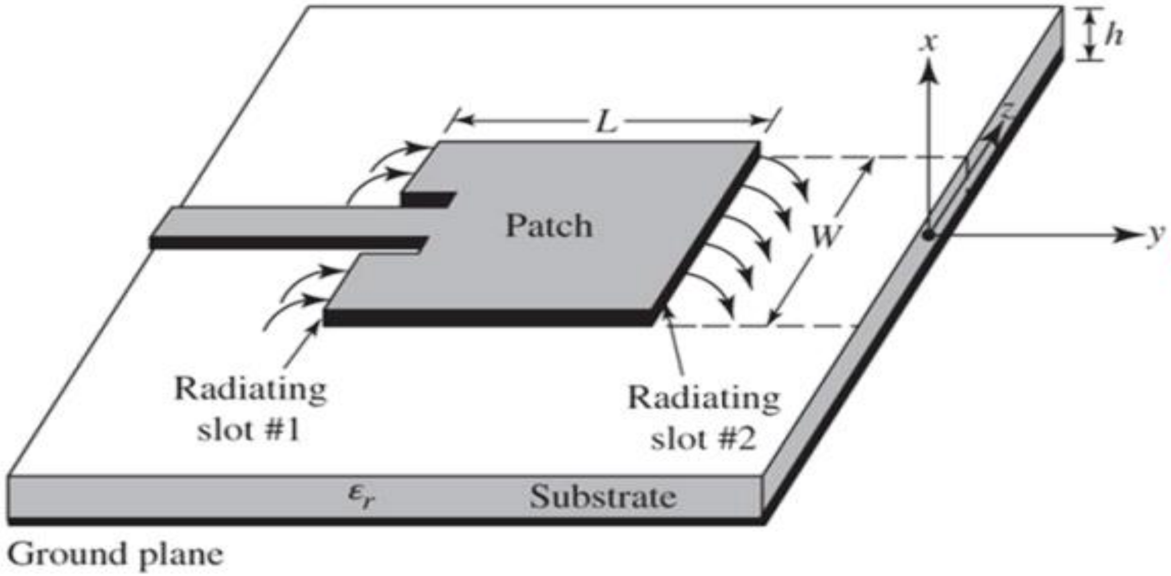
2) Decrease the dielectric constant of the substrate.

- However, this has detrimental effects on antenna size reduction since the resonant length of an MSA is shorter for higher substrate dielectric constant..
- In addition, the directivity of the MSA depends on the dielectric constant of the substrate.

3) Stack two patches on top of each other separated by a dielectric substrate or spacers.

- The application involved two identical circular patches stacked on top of each other. The lower patch was fed using a coaxial probe feed, and the top patch was electromagnetically coupled to the lower one .

Rectangular Microstrip Antenna



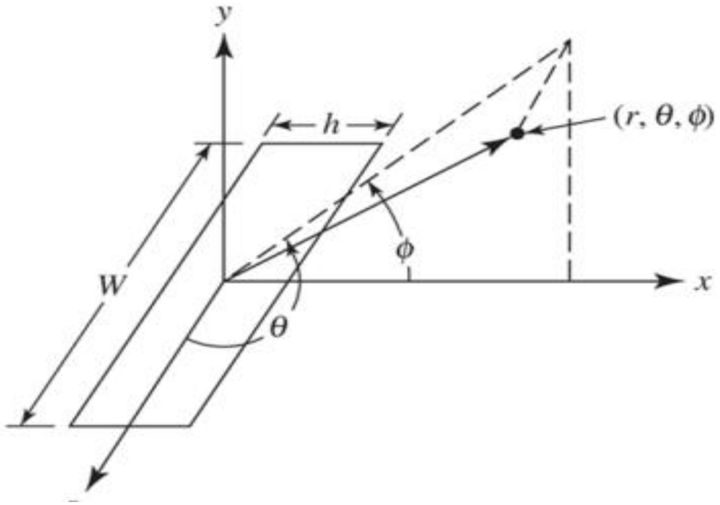
$$\frac{\lambda_0}{3} < L < \frac{\lambda_0}{2}$$

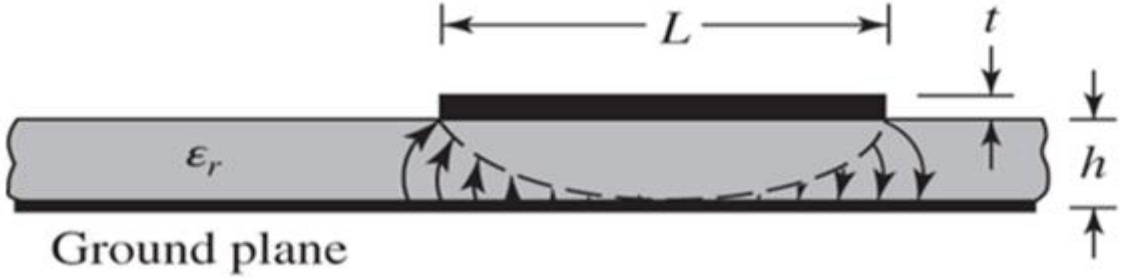
$$2.2 \le \epsilon_r \le 12$$

W is tuned to get desired impedance

- Easy to fabricate
- Simple to match
- Low spurious radiation
- Narrow bandwidth
- Good for low h

Coordinate System For Each Radiating Slot





$$t \ll \lambda_0$$

$$h \ll \lambda_0$$

$$(0.003\lambda_0 \le h \le 0.05\lambda_0)$$

Design of MSA patch length and width

Step 1: Calculation of the Width (W) -

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r + 1)}{2}}}$$

Step 2: Calculation of the Effective Dielectric Constant. This is based on the height, dielectric constant of the dielectric and the calculated width of the patch antenna.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}}$$

Step 3: Calculation of the Effective length

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{eff}}}$$

Length of Patch (L) $= L_{eff} - 2\Delta L$

Length of Substrate $(L_g) = 6h + L$

Width of Substrate$(W_g) = 6h + W$

Step 4: Calculation of the length extension ΔL

$$\Delta L = 0.412h\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

Step 5: Calculation of actual length of the patch

$$L = L_{eff} - 2\Delta L$$

Where the following parameters are used

f_0 is the Resonance Frequency

W is the Width of the Patch

L is the Length of the Patch

h is the thickness

ε_r is the relative Permittivity of the dielectric substrate

c is the Speed of light: 3×10^8

Rectangular Patch - Fields

$$f(\theta,\phi) = \frac{\sin\left[\frac{kW}{2}\sin(\theta)\sin(\phi)\right]}{\frac{kW}{2}\sin(\theta)\sin(\phi)}\cos\left(\frac{kL}{2}\sin(\theta)\cos(\phi)\right)$$

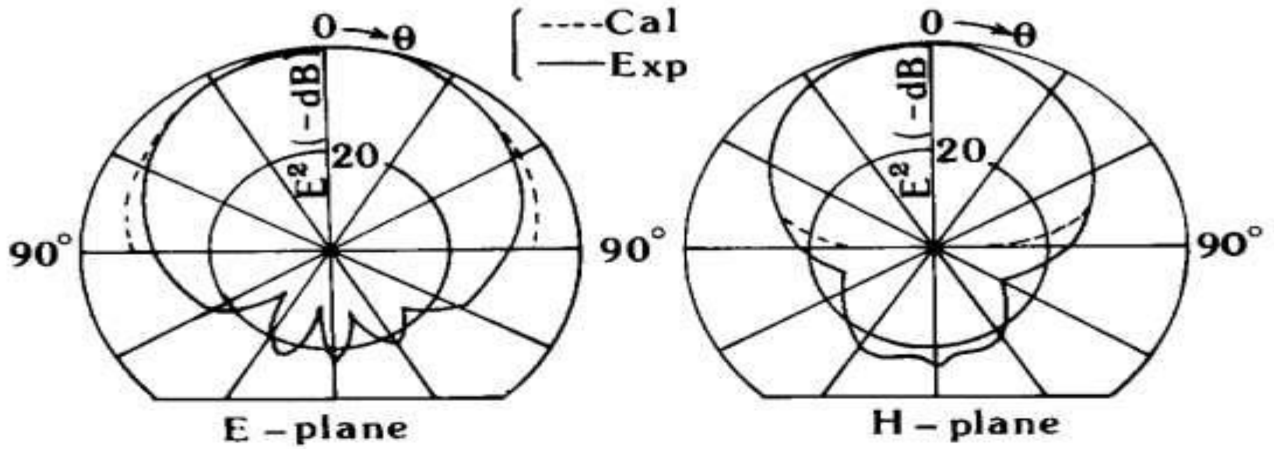
$$F_E(\theta) = \cos\left(\frac{kL}{2}\sin(\theta)\right), \qquad \phi = 0^\circ$$

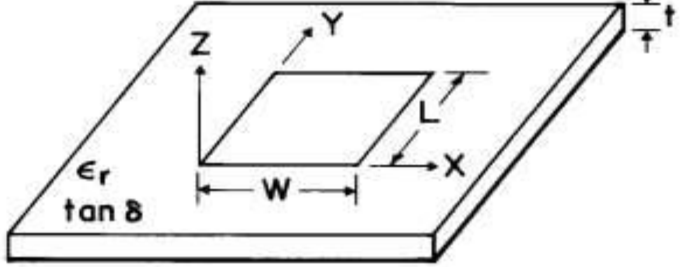
$$F_H(\theta) = \cos(\theta)\frac{\sin\left(\frac{kW}{2}\sin(\theta)\right)}{\frac{kW}{2}\sin(\theta)}, \qquad \phi = 90^\circ$$

An approximate expression of the bandwidth for VSWR ≤ 2, $|\Gamma| \leq \frac{1}{3}$,

$$\text{BW} = 3.771\left[\frac{\epsilon_r - 1}{(\epsilon_r)^2}\right]\frac{h}{\lambda_0}\left(\frac{W}{L}\right)$$

Radiation patterns of a rectangular microstrip patch antenna





Example

Design a rectangular microstrip antenna using a substrate (RT/duroid 5880) with dielectric constant of 2.2, $h = 0.1588$ cm (0.0625 inches) so as to resonate at 10 GHz.

Solution: Using (14-6), the width W of the patch is

$$W = \frac{30}{2(10)}\sqrt{\frac{2}{2.2+1}} = 1.186 \text{ cm } (0.467 \text{ in})$$

The effective dielectric constant of the patch is found using (14-1), or

$$\epsilon_{\text{reff}} = \frac{2.2+1}{2} + \frac{2.2-1}{2}\left(1 + 12\frac{0.1588}{1.186}\right)^{-1/2} = 1.972$$

The extended incremental length of the patch ΔL is, using (14-2)

$$\Delta L = 0.1588(0.412)\frac{(1.972+0.3)\left(\dfrac{1.186}{0.1588}+0.264\right)}{(1.972-0.258)\left(\dfrac{1.186}{0.1588}+0.8\right)}$$

$$= 0.081 \text{ cm } (0.032 \text{ in})$$

The actual length L of the patch is found using (14-3), or

$$L = \frac{\lambda}{2} - 2\Delta L = \frac{30}{2(10)\sqrt{1.972}} - 2(0.081) = 0.906 \text{ cm } (0.357 \text{ in})$$

Finally the effective length is

$$L_e = L + 2\Delta L = \frac{\lambda}{2} = 1.068 \text{ cm } (0.421 \text{ in})$$

An experimental rectangular patch based on this design was built and tested. It is probe fed from underneath by a coaxial line and is shown in Figure 14.8(a). Its principal E- and H-plane patterns are displayed in Figure 14.19(a,b).

Örnek: Design microstrip antenna fo=1.85GHz

$$W = \frac{c}{2f_o\sqrt{\frac{(\varepsilon_r+1)}{2}}}$$

c= 3x 10^8 m/sec
ε_r =11.9
fo= 1.85 GHz
Therefore,
W=31.9 mm =0.0319m

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}}$$

ε_r =11.9
h = 1.59 mm
W= 31.9 mm
Therefore ,
ε_{reff} is euqal to 10.7611

$$\Delta L = 0.412h\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)}$$

ε_r =11.9
h=1.59 mm
W = 31.9 mm
Therefore ,
The value of ΔL is 6.72x10^{-1} mm

The effective length of the patch L_{eff} now becomes:

$$L_{eff} = L + 2\Delta L$$

For a given resonance frequency f_o, the effective length is given by as:

$$L_{eff} = \frac{c}{2f_o\sqrt{\varepsilon_{reff}}}$$

ε_{reff} = 10.7611

therefore , the value of L_{eff} is 24.7 mm & value of L will be 23.36 mm.

Örnek: Design microstrip antenna fo=3GHz

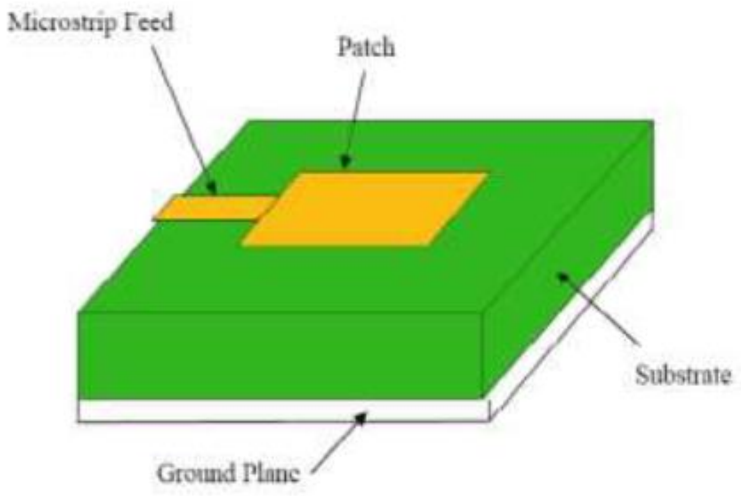


Figure -Structure of the patch

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad \textbf{(1)}$$

$$= \frac{(3\times10^8)}{2(3G)}\sqrt{\frac{2}{(2.33)+1}}$$

$$= 38.749 \text{ mm}$$

$$= 0.03874 \text{ m}$$

$$\varepsilon_{reff} = \left(\frac{\varepsilon_r+1}{2}\right) + \left(\frac{\varepsilon_r-1}{2}\right)\left[1+12\,\frac{h}{W}\right]^{-\frac{1}{2}}$$

$$= \left[\frac{(2.33)+1}{2}\right] + \left[\frac{(2.33)-1}{2}\right]\times$$

$$\left[1+12\,\frac{(0.508\times10^{-3})}{(38.749\times10^{-3})}\right]^{-\frac{1}{2}} = 1.665 + 0.665(1.1573)^{-\frac{1}{2}} = 2.2832$$

λ=0.1m=100mm
GND dimension: λ

$$\Delta L = 0.412h\left[\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)}\right]$$

$$= 0.412(0.508\times10^{-3})\times$$

$$\left\{\frac{[(2.2832)+0.3]\left[\frac{(38.749\times10^{-3})}{(0.508\times10^{-3})}+0.264\right]}{[(2.2832)-0.258]\left[\frac{(38.749\times10^{-3})}{(0.508\times10^{-3})}+0.8\right]}\right\}$$

$$= \frac{0.04138}{156.0975} = 0.2651 \text{ mm}$$

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{reff}}} = \frac{(3\times10^8)}{(3G)\sqrt{(2.2832)}} = 0.0662$$

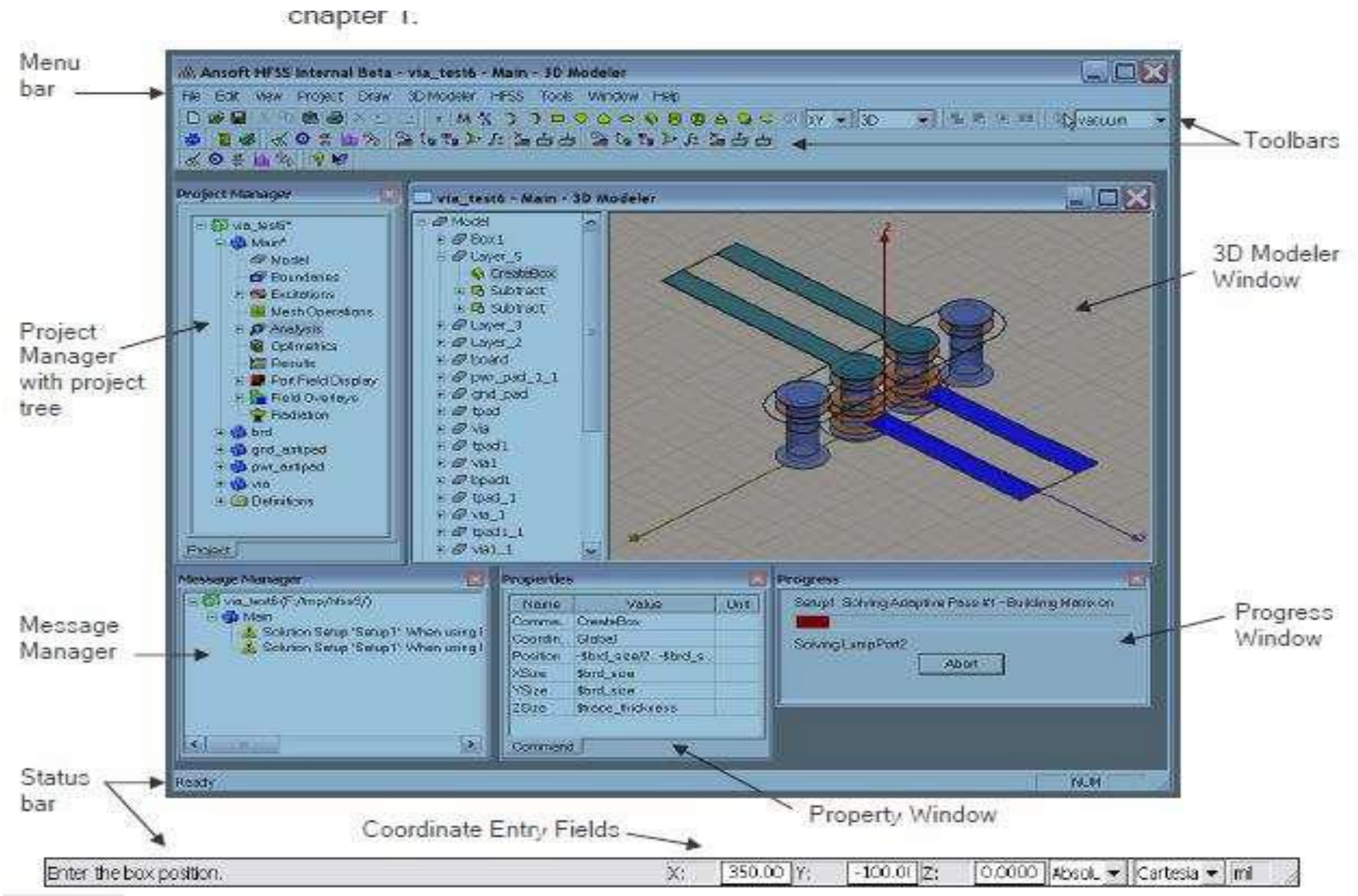
$$L = \frac{\lambda_g}{2} - 2\Delta L = \frac{(0.0662)}{2} - 2(0.2651\times10^{-3})$$

$$= 0.03257 = 32.57 \text{ mm} \approx 33\,mm$$

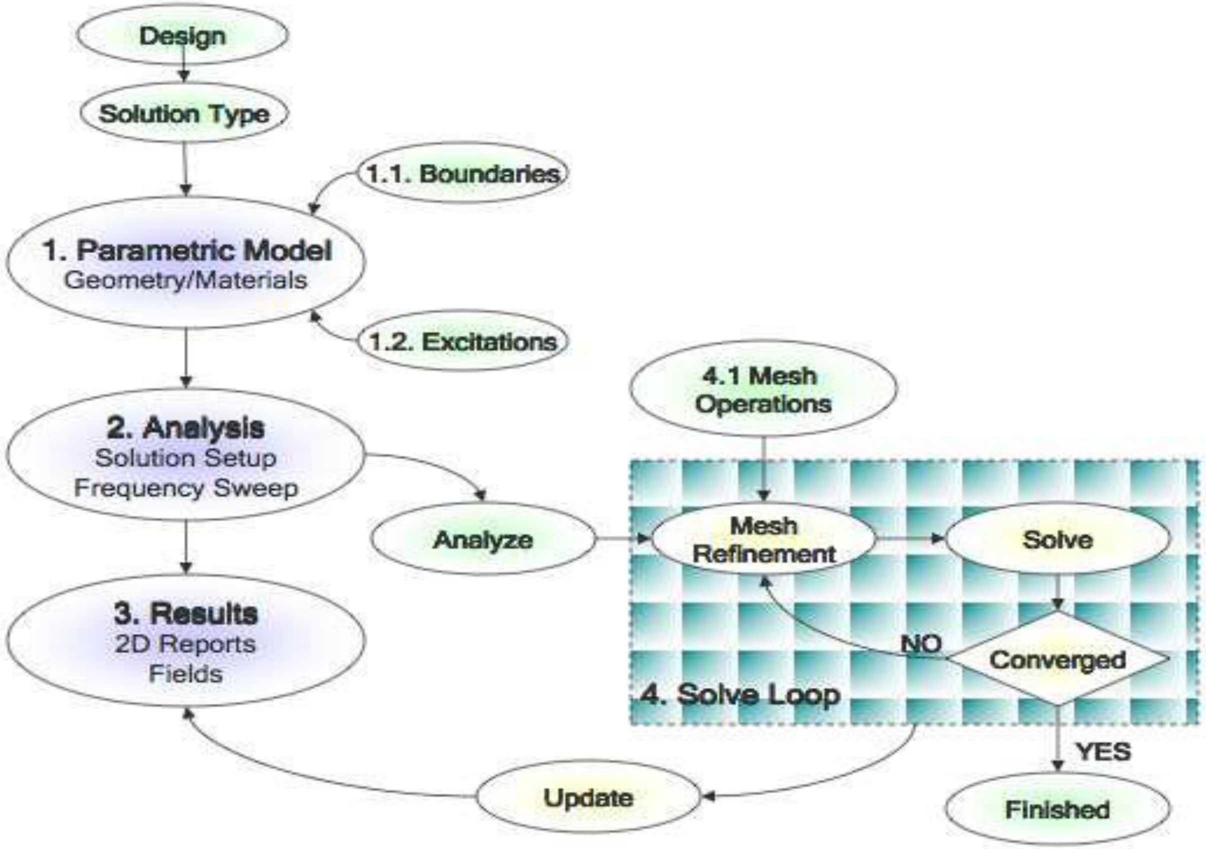
Designing Microstrip Patch Antenna by Using HFSS

Designing the Microstrip patch

- HFSS stands for high frequency structure simulator
- ANSYS HFSS software is the industry standard for simulating 3-D full wave electromagnetic fields.



Designing the Microstrip patch



Design specification of rectangular patch antenna

3D model

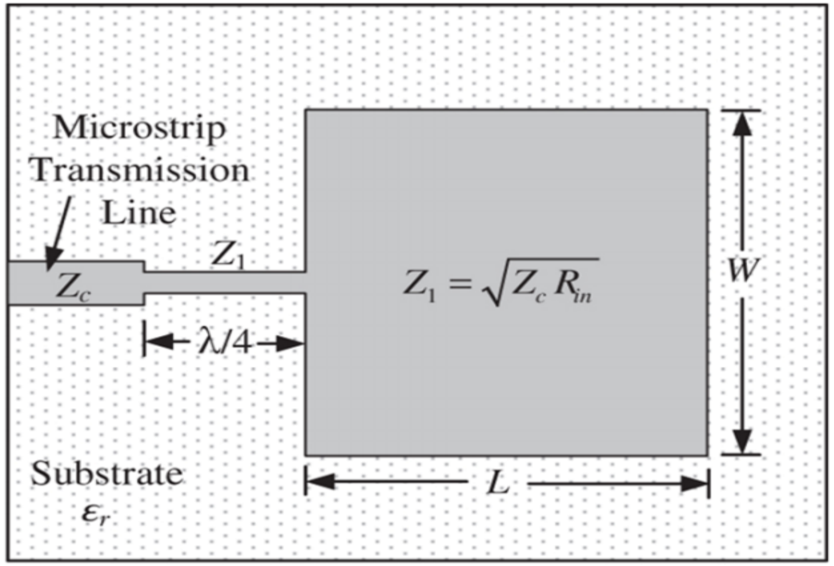
- Ground: Wg,Lg
- Substrate: Wg, Lg, h, ε_r
- Microstrip line(feed): Wf, Lf
- Radiated Patch: W, L
- Lumped Port: 1mm
- Radiation measure wall: R

Tüm uzunluklar dalga boyunun katsayı çarpımı ile ifade edilir.

Assigning boundary: Perfect E

Assigning excitation: Lumped Port, Radiation

Matching Techniques



λ/4 impedance transformer

Analysis of patch antenna

Analysis setup

- solution freq
- max number of passes
- max Delta S per pass

Freq sweep

- starting freq
- attenuating freq
- number of counting

Analyze

Örnek: Design microstrip antenna
fo=2.4GHz, εr=4.4, h=1.5mm

$\lambda = \frac{c}{f} = \frac{3x10^8}{2.4x10^9}$=0.125m=125mm

$W = \frac{\lambda/2}{2\sqrt{\frac{\varepsilon_r+1}{2}}}$ = 0.038m=38mm

$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+\frac{12h}{W}\right]^{-\frac{1}{2}}$= 4.24

$L_{eff} = \frac{\lambda/2}{2\sqrt{\varepsilon_{eff}}}$ = 30.34mm

$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)}$=0.69mm

Length of Ground Plane, L_g=λ

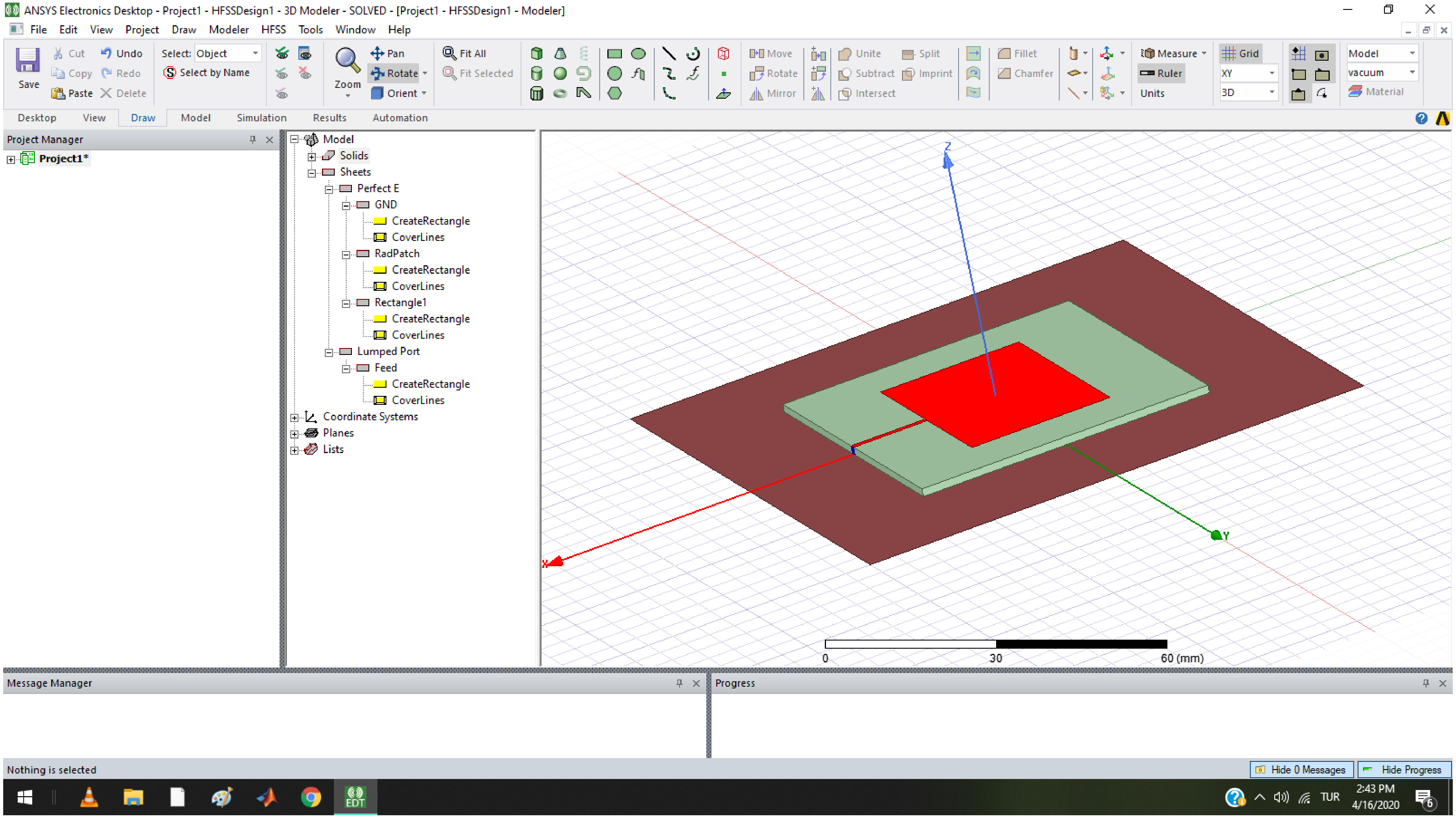
Width of Ground Plane, W_g=λ

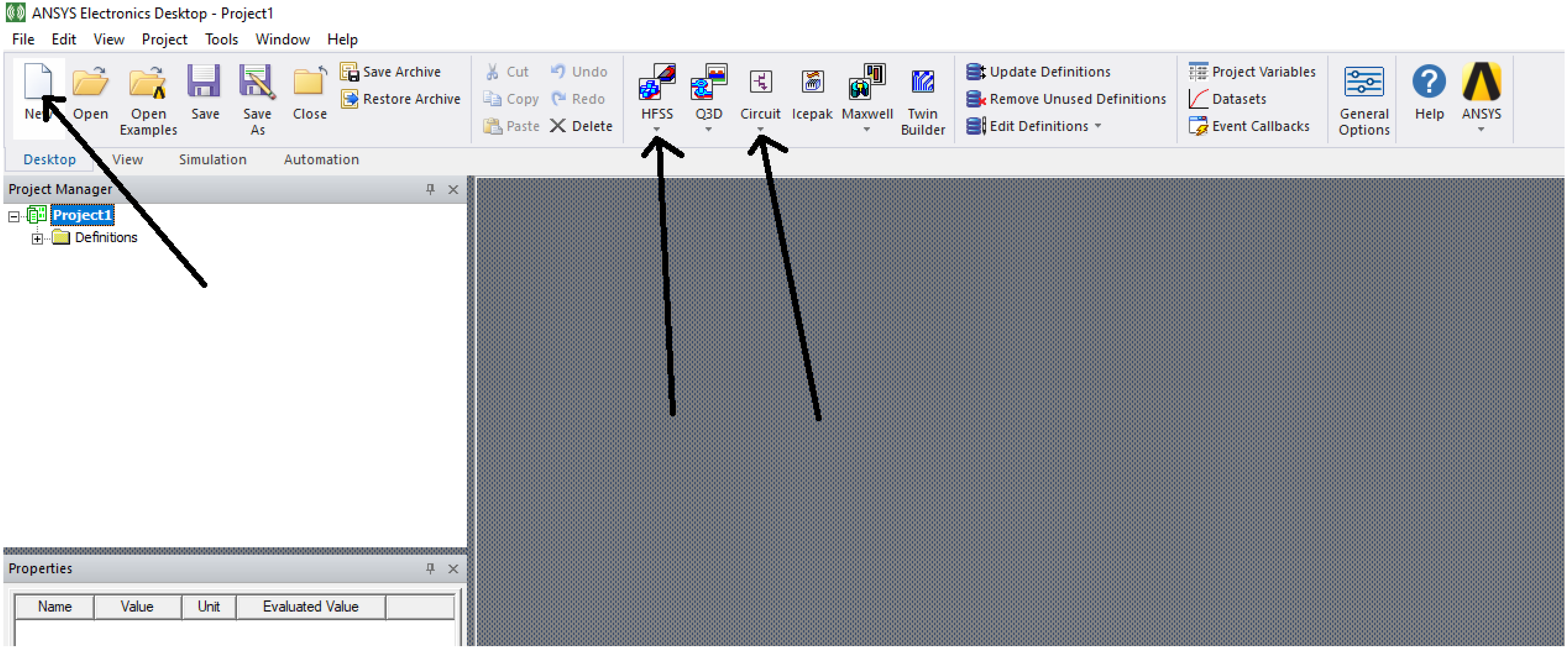
$L = L_{eff}$-2$\Delta L = 29mm$

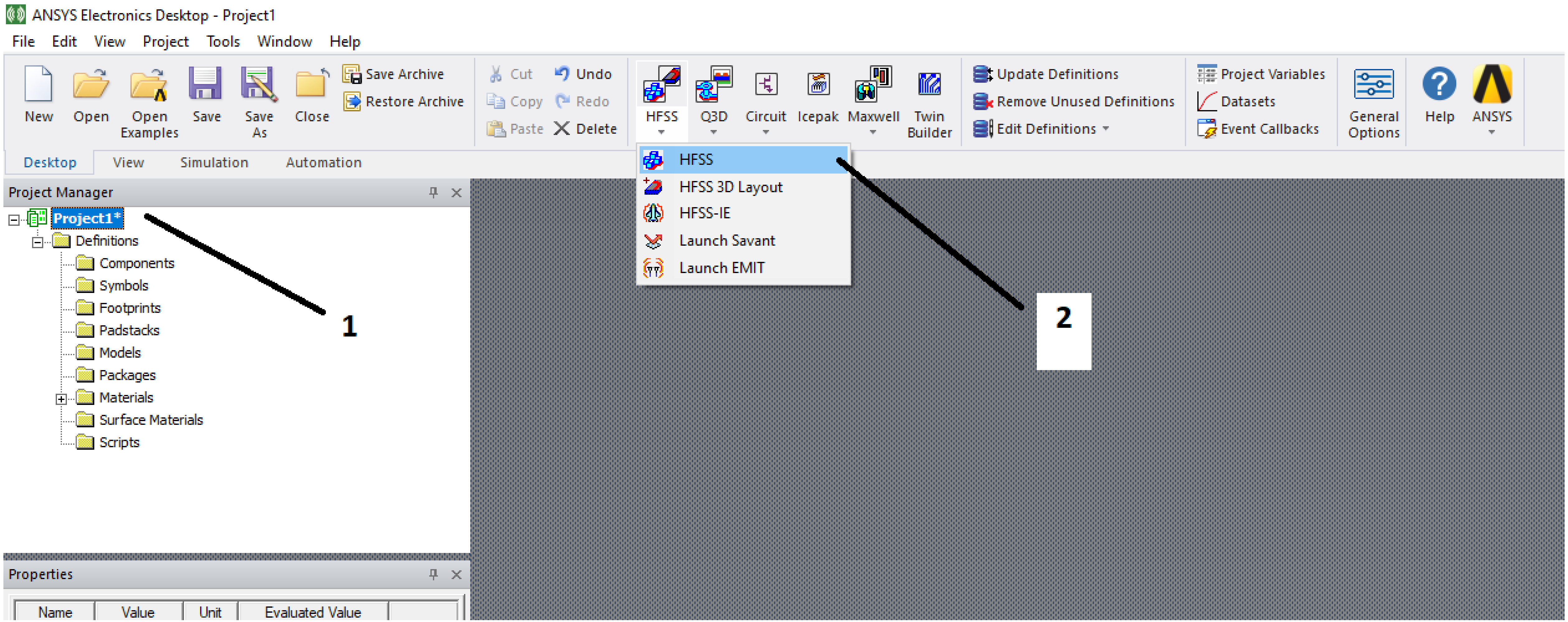
$\lambda_g = \frac{\lambda}{2\sqrt{\varepsilon_{eff}}}$=60mm

Length of Substrate, L_s=L+λg/2=59mmm

Width of Substrate, W_s=W+λg/4=68mm


ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]
File Edit View Project Draw Modeler HFSS Tools Window Help
Desktop View Draw Model Simulation Results Automation
Project Manager
Project1*
Model
Solids
Sheets
Perfect E
GND
CreateRectangle
CoverLines
RadPatch
CreateRectangle
CoverLines
Rectangle1
CreateRectangle
CoverLines
Lumped Port
Feed
CreateRectangle
CoverLines
Coordinate Systems
Planes
Lists
0
30
60 (mm)
Message Manager
Progress
Nothing is selected
Hide 0 Messages
Hide Progress
2:43 PM
4/16/2020


ANSYS Electronics Desktop - Project1
File Edit View Project Tools Window Help
New
Open
Open Examples
Save
Save As
Close
Save Archive
Restore Archive
Cut
Copy
Paste
Undo
Redo
Delete
HFSS
Q3D
Circuit
Icepak
Maxwell
Twin Builder
Update Definitions
Remove Unused Definitions
Edit Definitions
Project Variables
Datasets
Event Callbacks
General Options
Help
ANSYS
Desktop
View
Simulation
Automation
Project Manager
Project1
Definitions
Properties
Name
Value
Unit
Evaluated Value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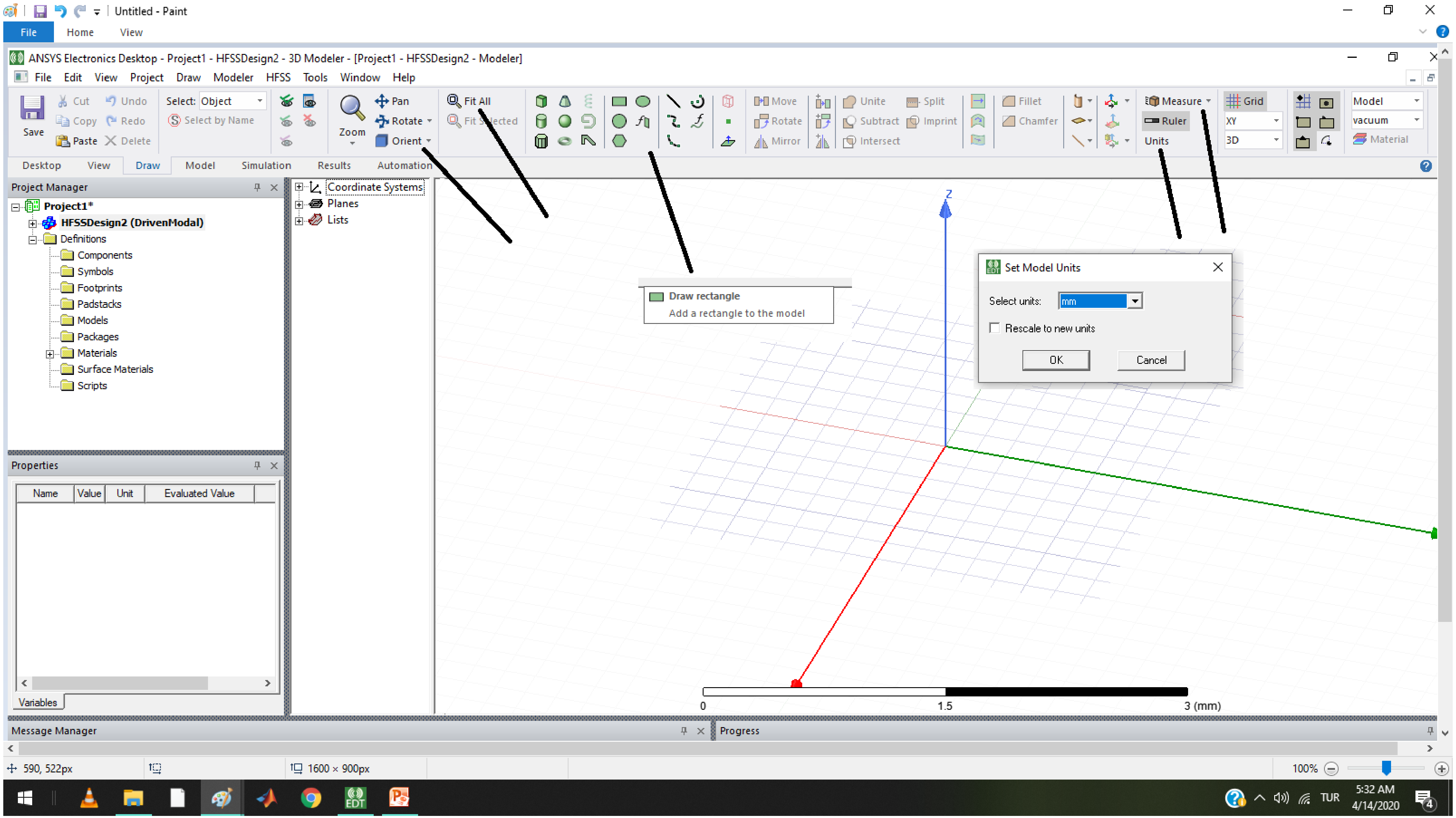
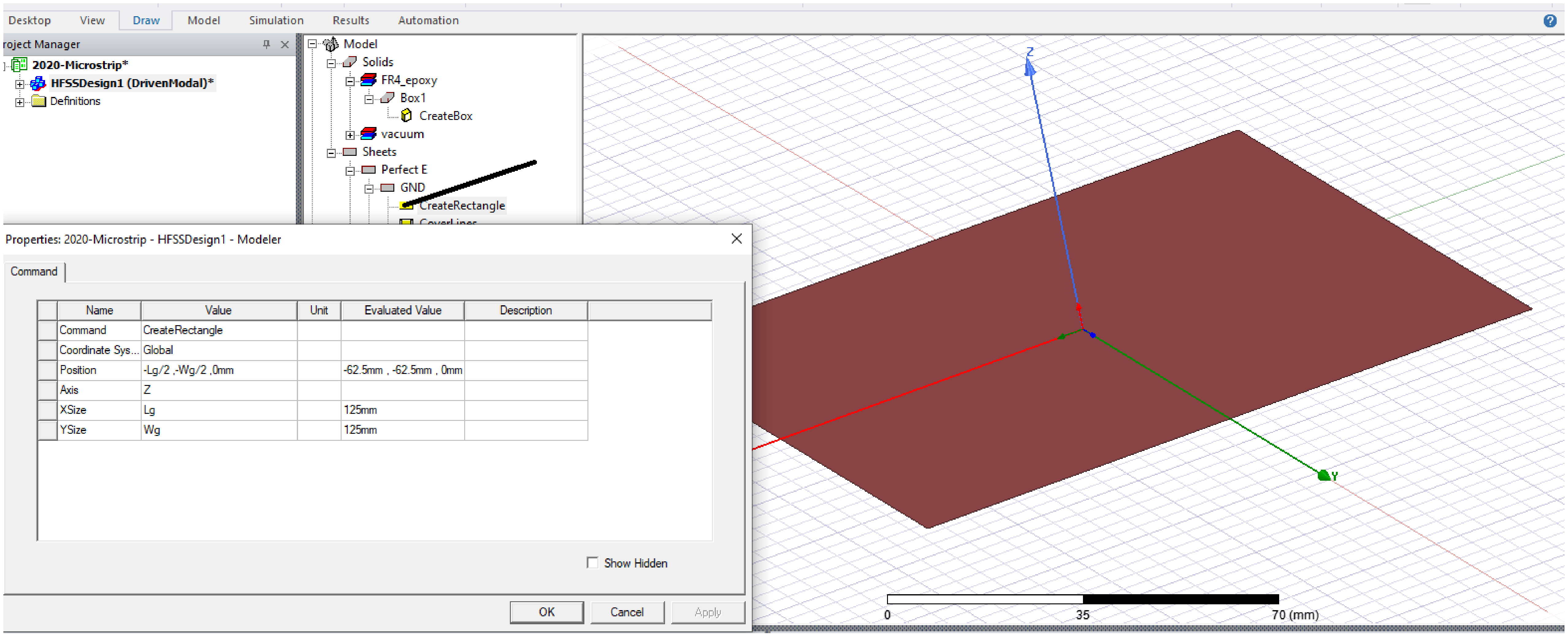
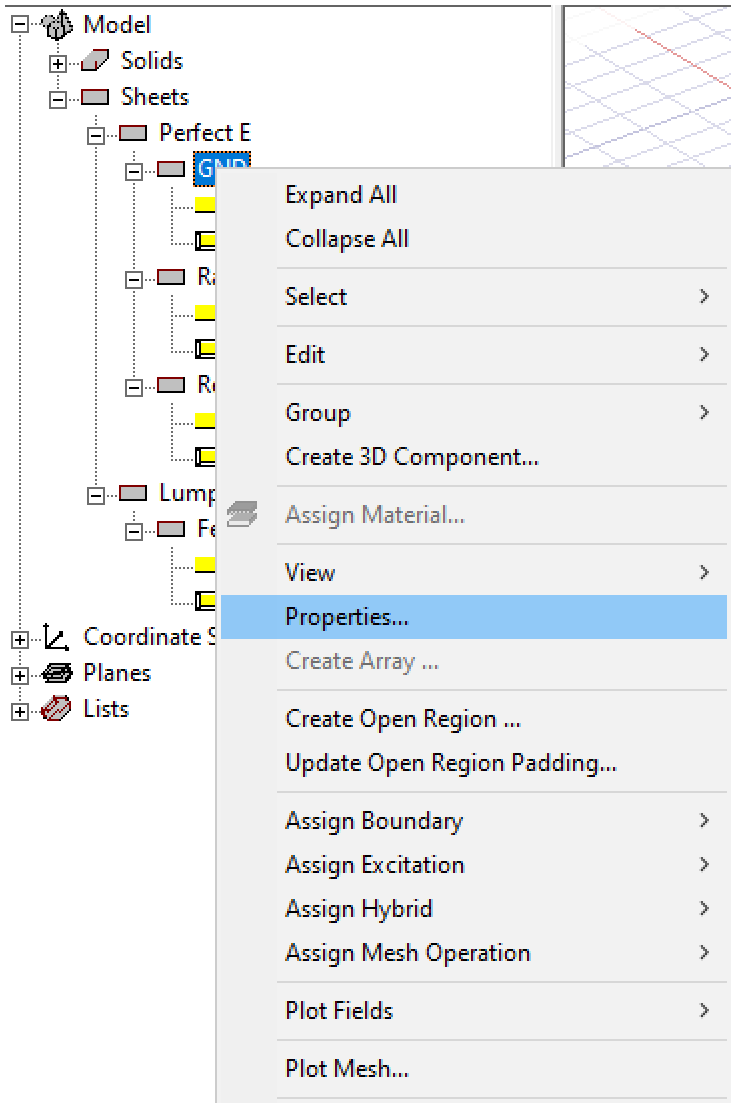
Save
Save As
Close
Save Archive
Restore Archive
Cut
Copy
Paste
Undo
Redo
Delete
HFSS
Q3D
Circuit
Icepak
Maxwell
Twin Builder
Update Definitions
Remove Unused Definitions
Edit Definitions
Project Variables
Datasets
Event Callbacks
General Options
Help
ANSYS
Desktop
View
Simulation
Automation
Project Manager
Project1*
Definitions
Components
Symbols
Footprints
Padstacks
Models
Packages
Materials
Surface Materials
Scripts
HFSS
HFSS 3D Layout
HFSS-IE
Launch Savant
Launch EMIT
1
2
Properties
Name
Value
Unit
Evaluated Value

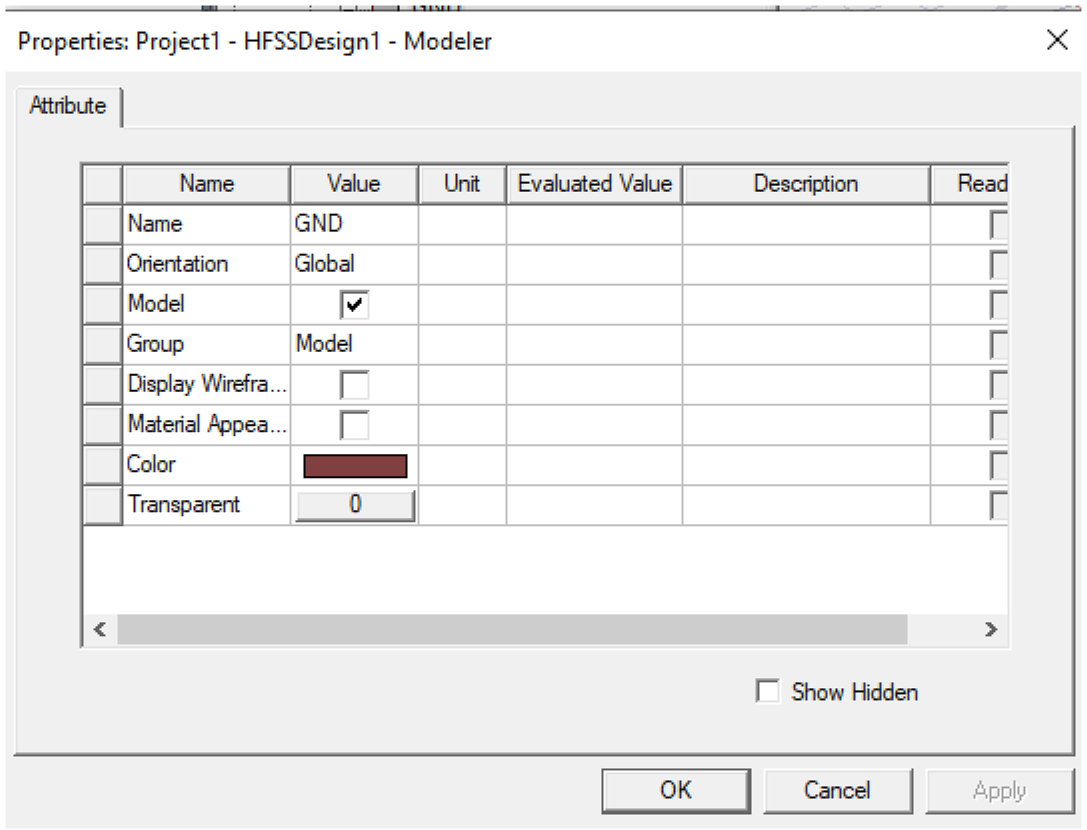

Untitled - Paint
ANSYS Electronics Desktop - Project1 - HFSSDesign2 - 3D Modeler - [Project1 - HFSSDesign2 - Modeler]
File Edit View Project Draw Modeler HFSS Tools Window Help
Desktop View Draw Model Simulation Results Automation
Project Manager
Project1*
HFSSDesign2 (DrivenModal)
Definitions
Components
Symbols
Footprints
Padstacks
Models
Packages
Materials
Surface Materials
Scripts
Properties
Name Value Unit Evaluated Value
Variables
Coordinate Systems
Planes
Lists
Draw rectangle
Add a rectangle to the model
Set Model Units
Select units: mm
Rescale to new units
OK
Cancel
0
1.5
3 (mm)
Message Manager
Progress
590, 522px
1600 × 900px
100%
5:32 AM
4/14/2020

GND

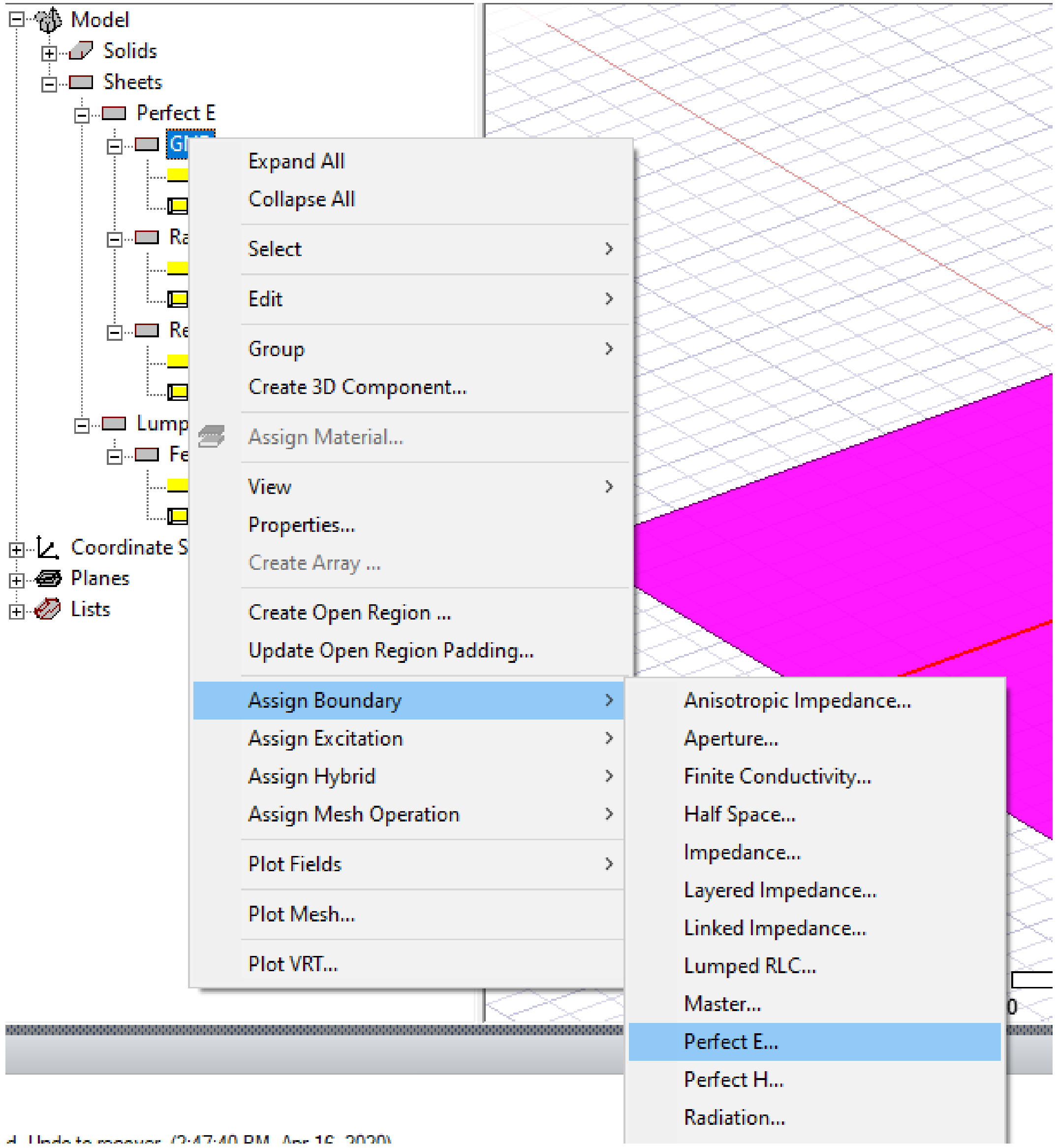

Desktop
View
Draw
Model
Simulation
Results
Automation
roject Manager
2020-Microstrip*
HFSSDesign1 (DrivenModal)*
Definitions
Model
Solids
FR4_epoxy
Box1
CreateBox
vacuum
Sheets
Perfect E
GND
CreateRectangle
Properties: 2020-Microstrip - HFSSDesign1 - Modeler
Command
Name
Value
Unit
Evaluated Value
Description
Command
CreateRectangle
Coordinate Sys...
Global
Position
-Lg/2 ,-Wg/2 ,0mm
-62.5mm , -62.5mm , 0mm
Axis
Z
XSize
Lg
125mm
YSize
Wg
125mm
Show Hidden
OK
Cancel
Apply
Z
Y
0
35
70 (mm)

GND – Properties: Name, Color

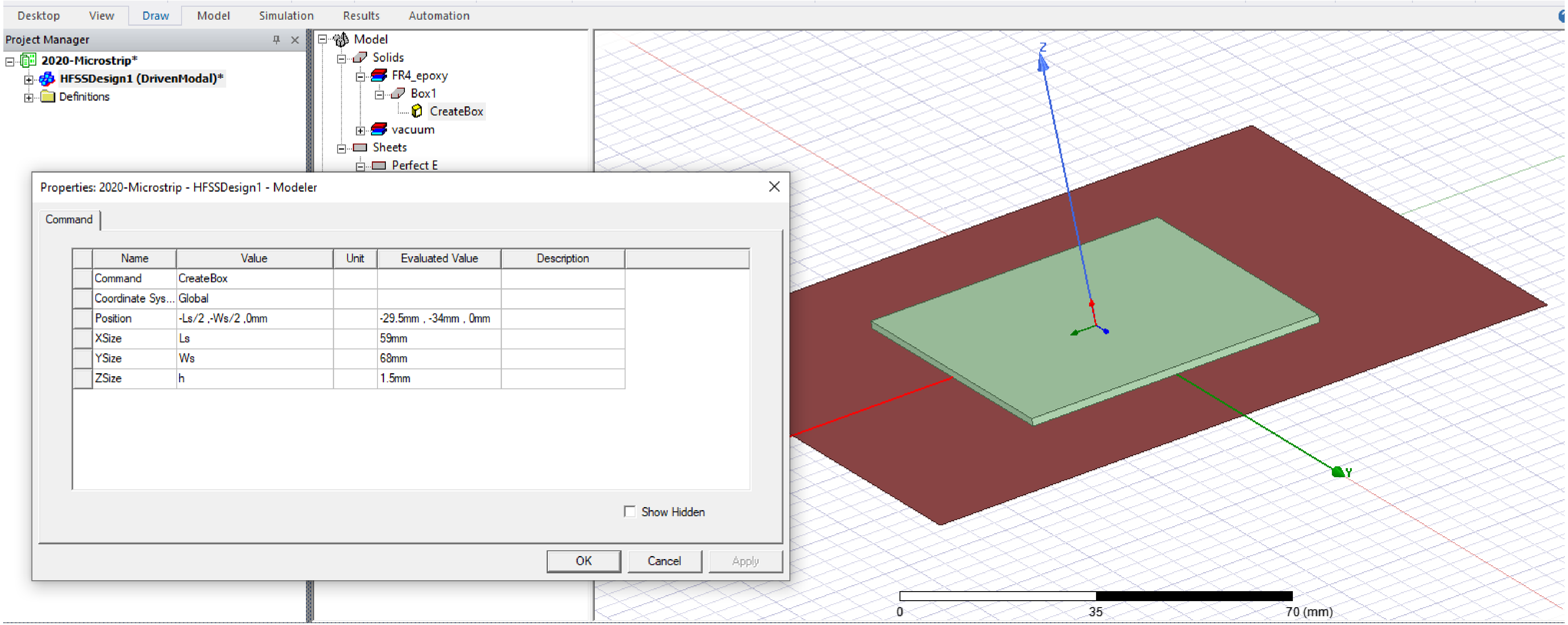




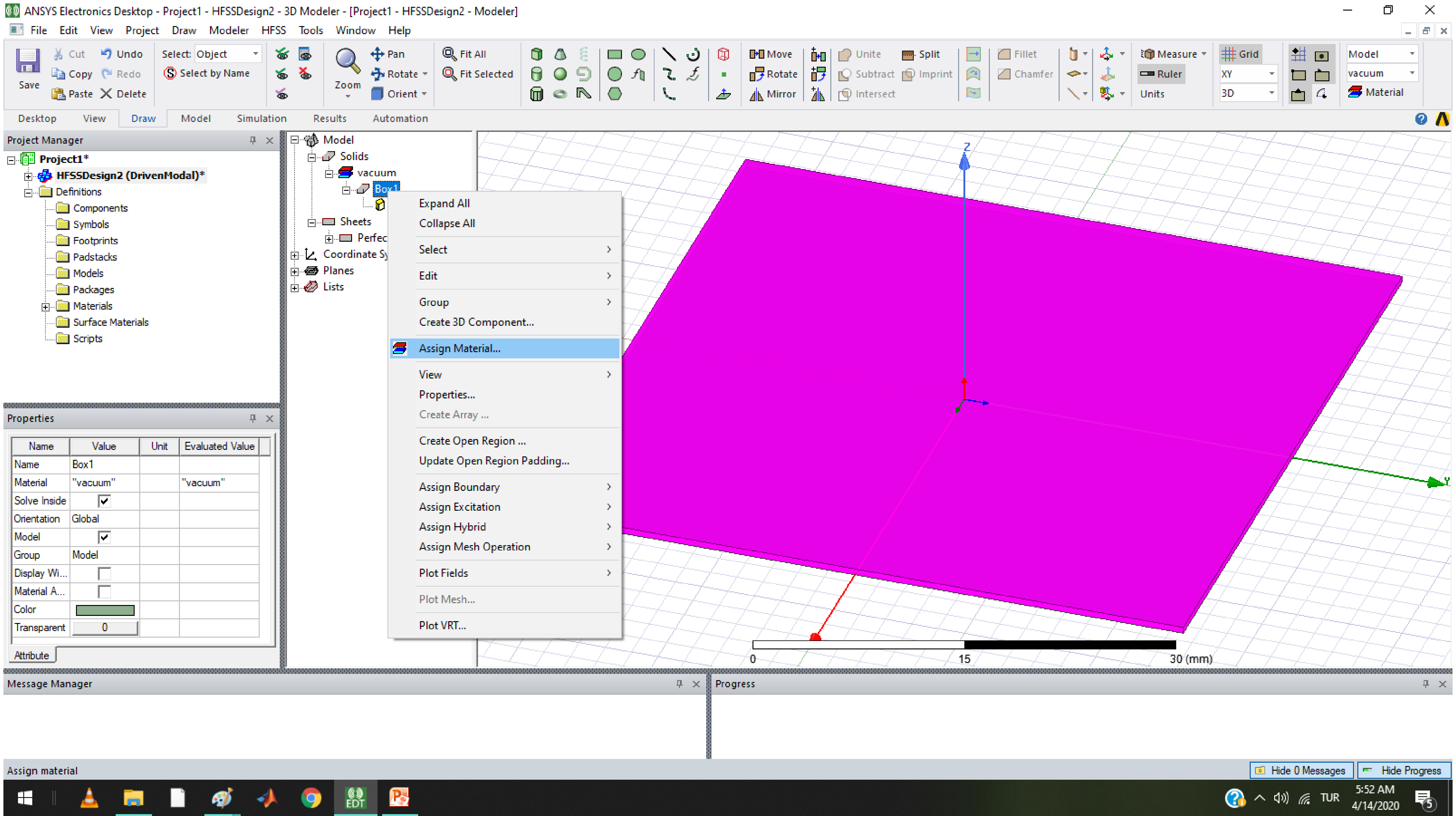
GND – Properties: Assign Boundary - Perfect E



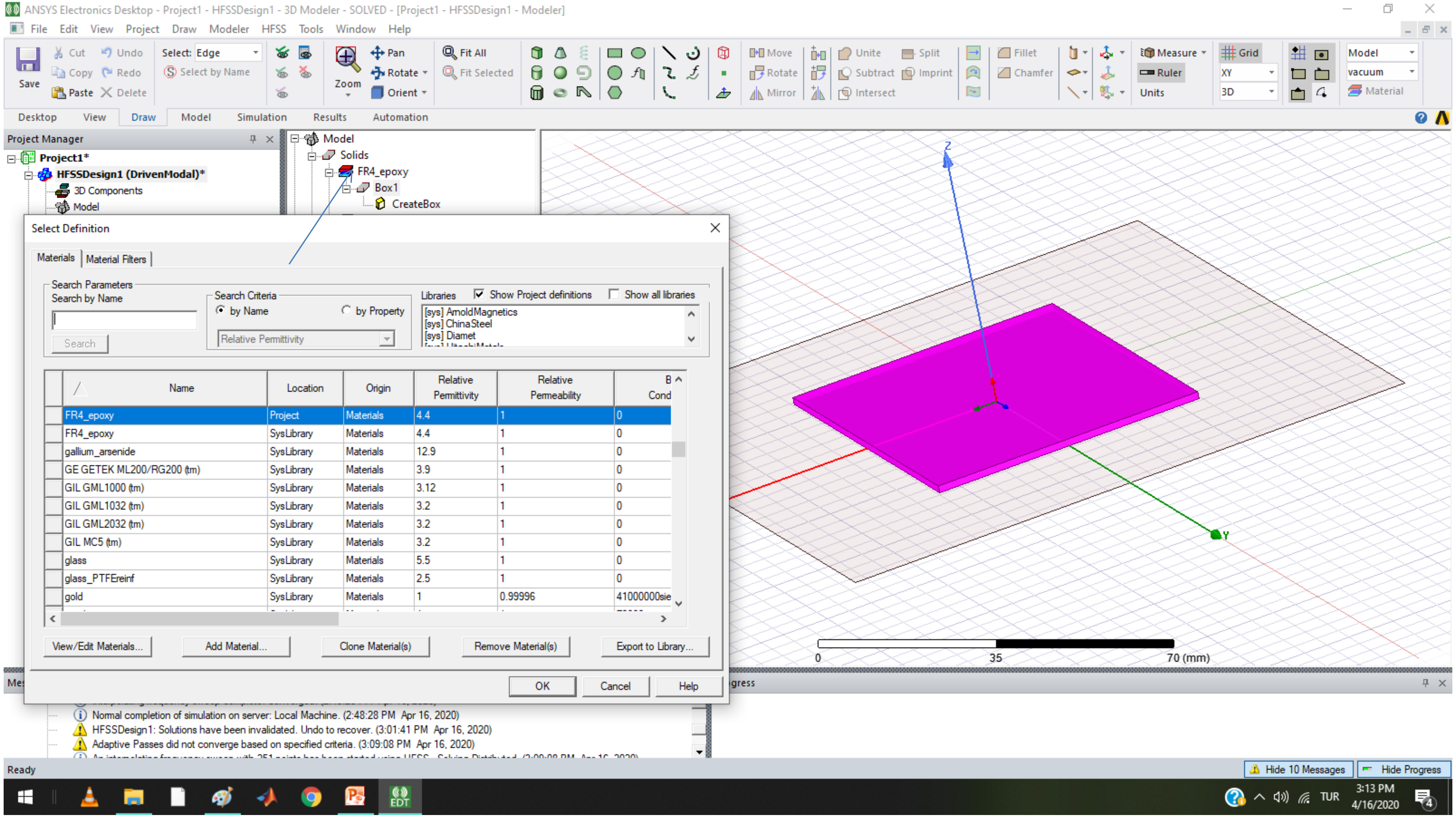
Substrate


Desktop
View
Draw
Model
Simulation
Results
Automation
Project Manager
2020-Microstrip*
HFSSDesign1 (DrivenModal)*
Definitions
Model
Solids
FR4_epoxy
Box1
CreateBox
vacuum
Sheets
Perfect E
Properties: 2020-Microstrip - HFSSDesign1 - Modeler
Command
Name | Value | Unit | Evaluated Value | Description
Command | CreateBox
Coordinate Sys... | Global
Position | -Ls/2 ,-Ws/2 ,0mm | | -29.5mm , -34mm , 0mm
XSize | Ls | | 59mm
YSize | Ws | | 68mm
ZSize | h | | 1.5mm
Show Hidden
OK
Cancel
Apply
Z
Y
0
35
70 (mm)

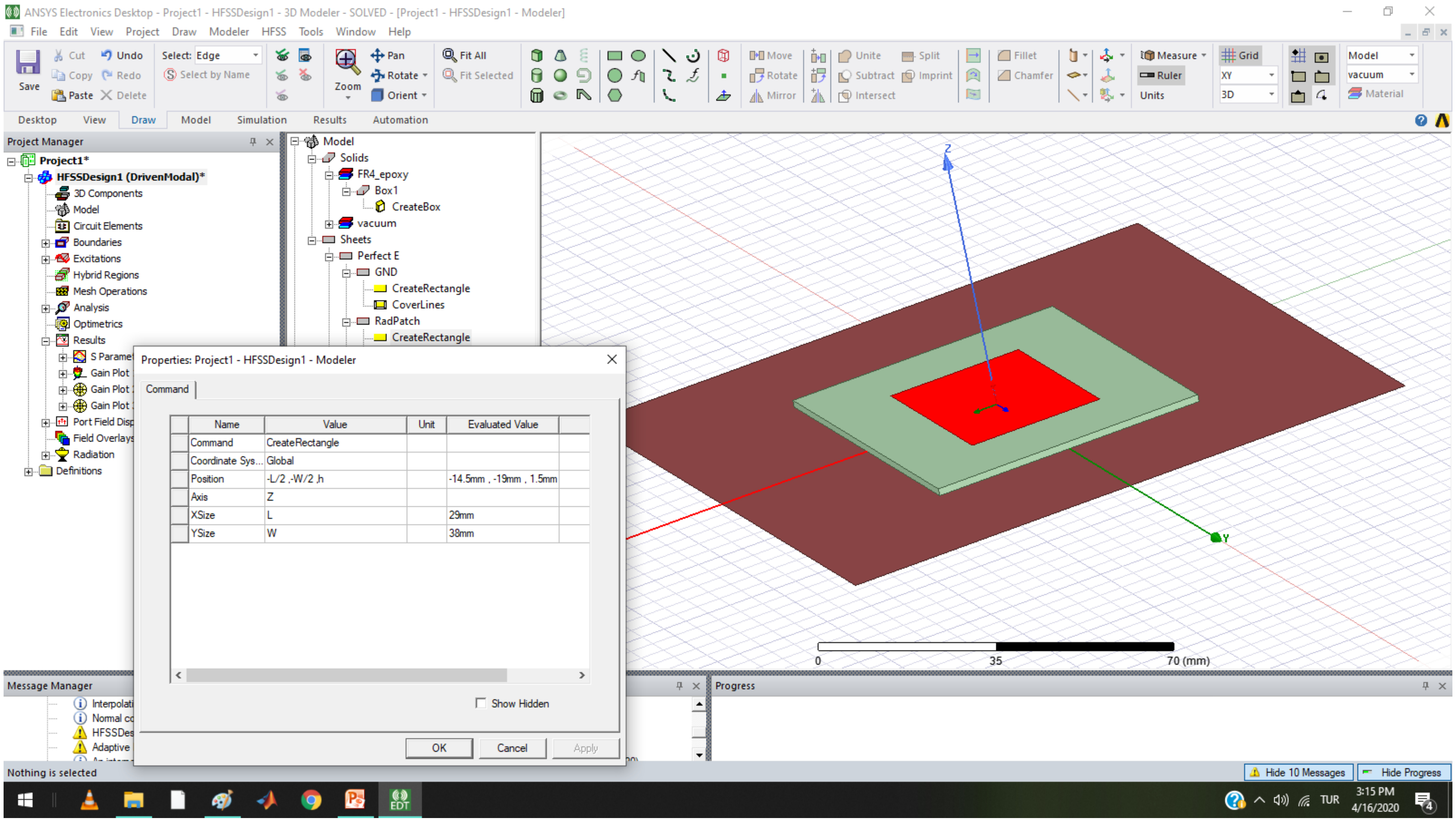
Substrate – Assign material



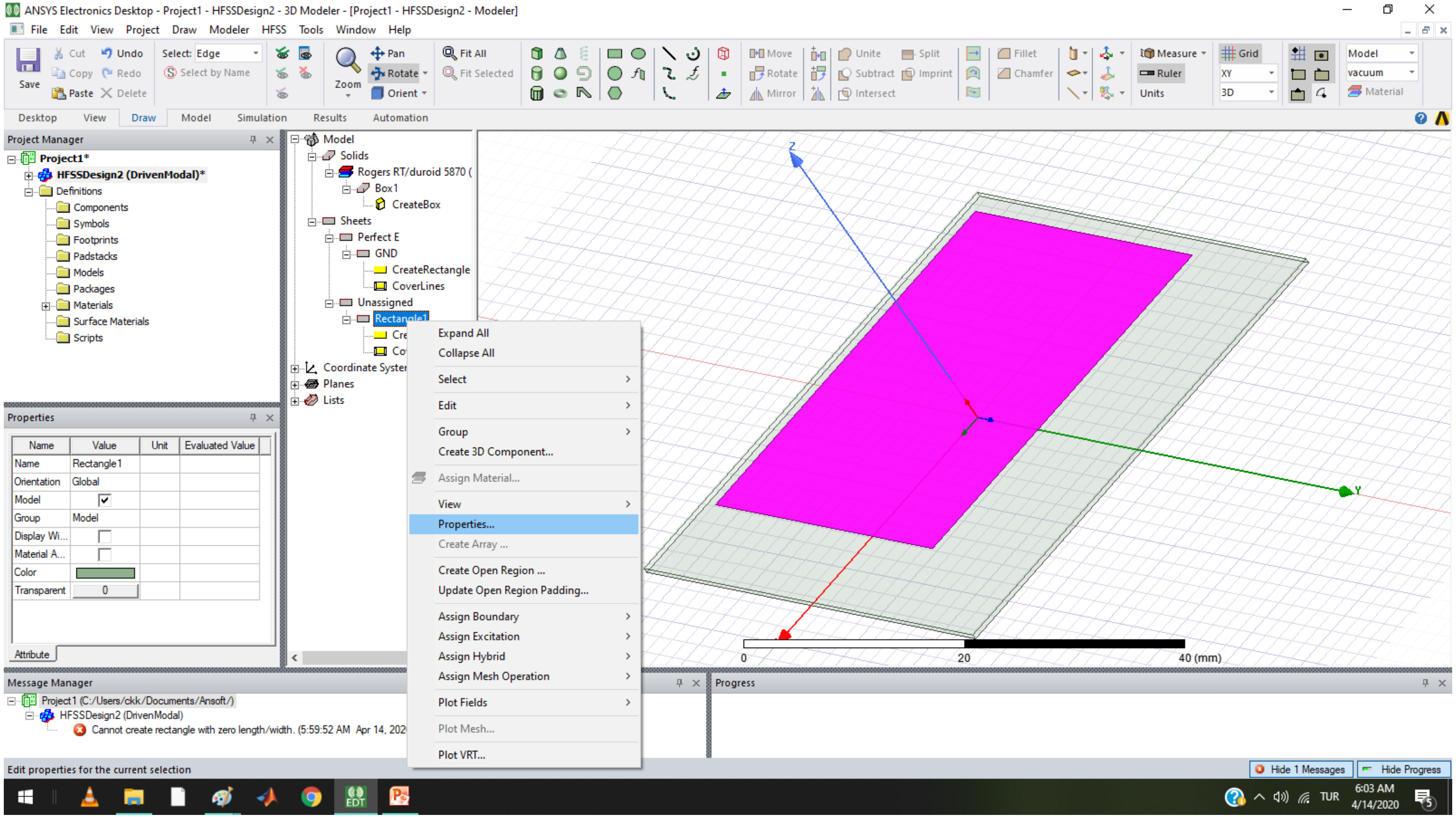
Substrate - Material



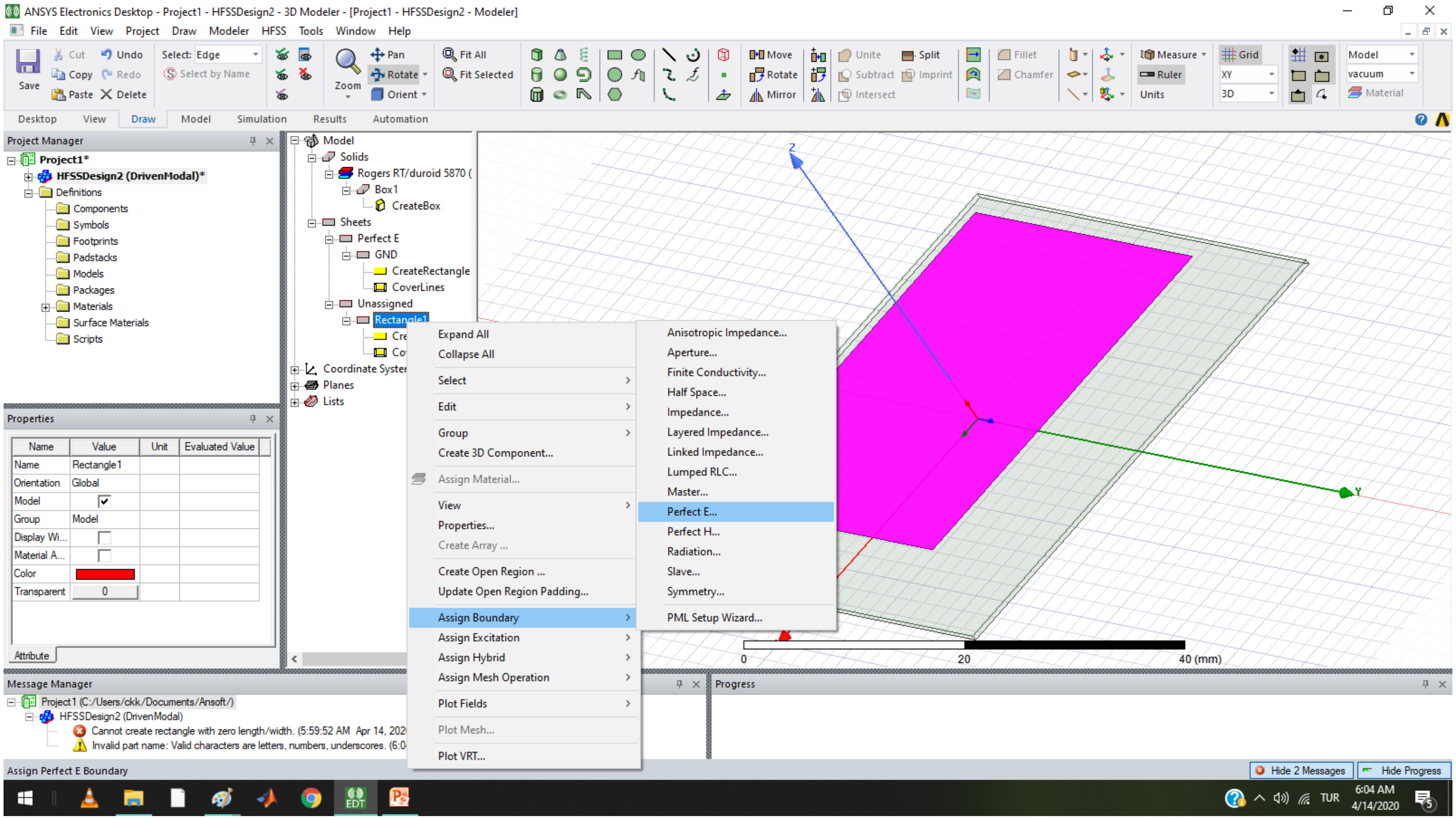
Radiated Part



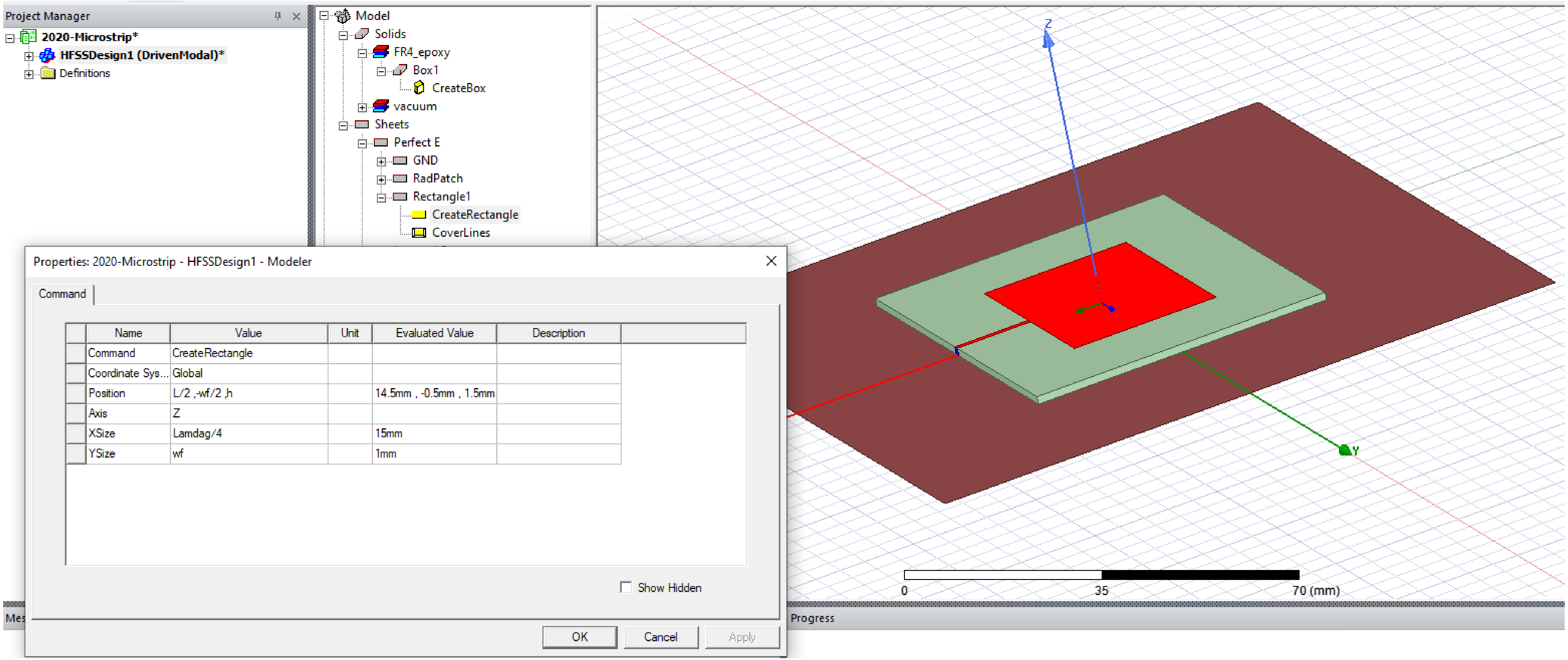
Radiated Part – Properties (Name, Color)



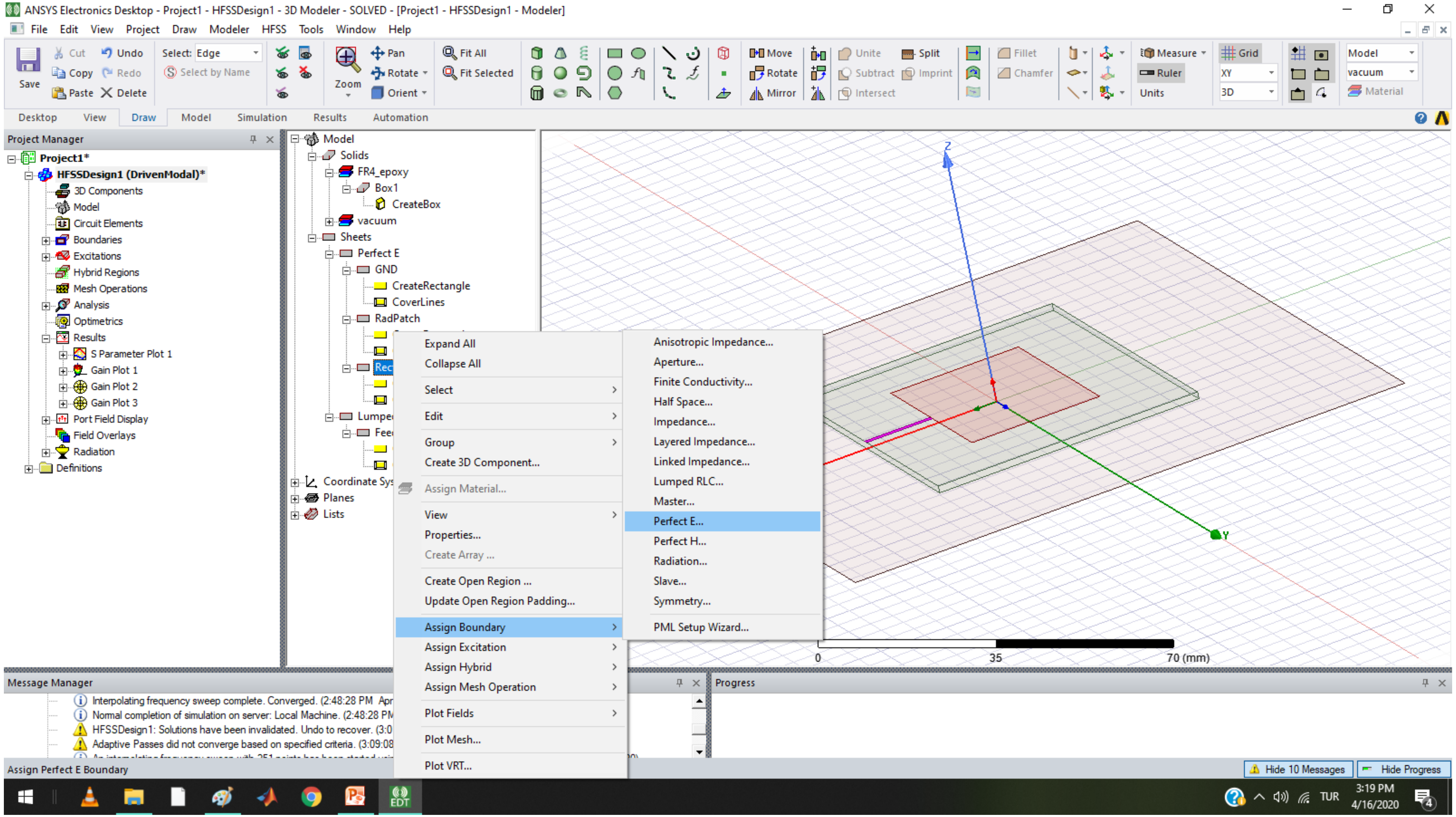
Radiated Part – Assign Boundary- Perfect E



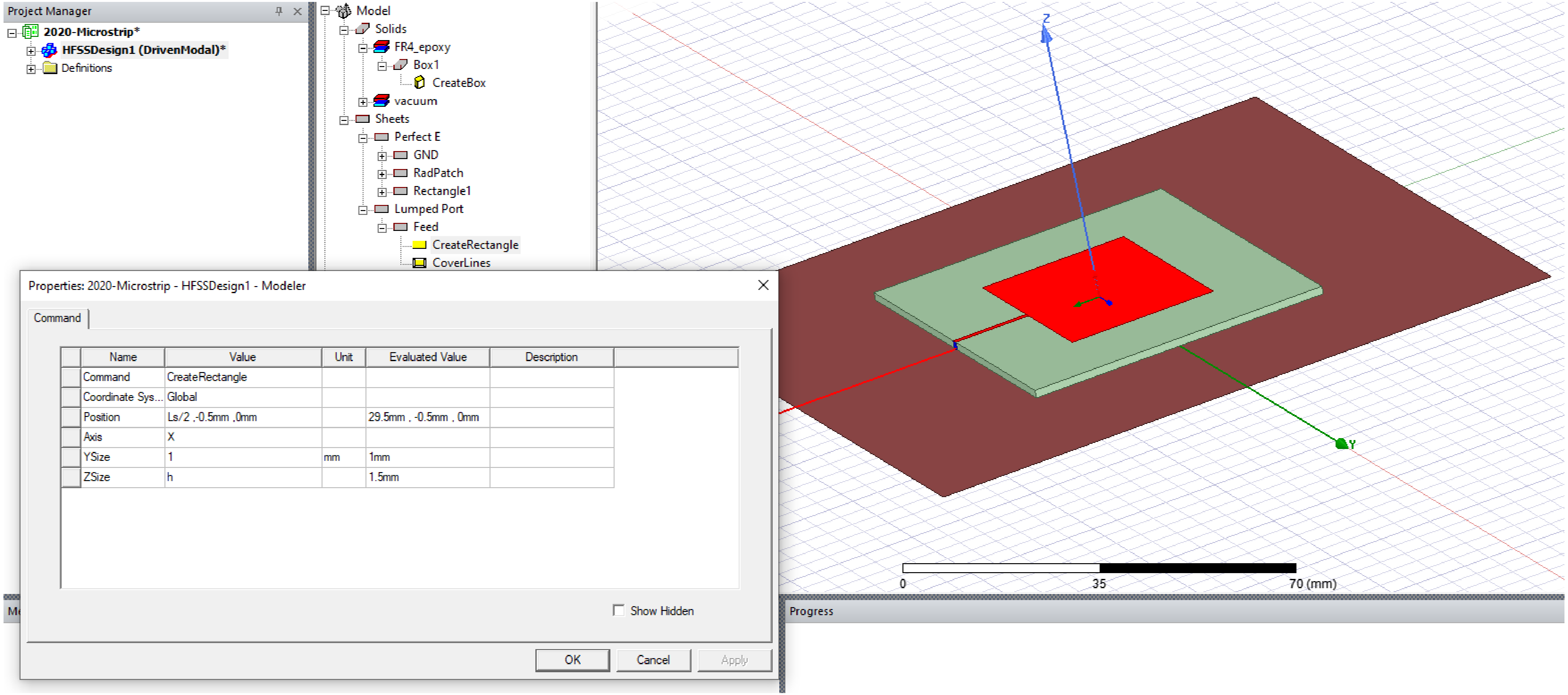
Feed Line


Project Manager
2020-Microstrip*
HFSSDesign1 (DrivenModal)*
Definitions
Model
Solids
FR4_epoxy
Box1
CreateBox
vacuum
Sheets
Perfect E
GND
RadPatch
Rectangle1
CreateRectangle
CoverLines
Properties: 2020-Microstrip - HFSSDesign1 - Modeler
Command
Name
Value
Unit
Evaluated Value
Description
Command
CreateRectangle
Coordinate Sys...
Global
Position
L/2 ,-wf/2 ,h
14.5mm , -0.5mm , 1.5mm
Axis
Z
XSize
Lamdag/4
15mm
YSize
wf
1mm
Show Hidden
OK
Cancel
Apply
Z
Y
0
35
70 (mm)
Progress

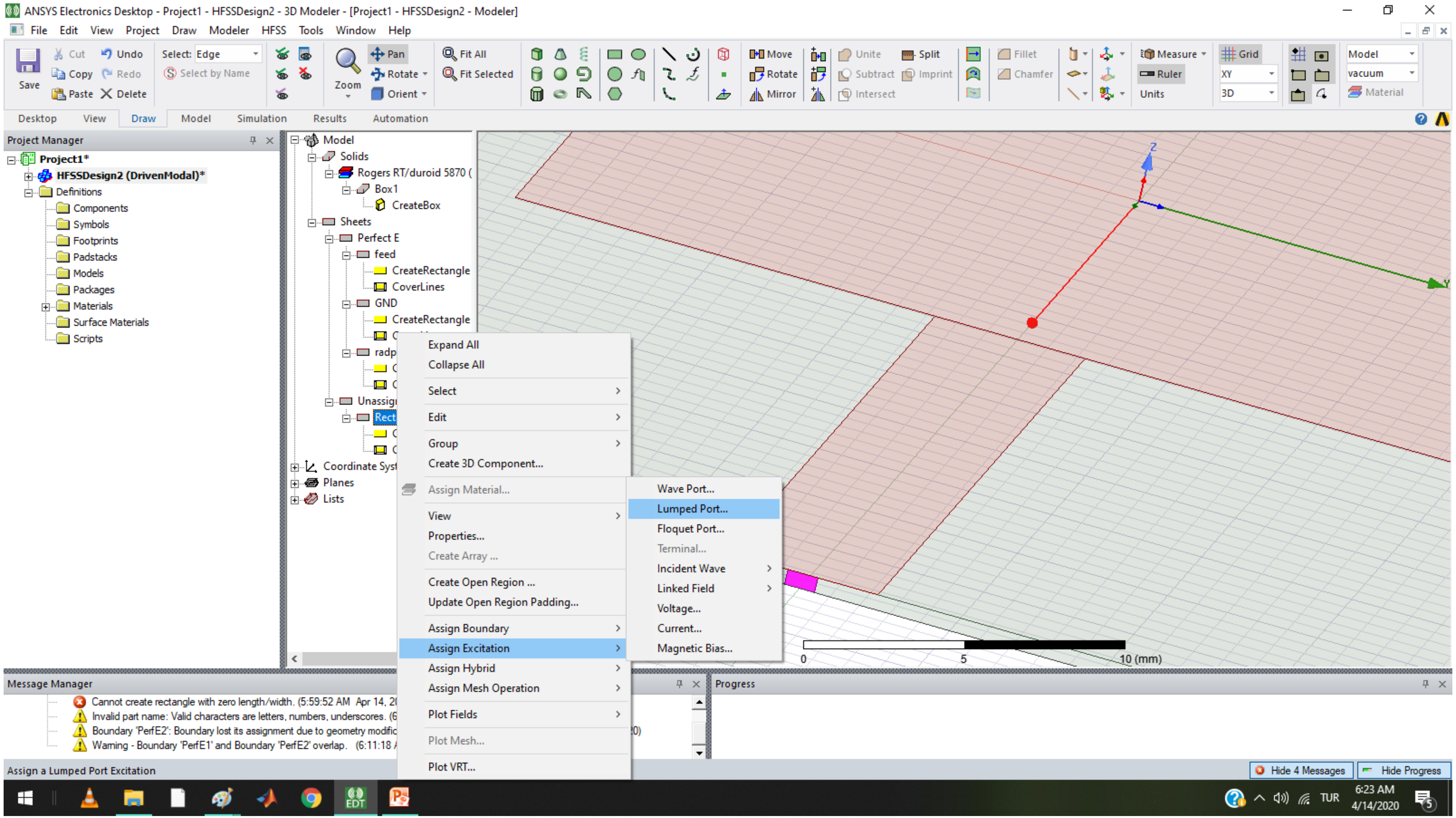
Feed Line– Assign Boundary- Perfect E



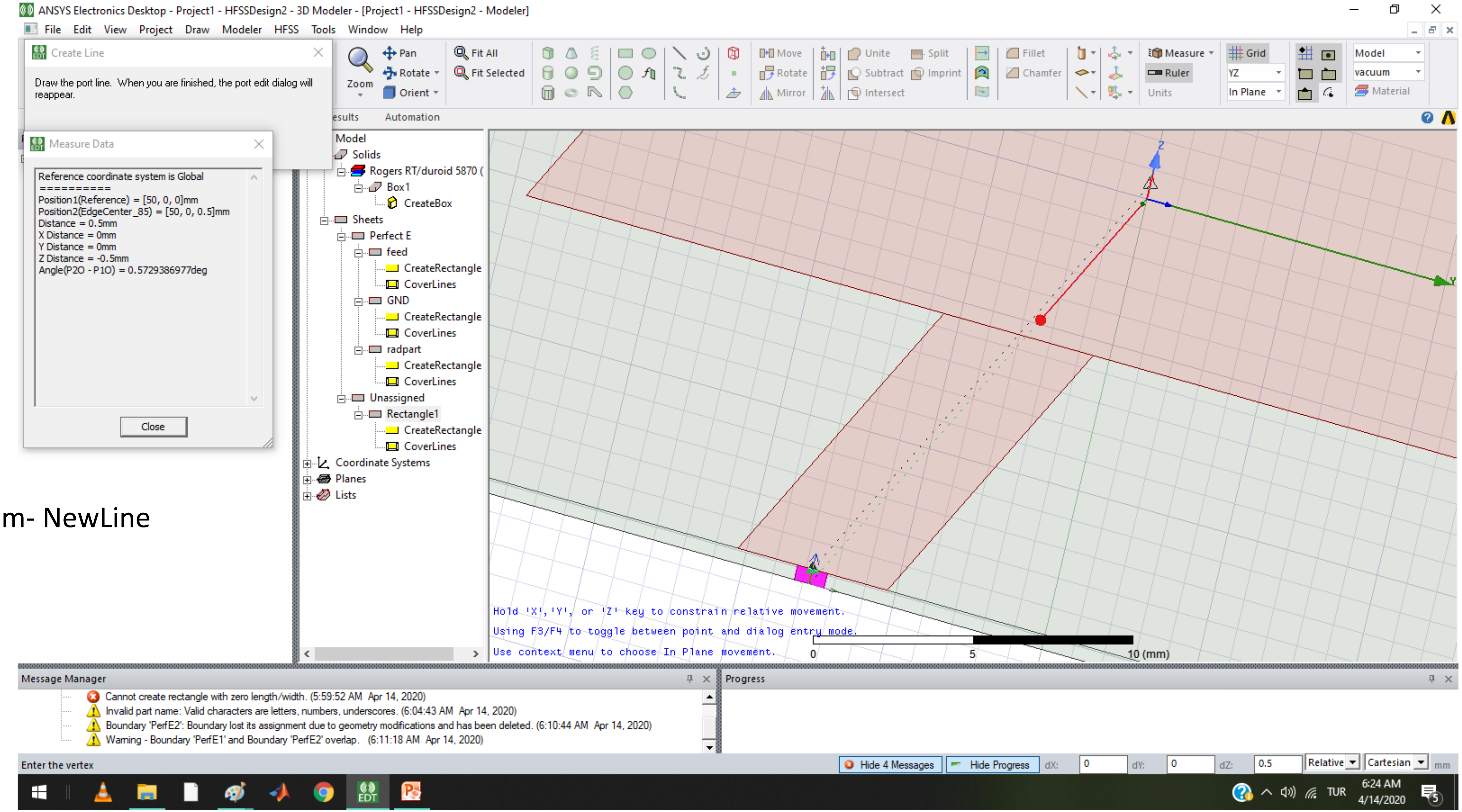
Feed – Lumped Port



Feed – Lumped Port

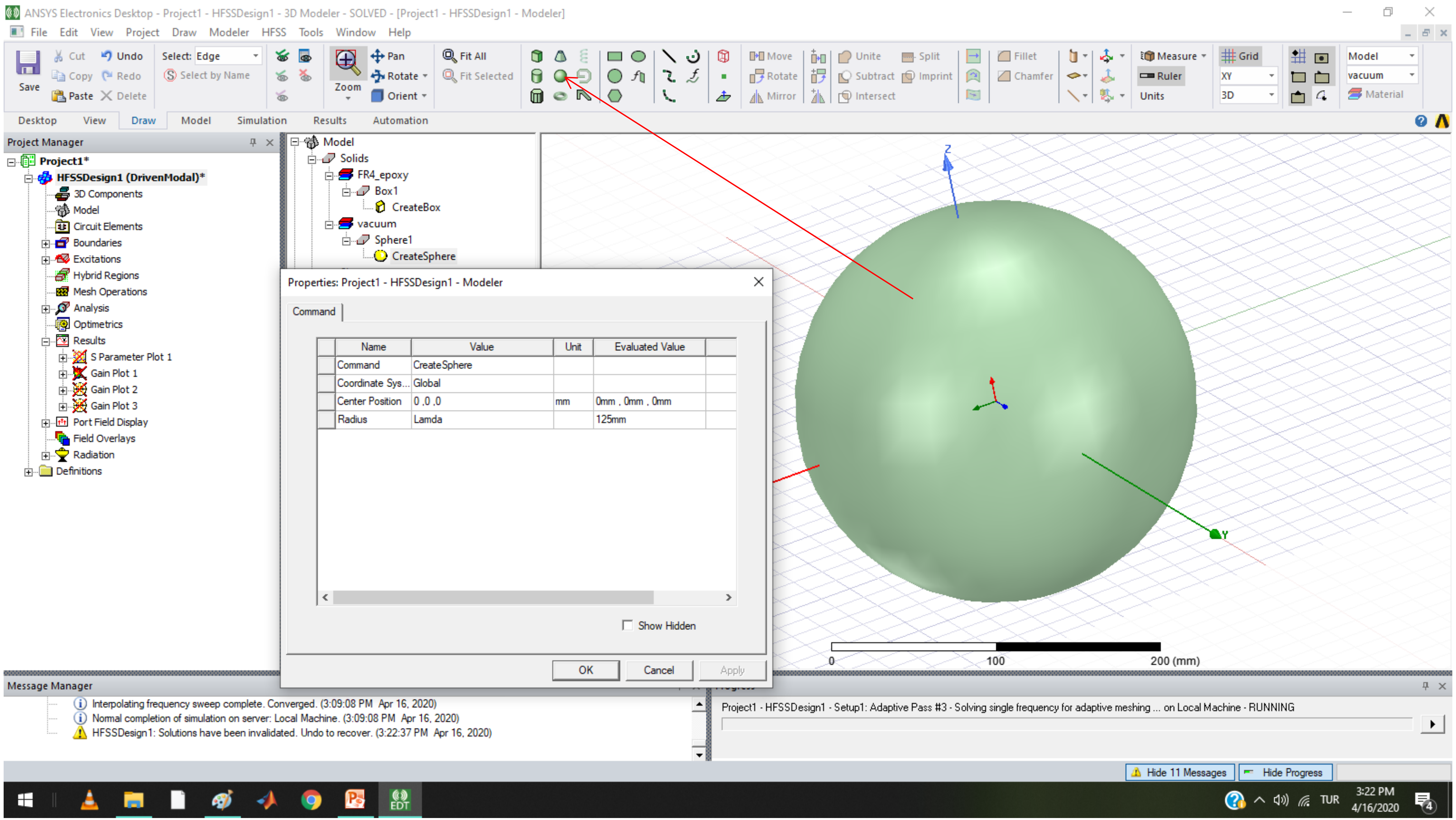


Feed – Lumped Port



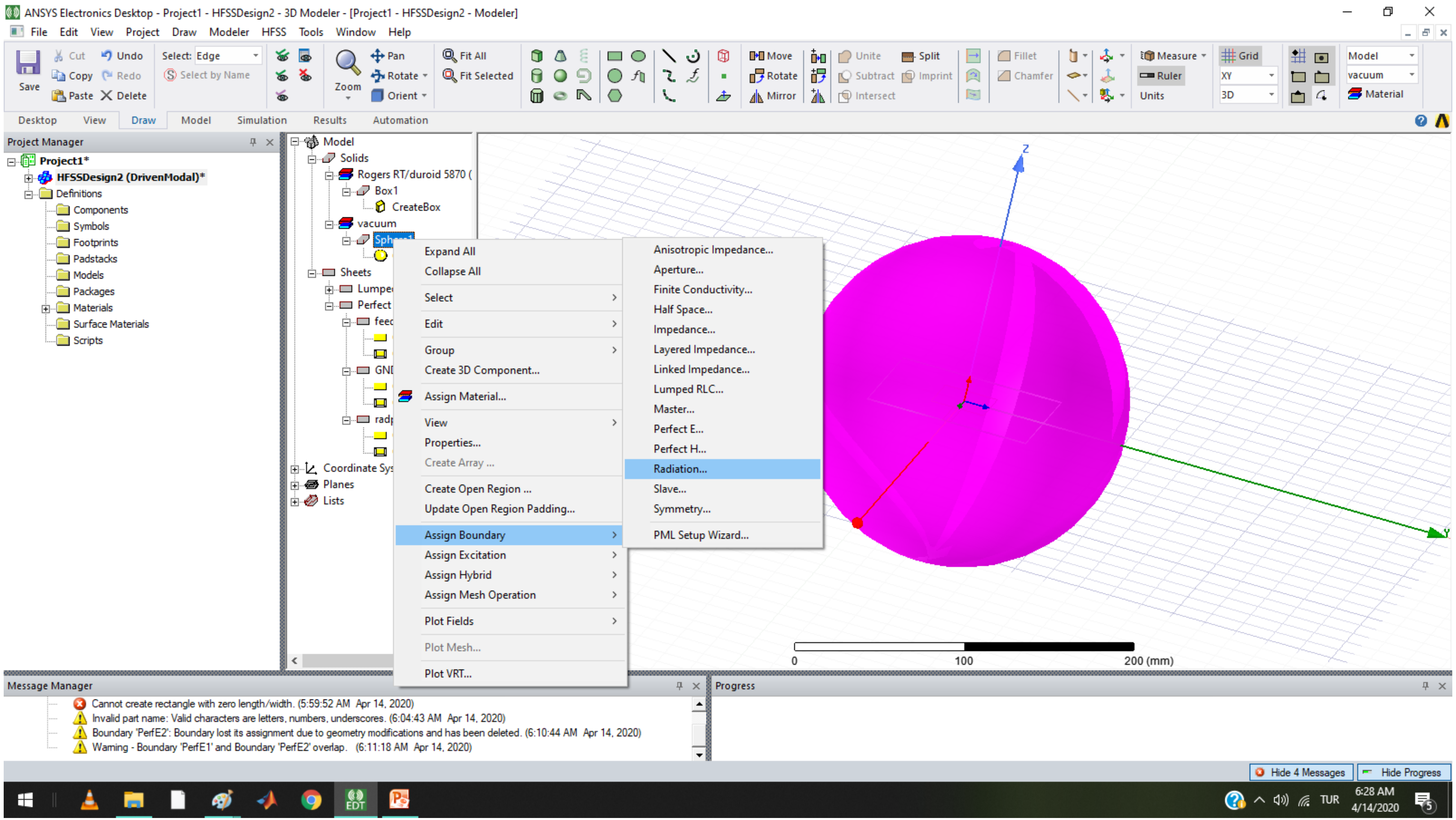
50ohm- NewLine

Radiation

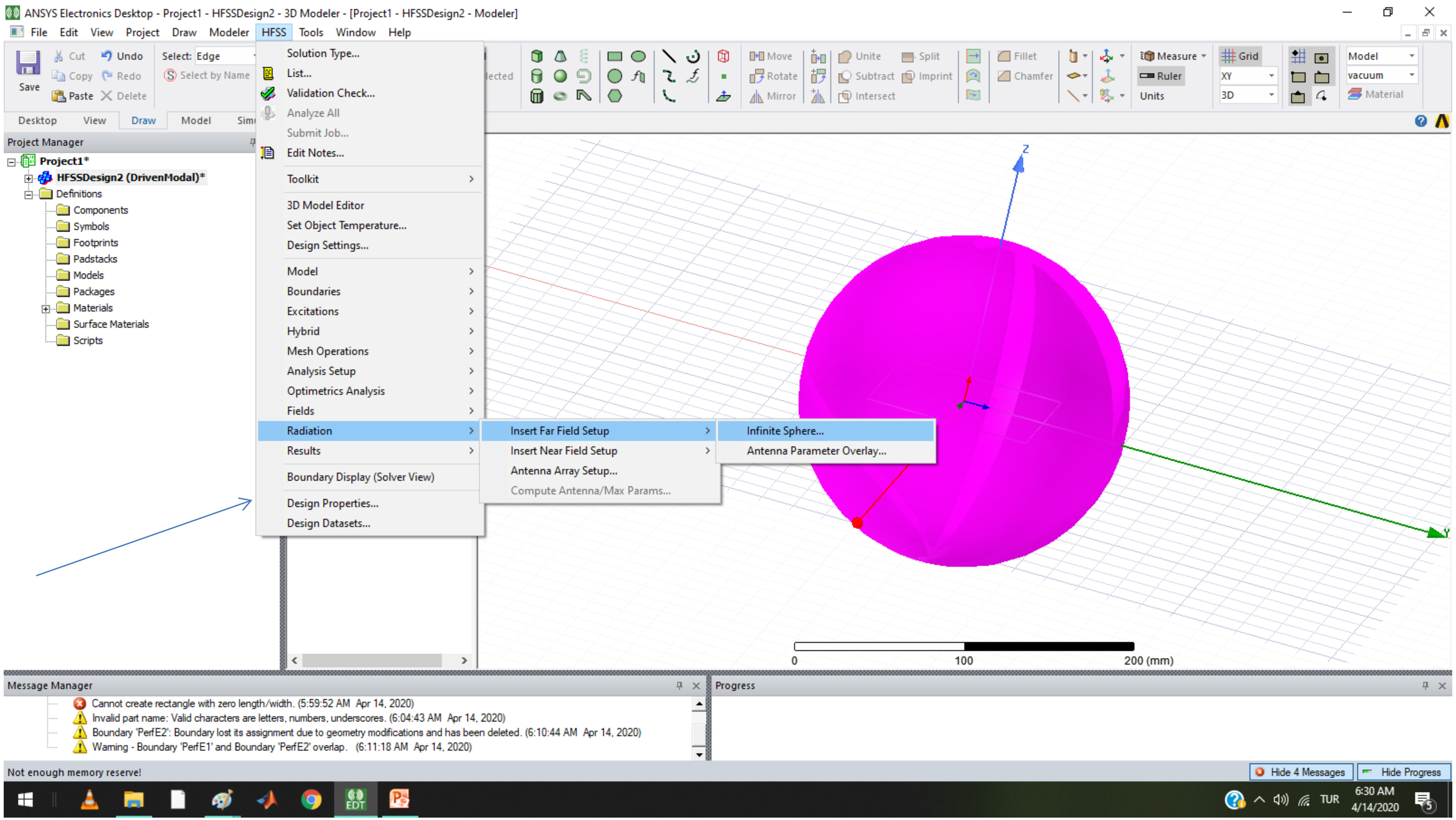


ANSYS Electronics Desktop - Project1 - HFSSDesign1 - 3D Modeler - SOLVED - [Project1 - HFSSDesign1 - Modeler]
Project Manager
Project1*
HFSSDesign1 (DrivenModal)*
3D Components
Model
Circuit Elements
Boundaries
Excitations
Hybrid Regions
Mesh Operations
Analysis
Optimetrics
Results
S Parameter Plot 1
Gain Plot 1
Gain Plot 2
Gain Plot 3
Port Field Display
Field Overlays
Radiation
Definitions
Model
Solids
FR4_epoxy
Box1
CreateBox
vacuum
Sphere1
CreateSphere
Properties: Project1 - HFSSDesign1 - Modeler
Command
Name | Value | Unit | Evaluated Value
Command | CreateSphere
Coordinate Sys... | Global
Center Position | 0 ,0 ,0 | mm | 0mm , 0mm , 0mm
Radius | Lamda | | 125mm
Show Hidden
OK
Cancel
Apply
0
100
200 (mm)
Message Manager
Interpolating frequency sweep complete. Converged. (3:09:08 PM Apr 16, 2020)
Normal completion of simulation on server: Local Machine. (3:09:08 PM Apr 16, 2020)
HFSSDesign1: Solutions have been invalidated. Undo to recover. (3:22:37 PM Apr 16, 2020)
Project1 - HFSSDesign1 - Setup1: Adaptive Pass #3 - Solving single frequency for adaptive meshing ... on Local Machine - RUNNING
Hide 11 Messages
Hide Progress
3:22 PM
4/16/2020

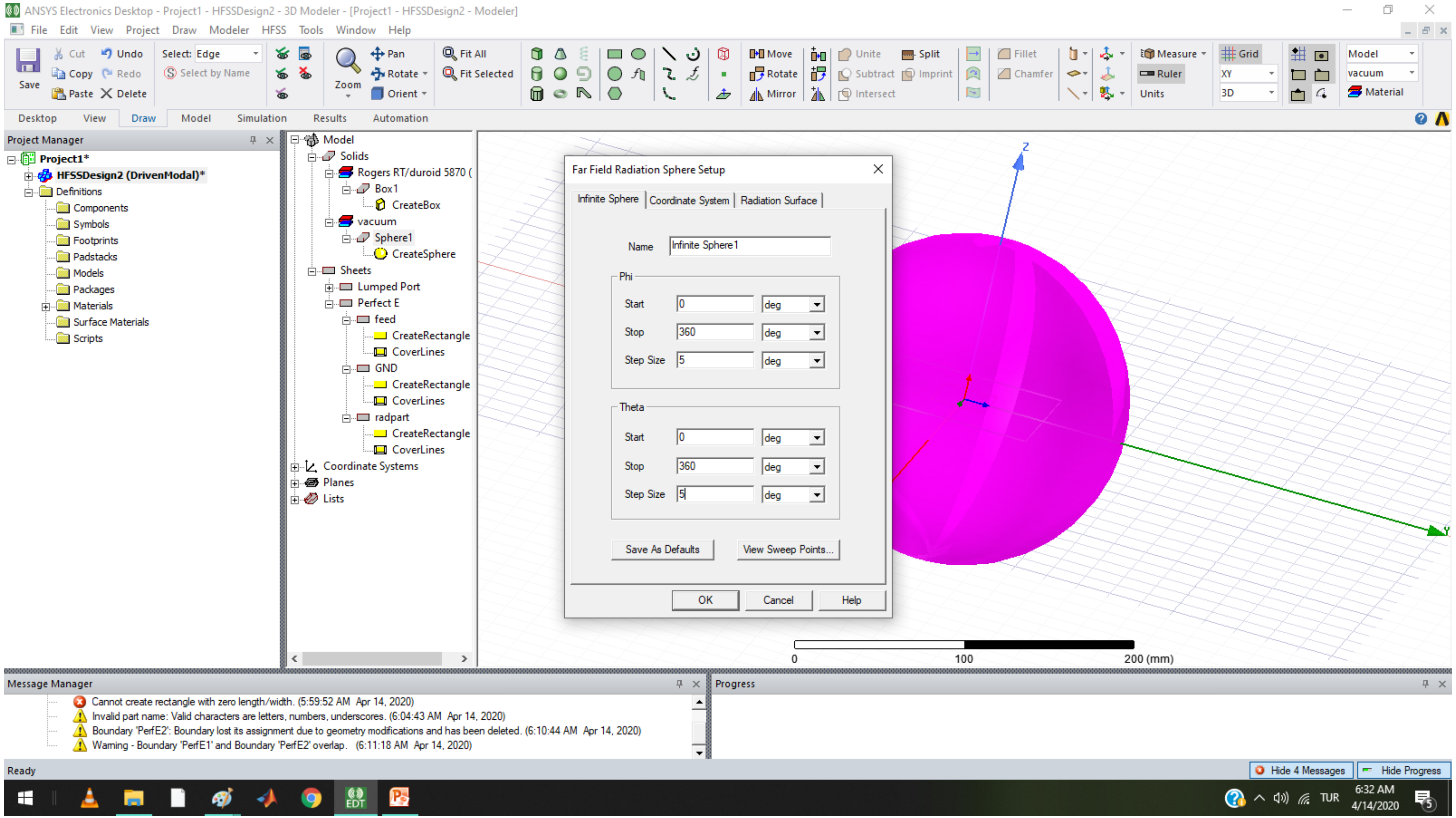
Assign Boundary - Radiation



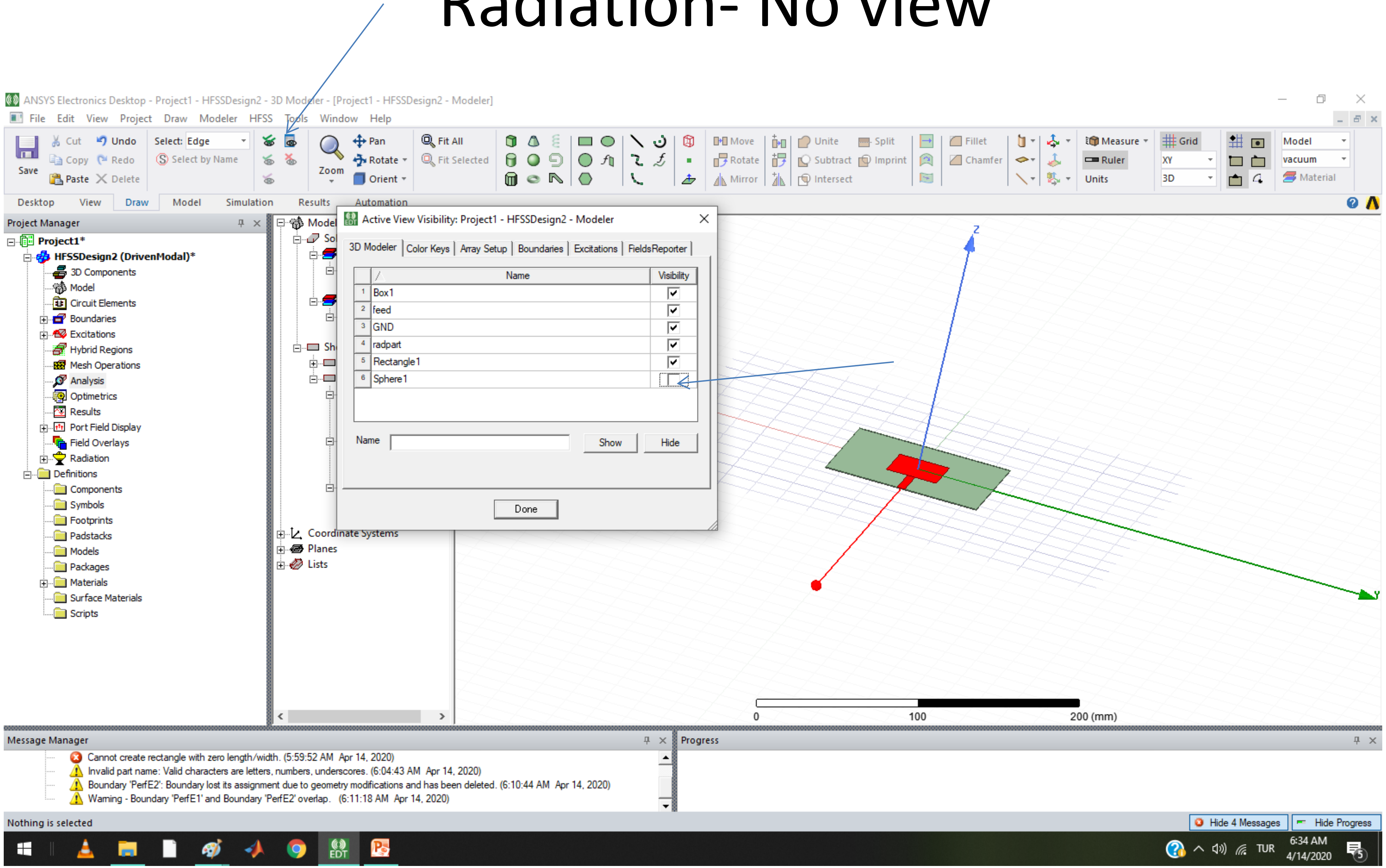
HFSS-Radiation-Insert Far Field Setup – Infinite Sphere



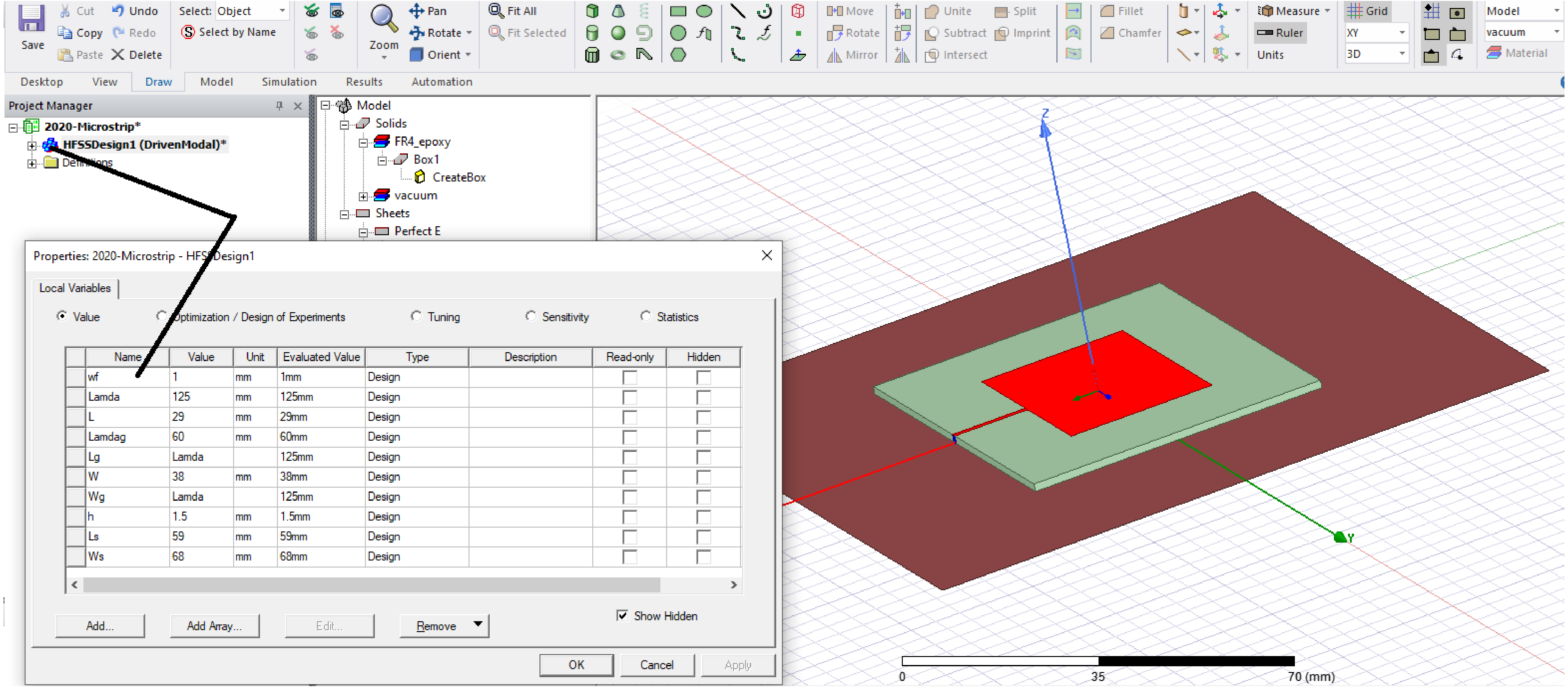
HFSS-Radiation-Insert Far Field Setup – Infinite Sphere



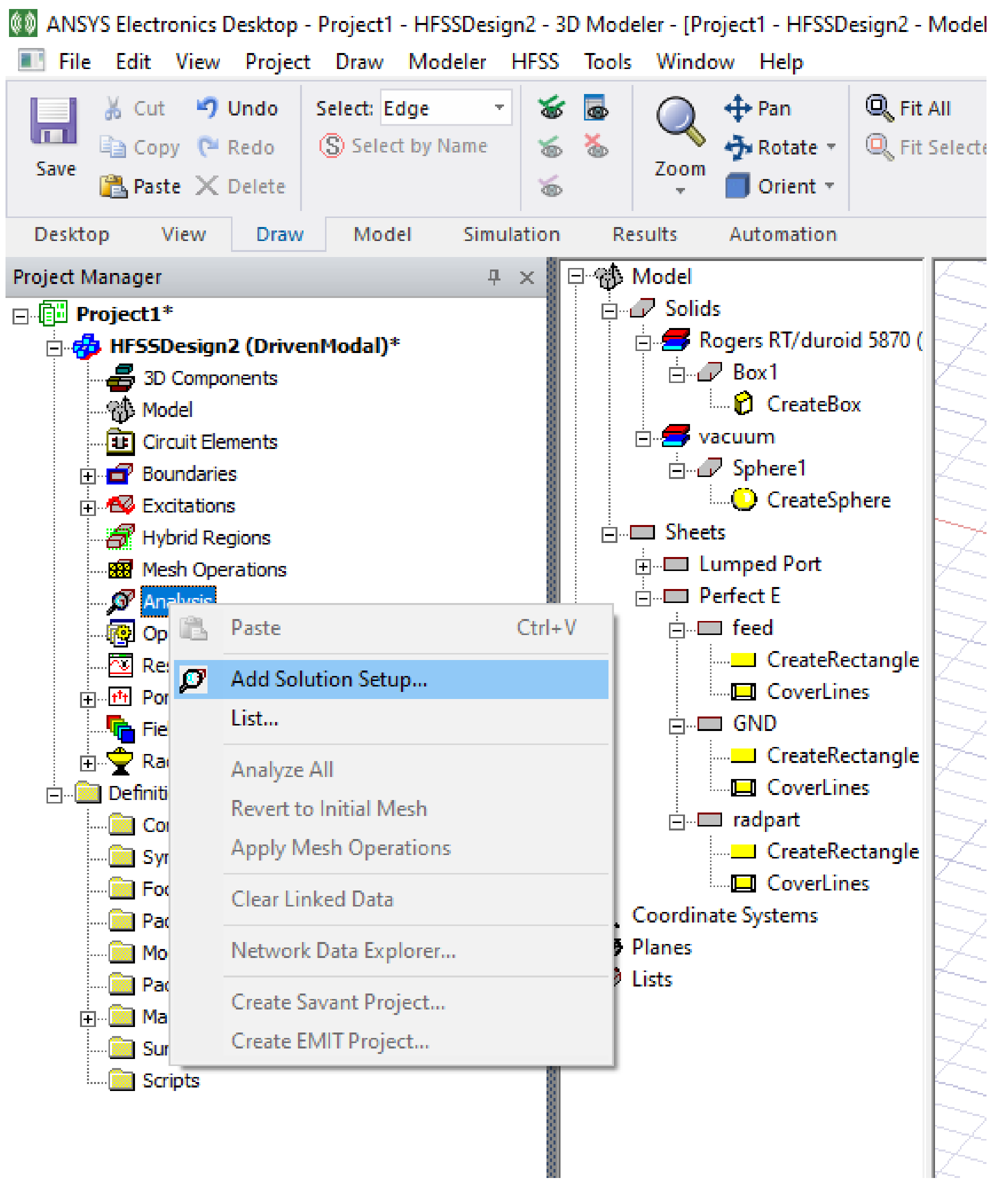
Radiation- No view

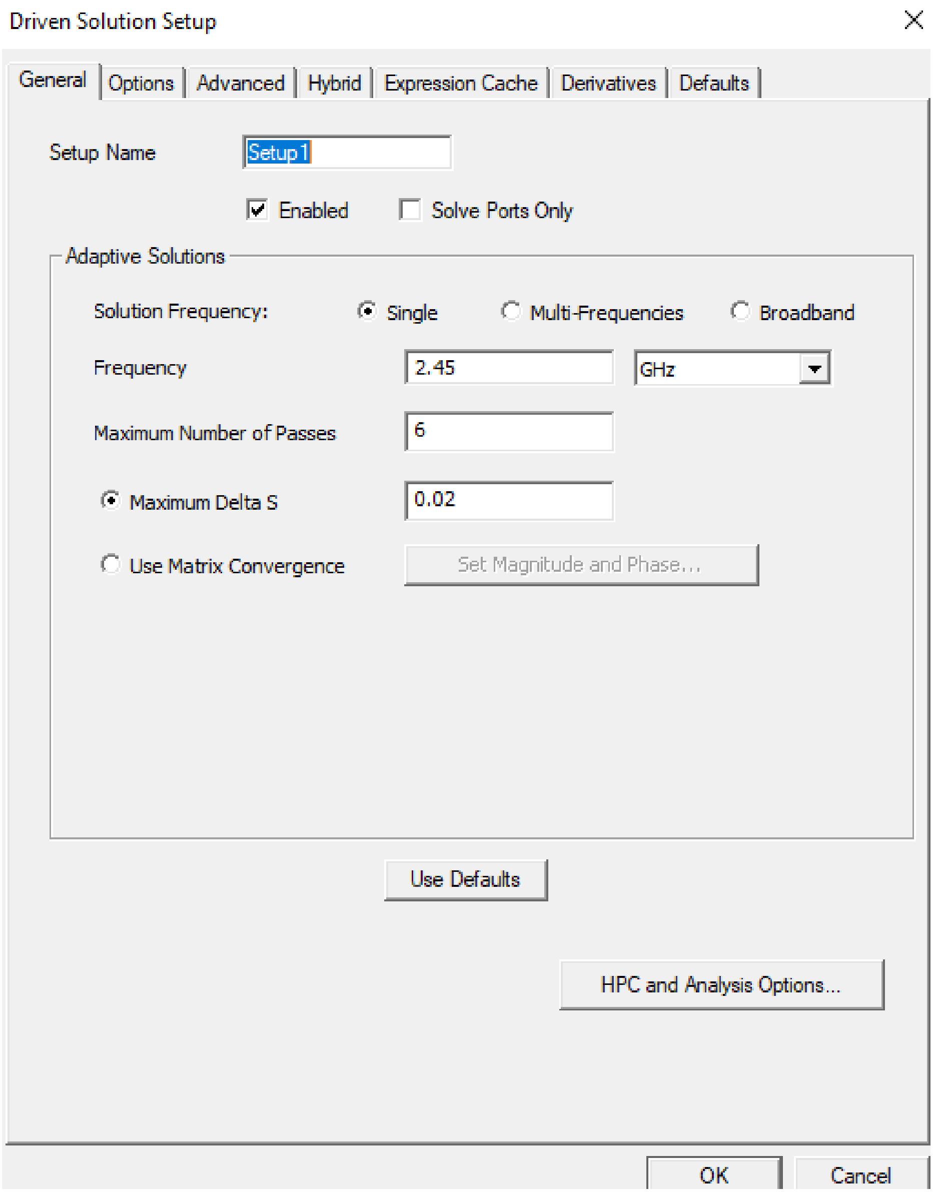


Parametrik değerlerin değiştirilmesi

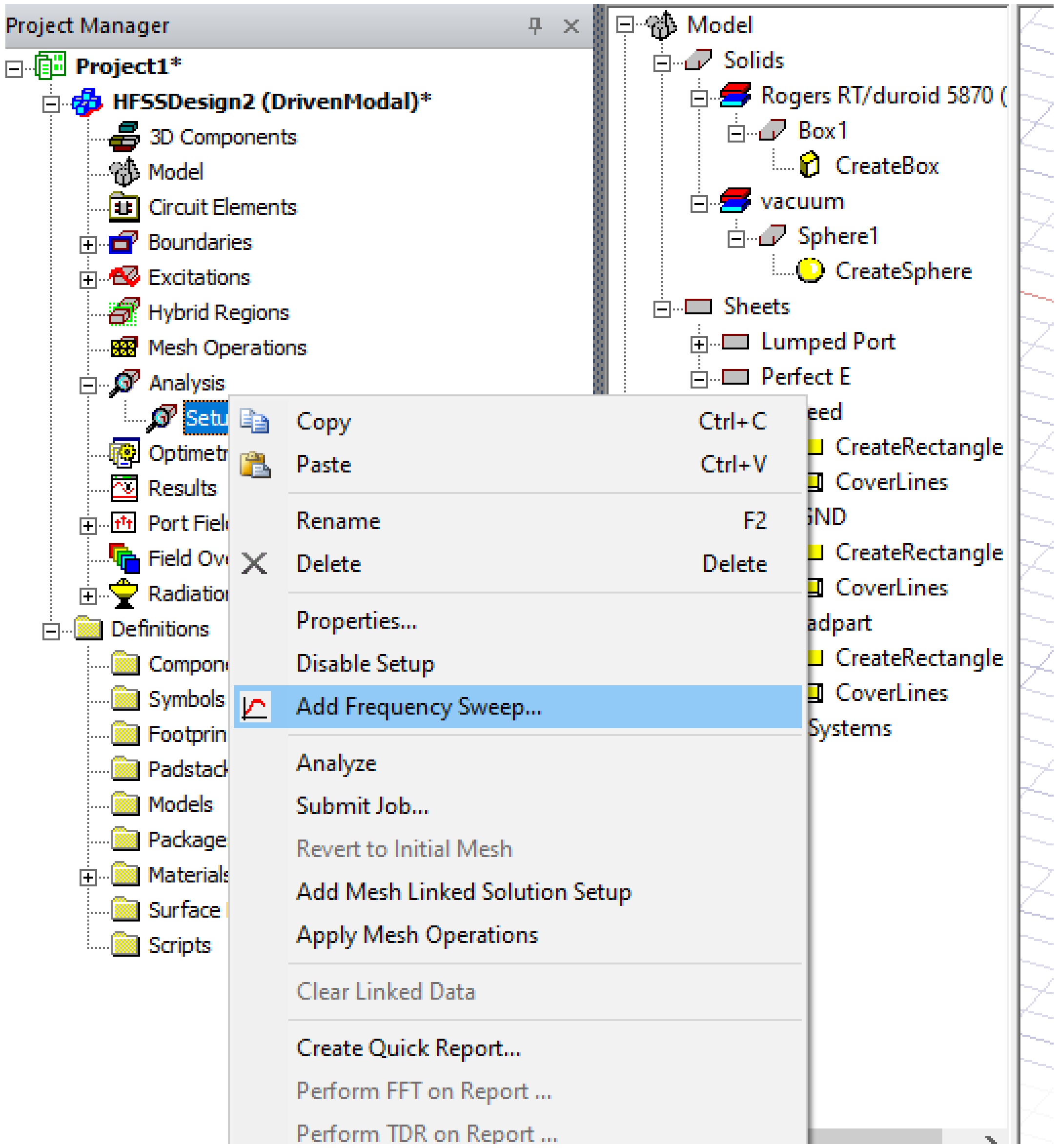


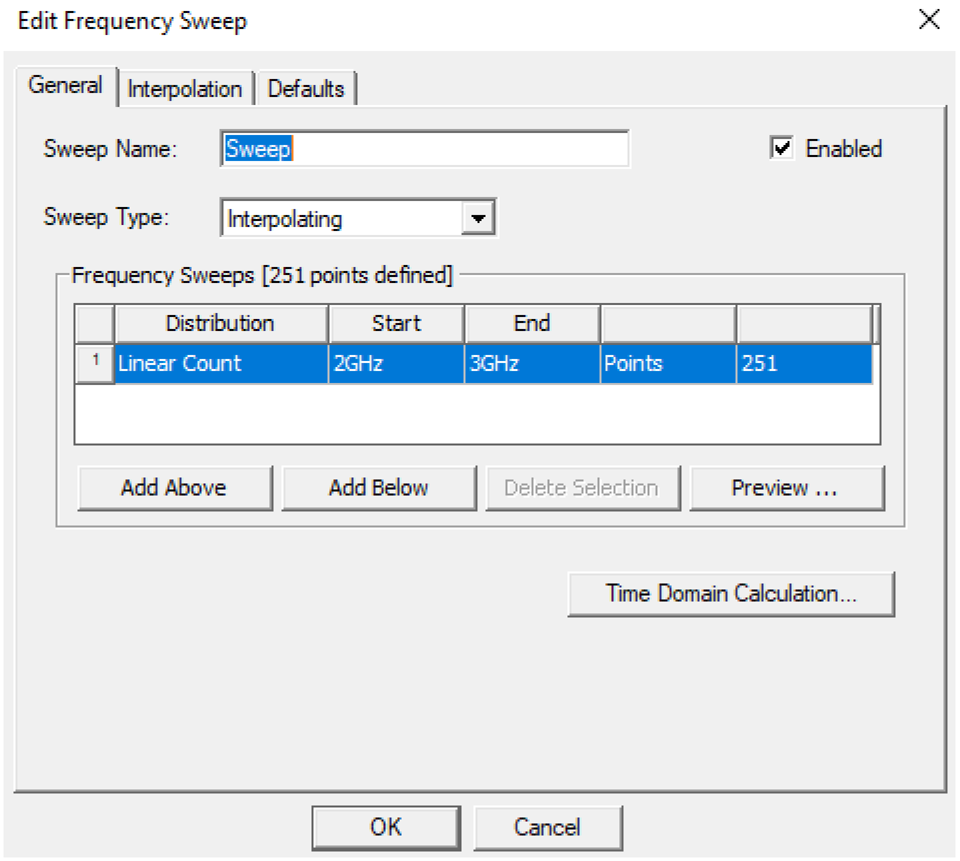
Analysis


ANSYS Electronics Desktop - Project1 - HFSSDesign2 - 3D Modeler - [Project1 - HFSSDesign2 - Model
File Edit View Project Draw Modeler HFSS Tools Window Help
Project Manager
Project1*
HFSSDesign2 (DrivenModal)*
3D Components
Model
Circuit Elements
Boundaries
Excitations
Hybrid Regions
Mesh Operations
Analysis
Paste Ctrl+V
Add Solution Setup...
List...
Analyze All
Revert to Initial Mesh
Apply Mesh Operations
Clear Linked Data
Network Data Explorer...
Create Savant Project...
Create EMIT Project...
Scripts
Model
Solids
Rogers RT/duroid 5870 (
Box1
CreateBox
vacuum
Sphere1
CreateSphere
Sheets
Lumped Port
Perfect E
feed
CreateRectangle
CoverLines
GND
CreateRectangle
CoverLines
radpart
CreateRectangle
CoverLines
Coordinate Systems
Planes
Lists

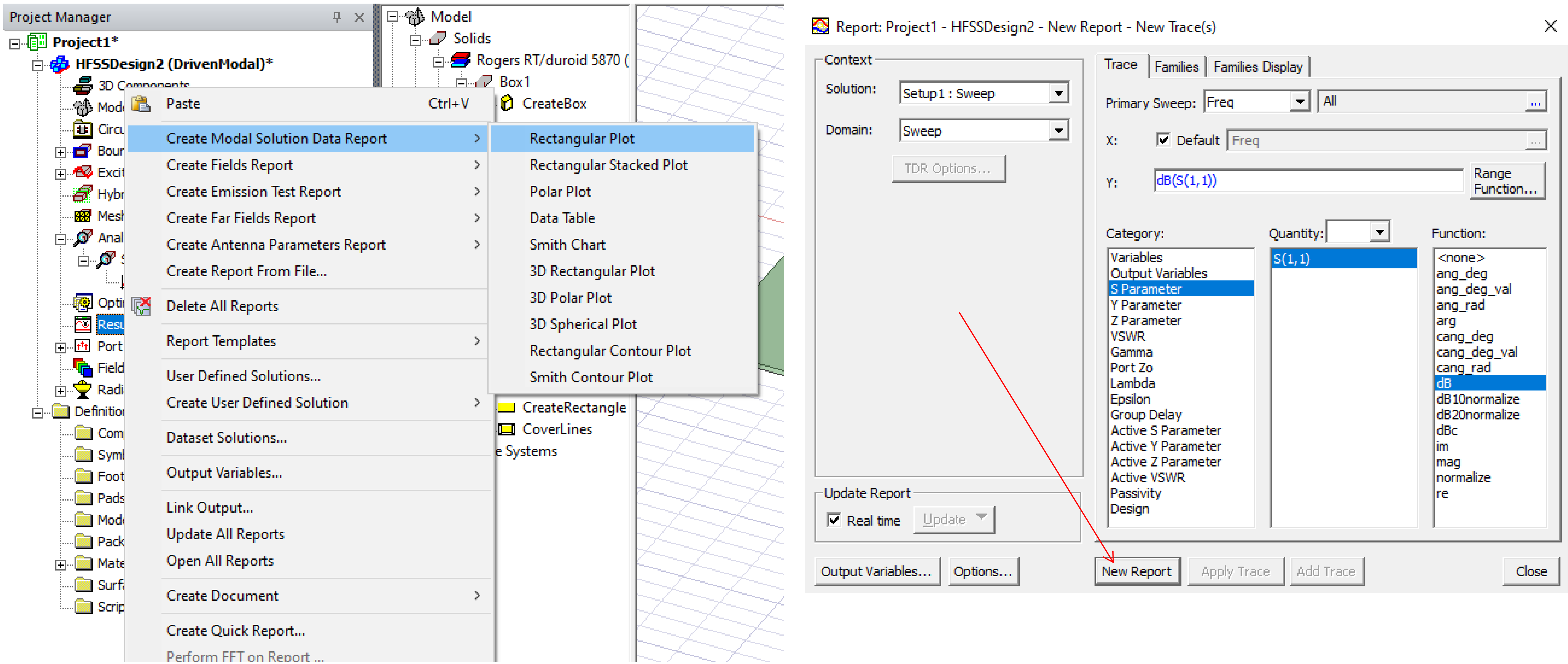

Driven Solution Setup
General
Options
Advanced
Hybrid
Expression Cache
Derivatives
Defaults
Setup Name
Setup1
Enabled
Solve Ports Only
Adaptive Solutions
Solution Frequency:
Single
Multi-Frequencies
Broadband
Frequency
2.45
GHz
Maximum Number of Passes
6
Maximum Delta S
0.02
Use Matrix Convergence
Set Magnitude and Phase...
Use Defaults
HPC and Analysis Options...
OK
Cancel

Analysis

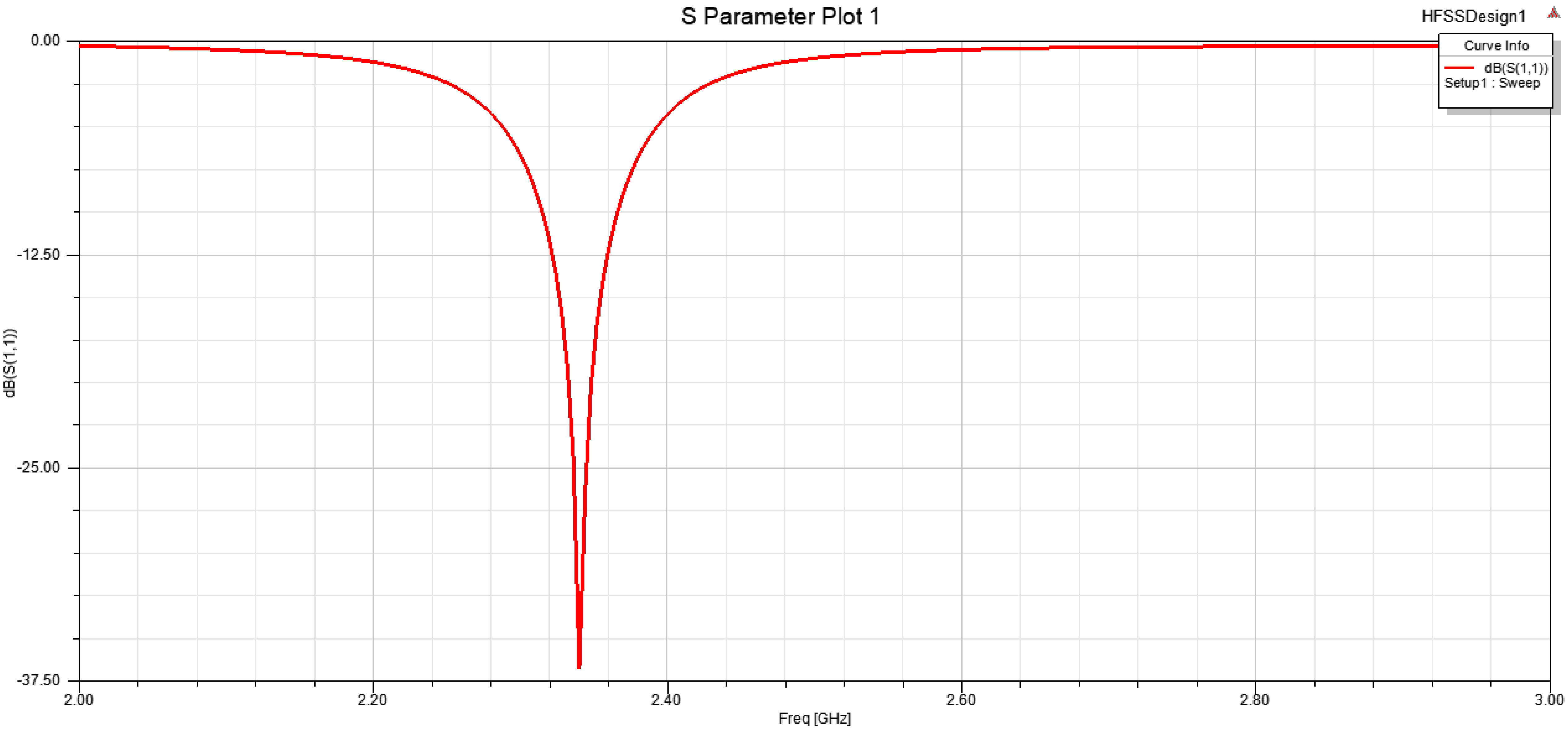

Project Manager
Project1*
HFSSDesign2 (DrivenModal)*
3D Components
Model
Circuit Elements
Boundaries
Excitations
Hybrid Regions
Mesh Operations
Analysis
Setu
Optimetr
Results
Port Fiel
Field Ov
Radiatio
Definitions
Compon
Symbols
Footprin
Padstac
Models
Package
Material
Surface
Scripts
Copy Ctrl+C
Paste Ctrl+V
Rename F2
Delete Delete
Properties...
Disable Setup
Add Frequency Sweep...
Analyze
Submit Job...
Revert to Initial Mesh
Add Mesh Linked Solution Setup
Apply Mesh Operations
Clear Linked Data
Create Quick Report...
Perform FFT on Report ...
Perform TDR on Report ...
Model
Solids
Rogers RT/duroid 5870 (
Box1
CreateBox
vacuum
Sphere1
CreateSphere
Sheets
Lumped Port
Perfect E
eed
CreateRectangle
CoverLines
ND
CreateRectangle
CoverLines
adpart
CreateRectangle
CoverLines
Systems


Edit Frequency Sweep
General
Interpolation
Defaults
Sweep Name:
Sweep
Enabled
Sweep Type:
Interpolating
Frequency Sweeps [251 points defined]
Distribution
Start
End
1
Linear Count
2GHz
3GHz
Points
251
Add Above
Add Below
Delete Selection
Preview ...
Time Domain Calculation...
OK
Cancel

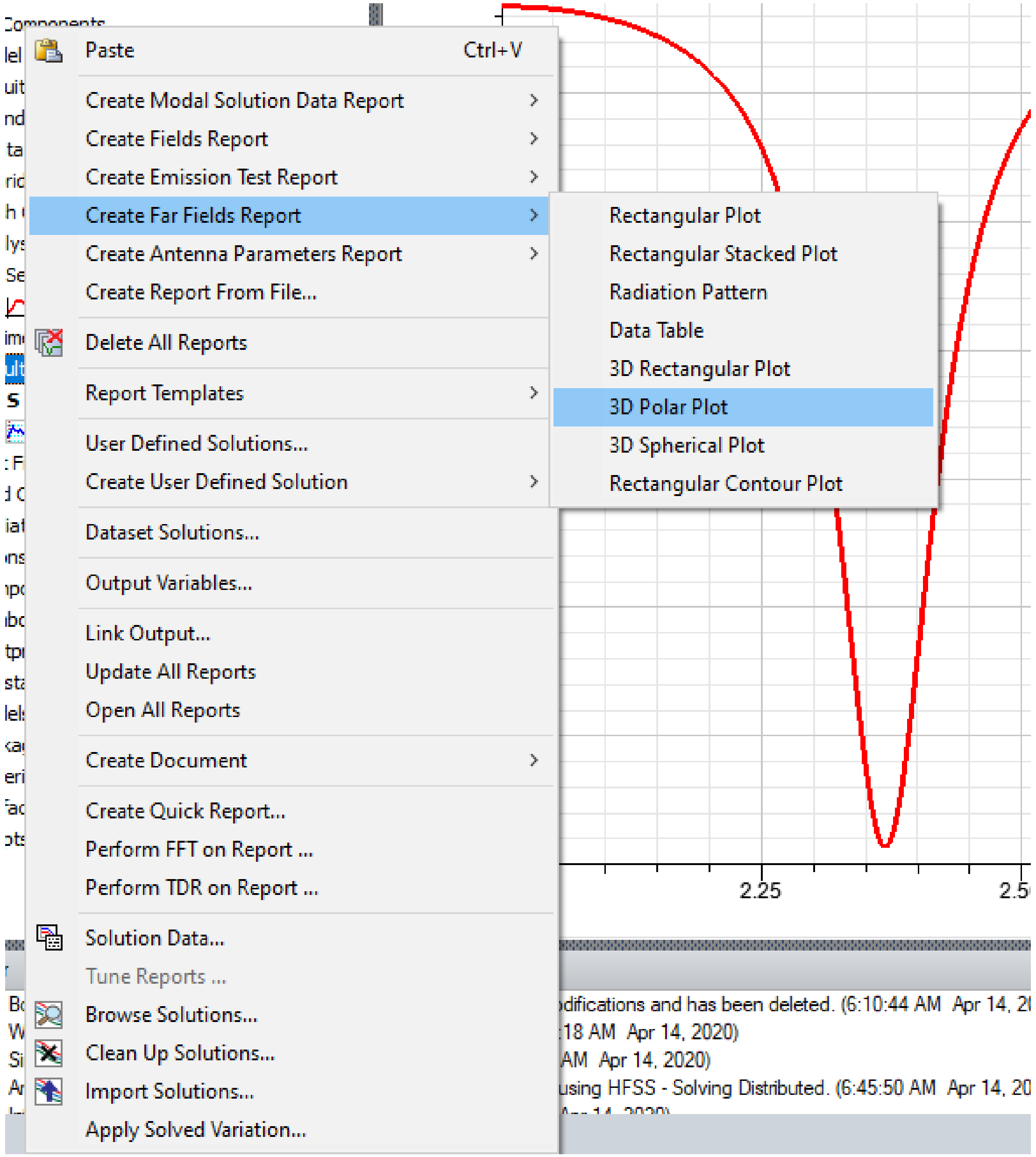
Test: Return Loss, S11

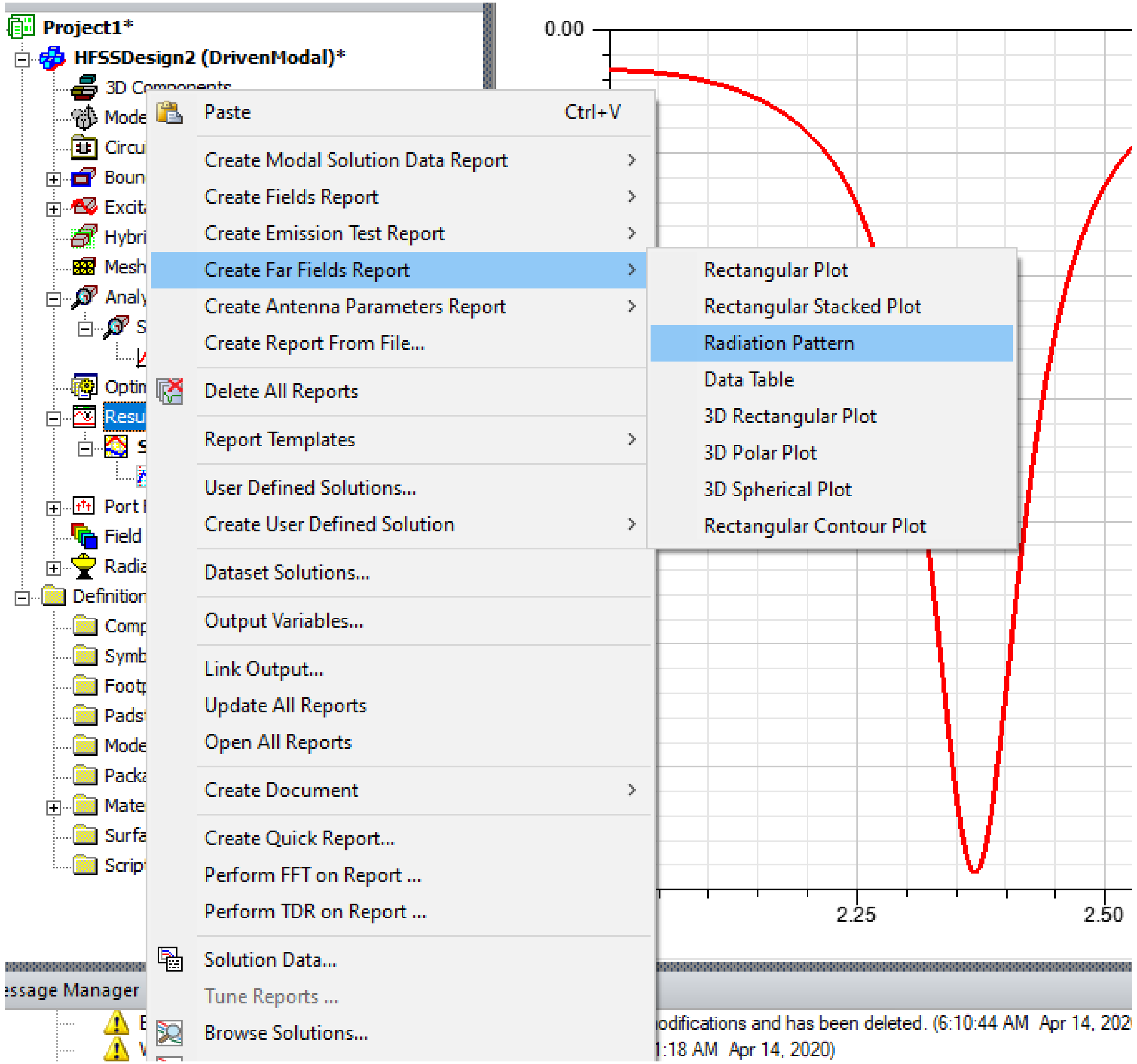


Test S11

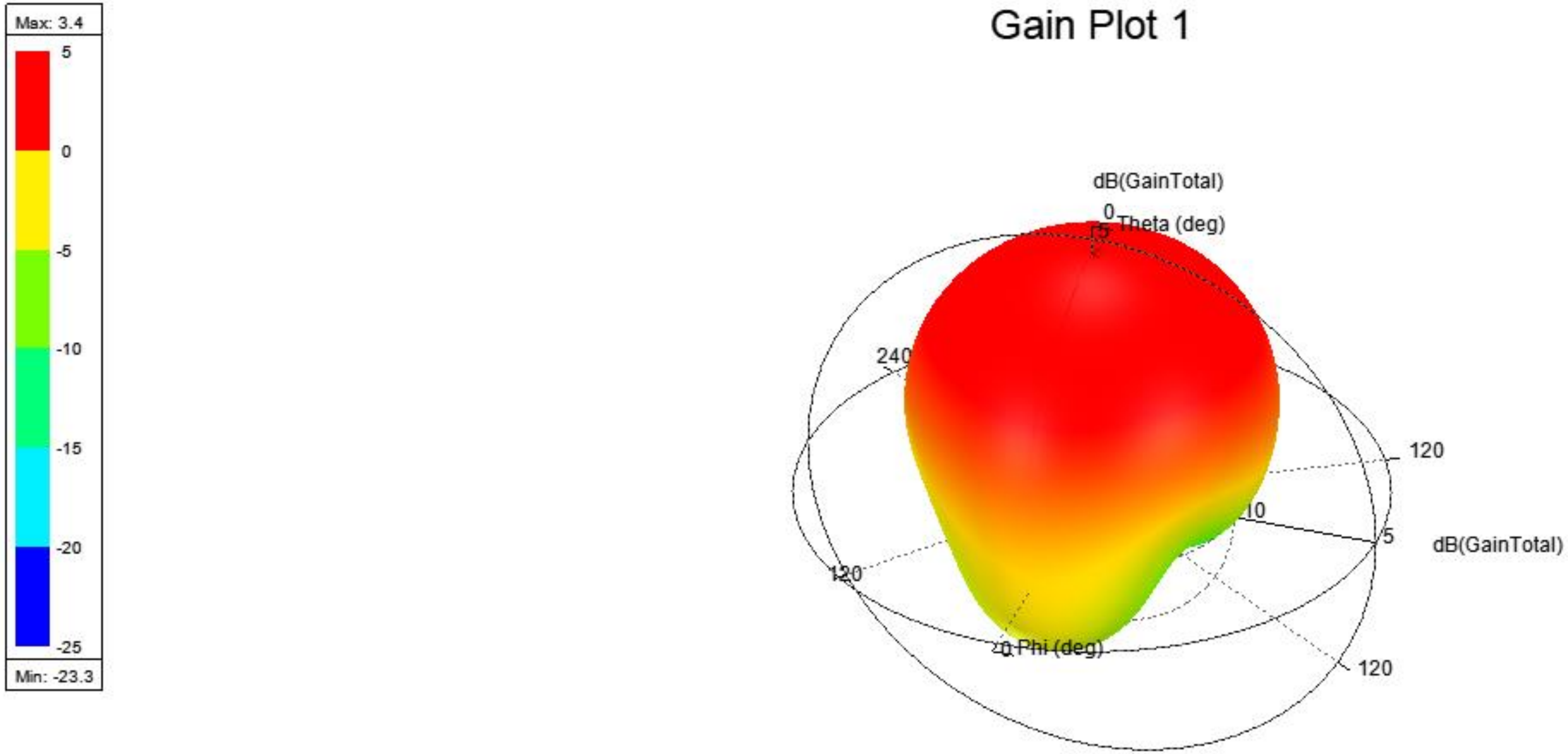

S Parameter Plot 1
HFSSDesign1
Curve Info
dB(S(1,1))
Setup1 : Sweep
0.00
-12.50
-25.00
-37.50
dB(S(1,1))
2.00
2.20
2.40
2.60
2.80
3.00
Freq [GHz]

Test – Pattern

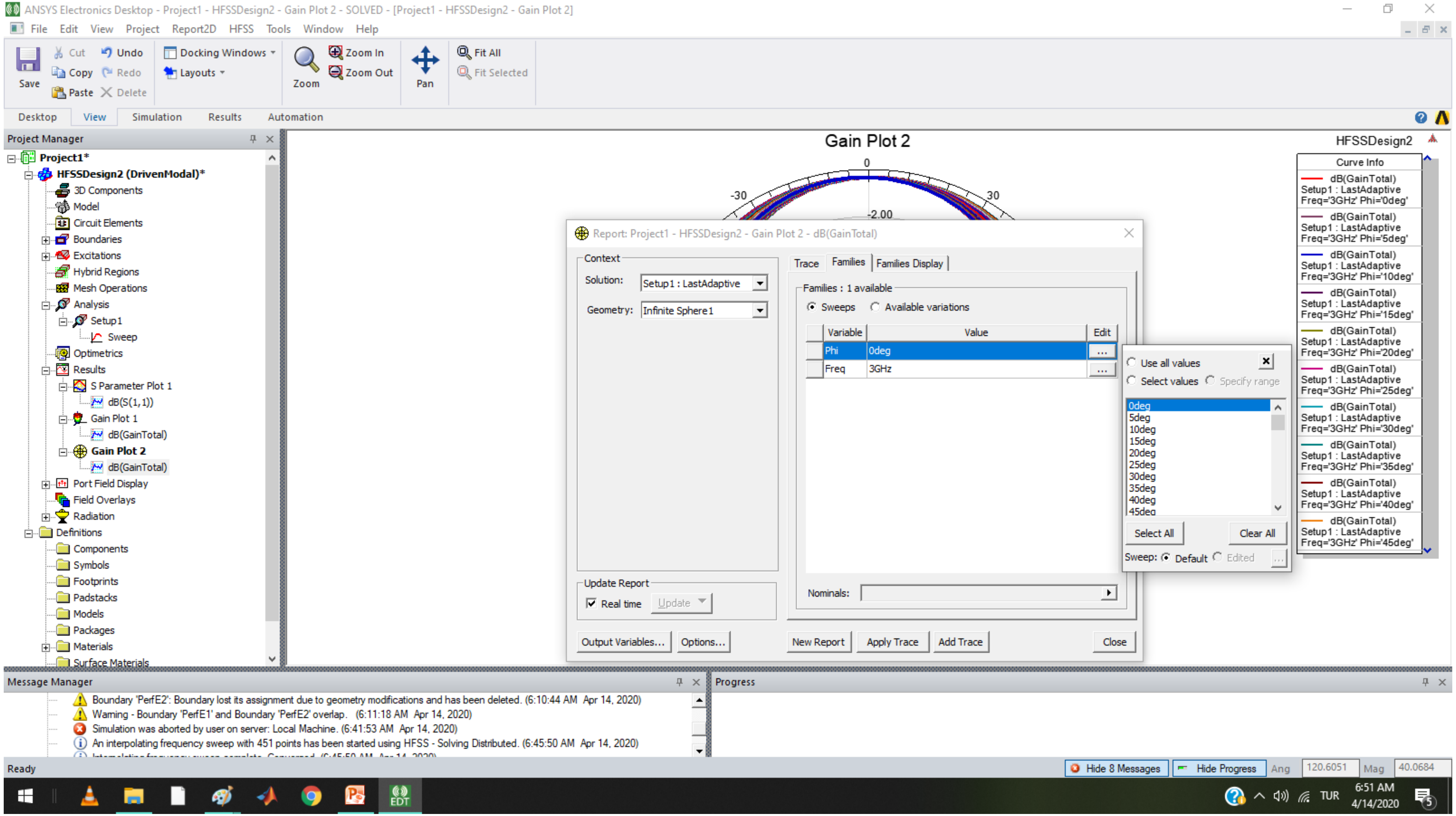




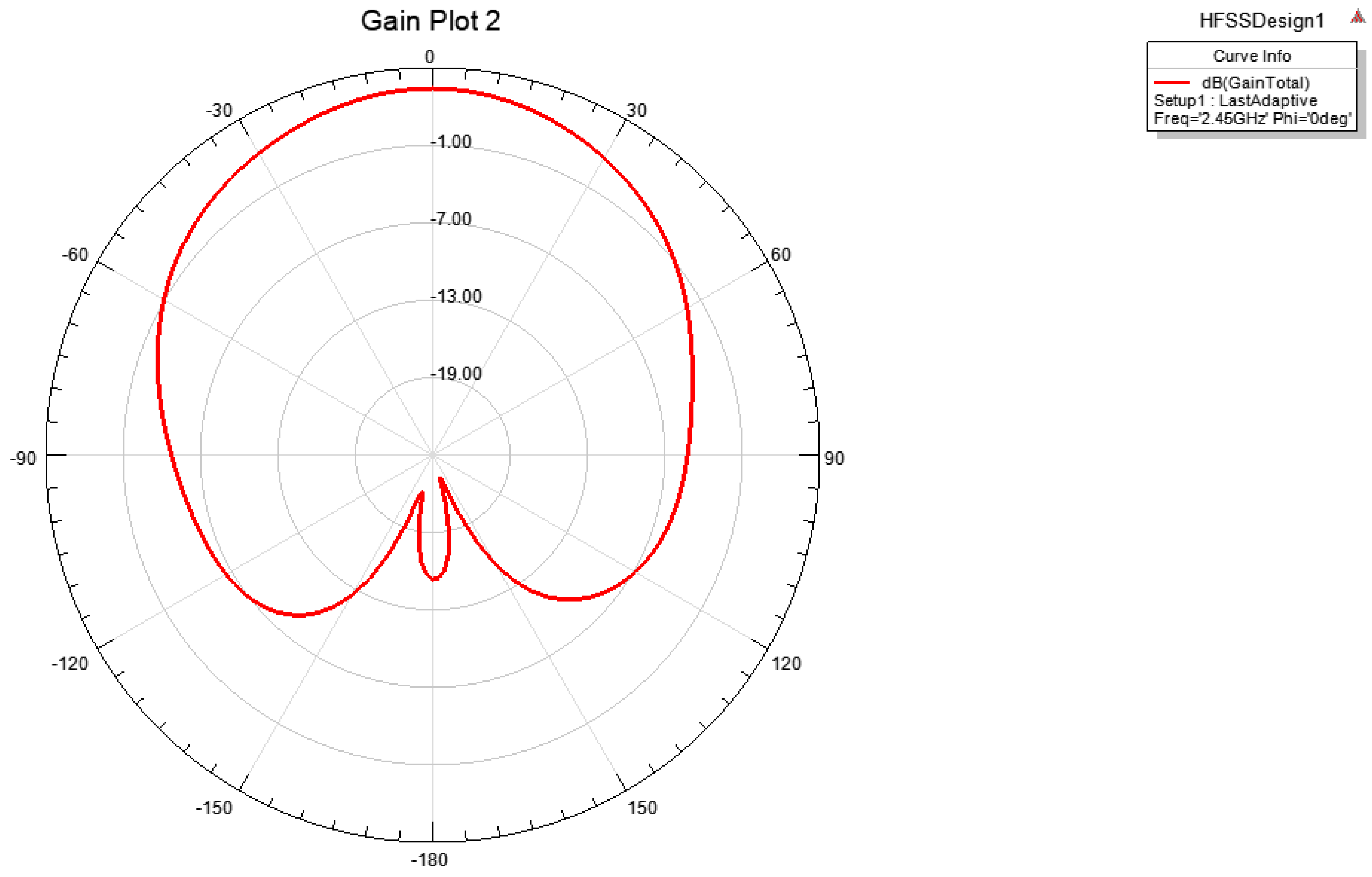
Test – Pattern



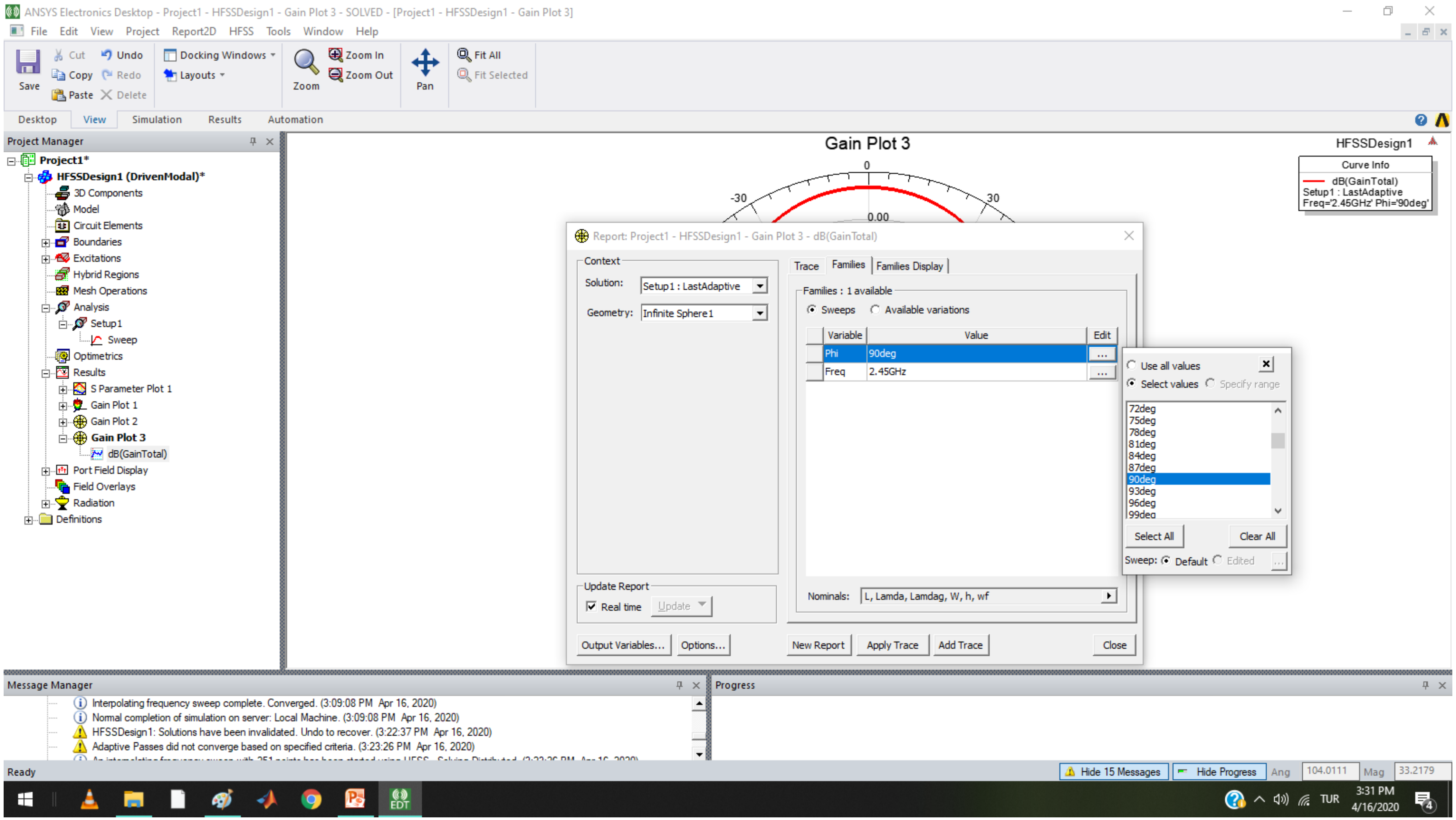
Test: E-Pattern



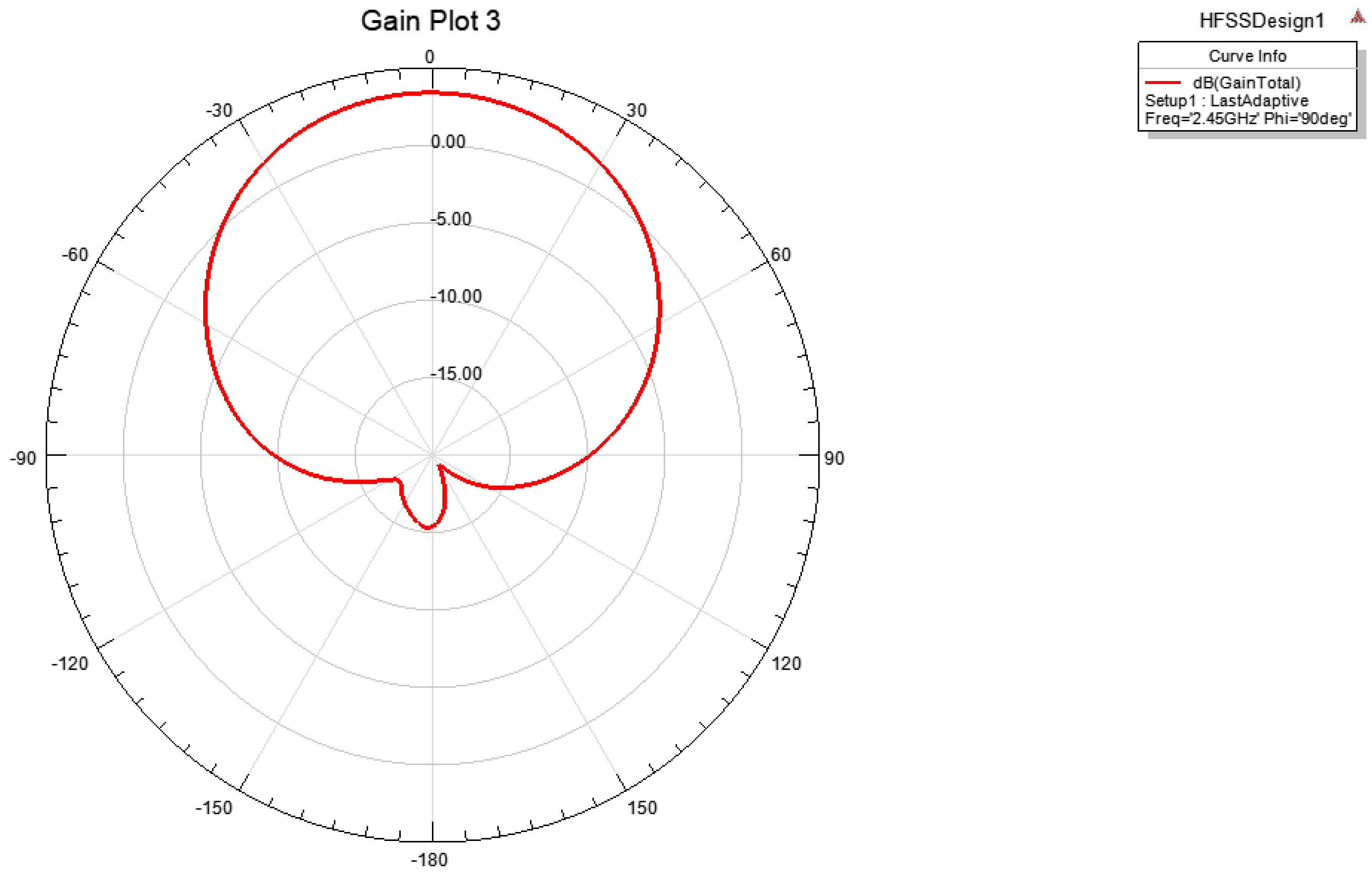
Test: E-Pattern



Test: H-Pattern



Test: H-Pattern

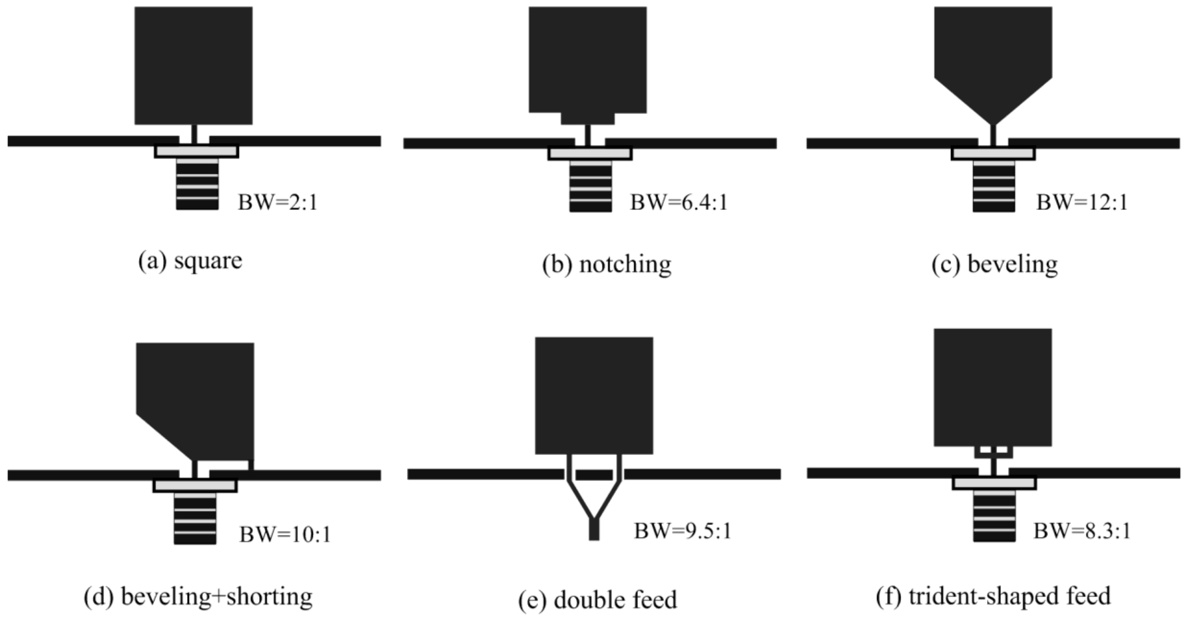


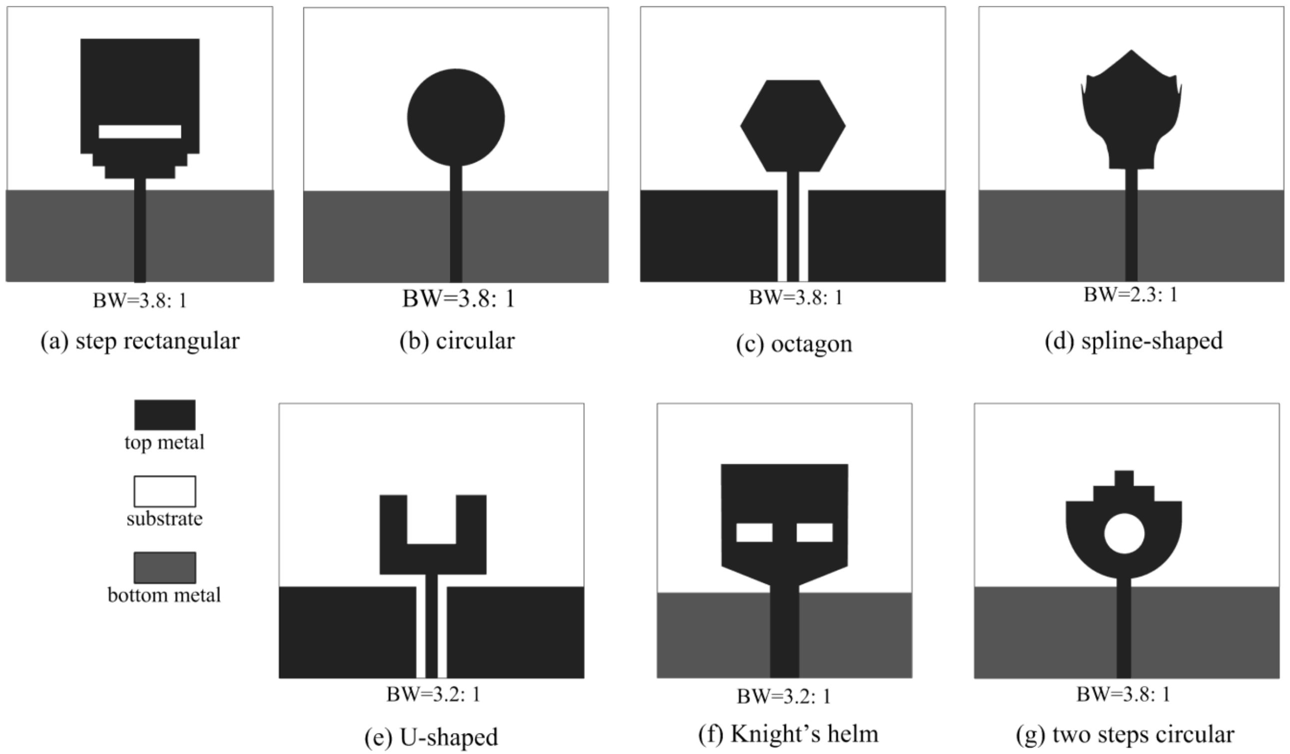
SQUARE PLANAR MONOPOLE ANTENNA

Square Planar Monopole Antenna

- 1991 yılında Honda tarafından düzlemsel bir disk tekel anteni incelendi.
- Japon televizyonları için bu anteni (90-770 MHz) geliştirdi.
- 1992'de tüm S, C, X ve Ku bantları için geri dönüş kaybı 10 dB'den fazla olan, yani 1:18 bant genişliği olduğunu bildirdi.
- Düzlemsel bir monopol, geleneksel bir monopolün tel elemanının bir düzlemsel eleman ile değiştirilmesiyle gerçekleştirilir.
- Kare olan düzlemsel eleman, bir toprak düzleminin üzerine yerleştirilir ve bir SMA konektörü kullanılarak beslenir.

Monopole Antenna Types





Square Planar Monopole Antenna

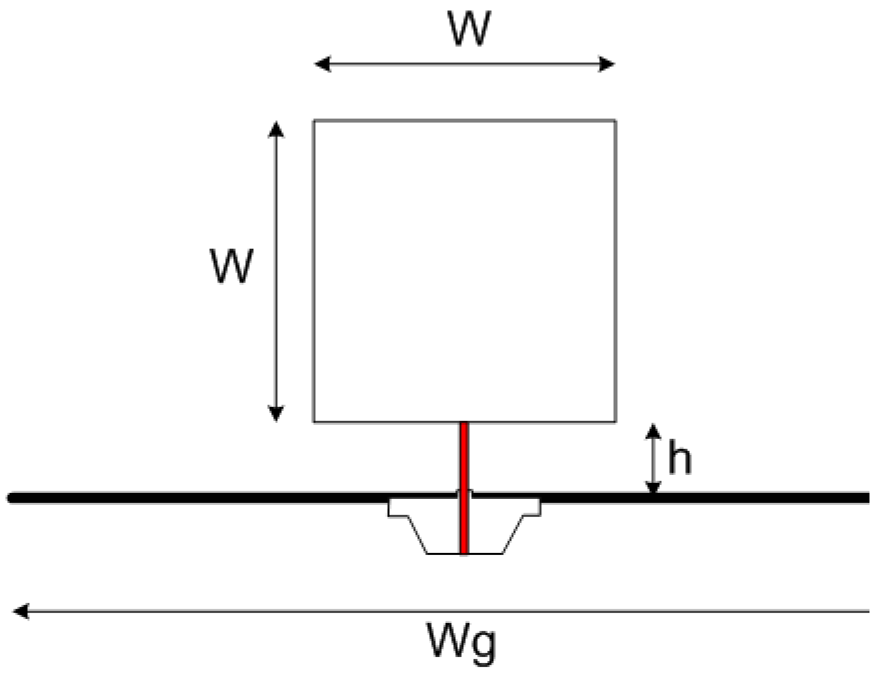
$$\lambda = \frac{c}{f}$$

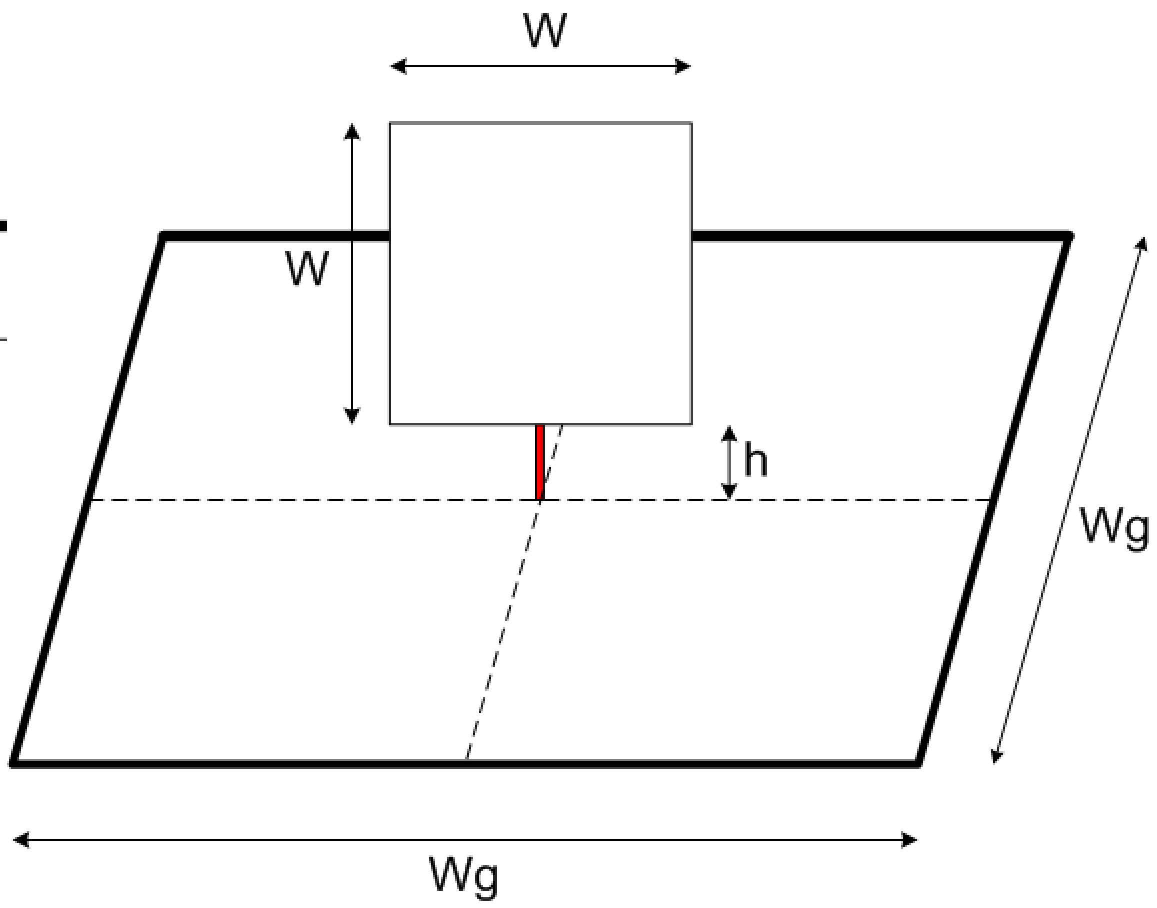
$$W = 0.3\lambda$$

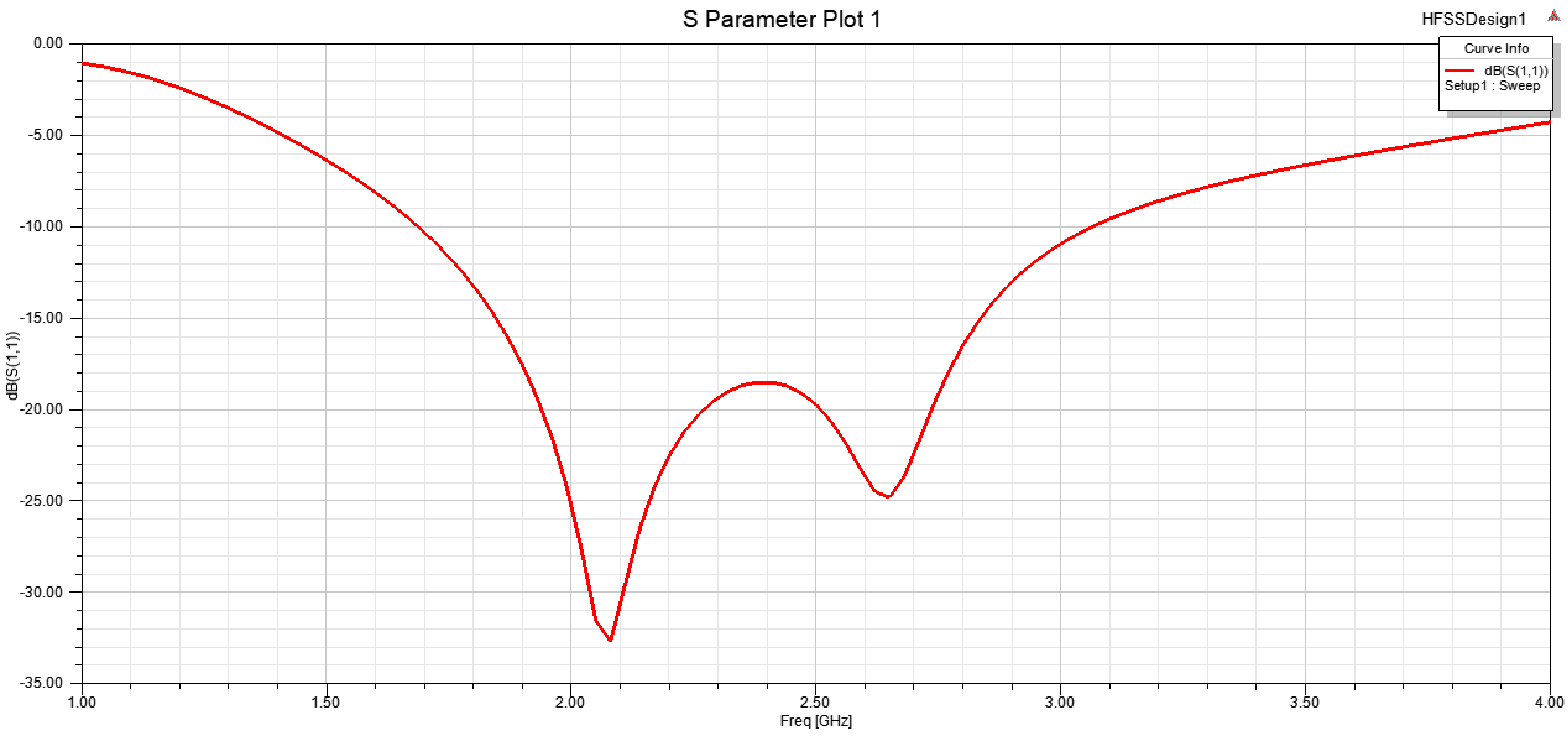
$$W_g = \lambda$$

$$h = 0.02\lambda$$

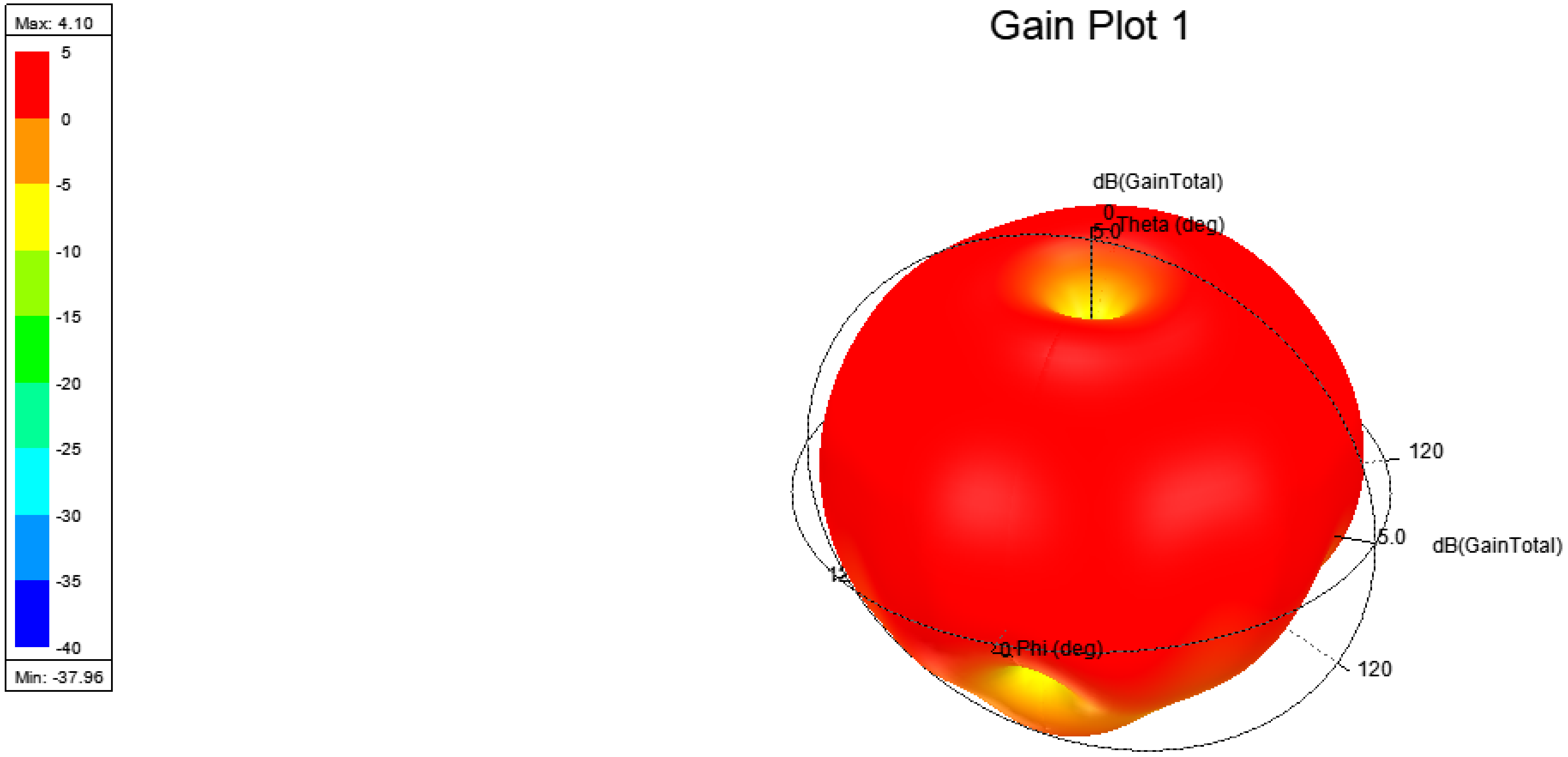
Konnektör çapı 0.01λ alınır.



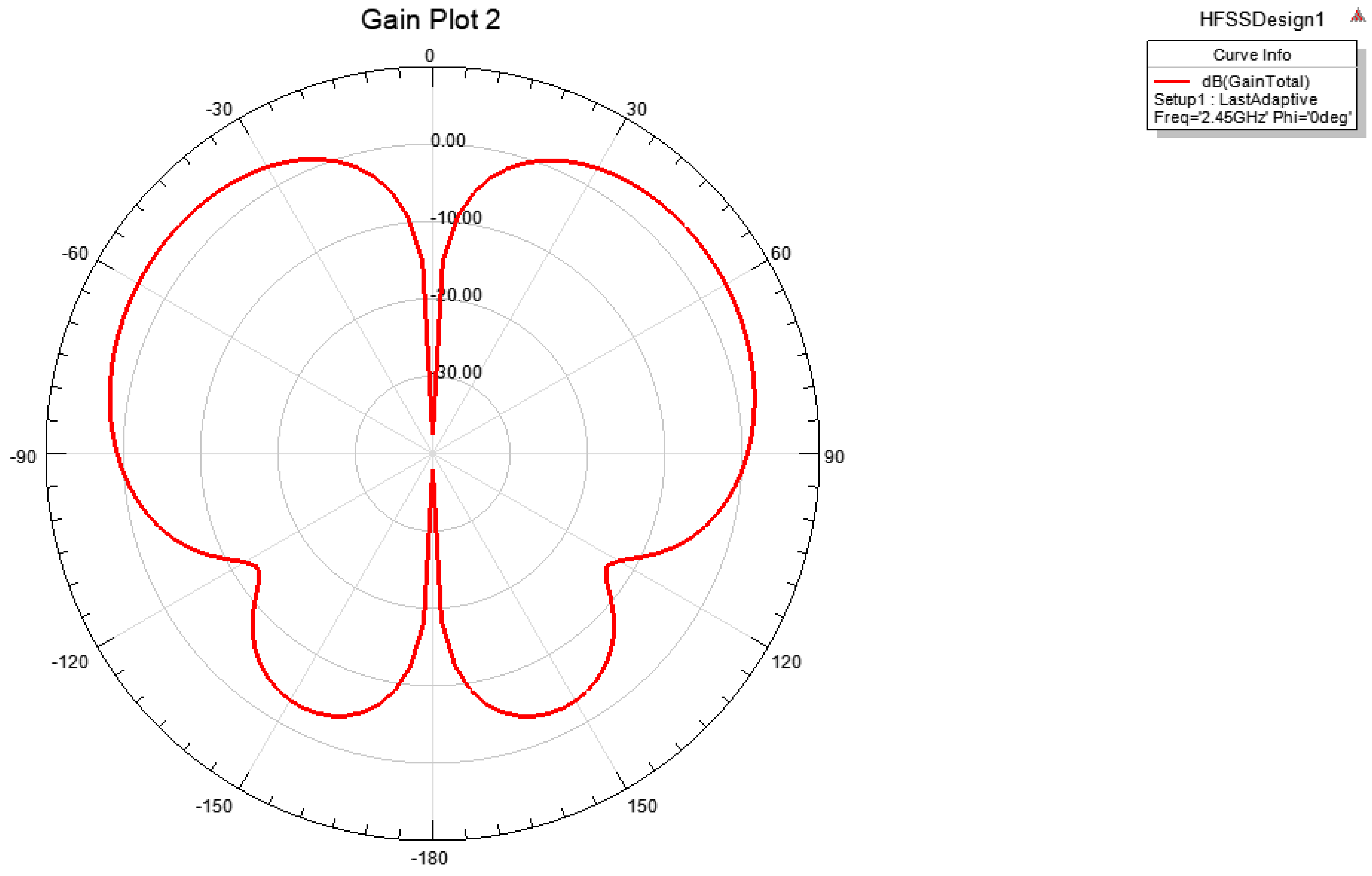



S Parameter Plot 1
HFSSDesign1
Curve Info
dB(S(1,1))
Setup1 : Sweep
0.00
-5.00
-10.00
-15.00
-20.00
-25.00
-30.00
-35.00
dB(S(1,1))
1.00
1.50
2.00
2.50
3.00
3.50
4.00
Freq [GHz]

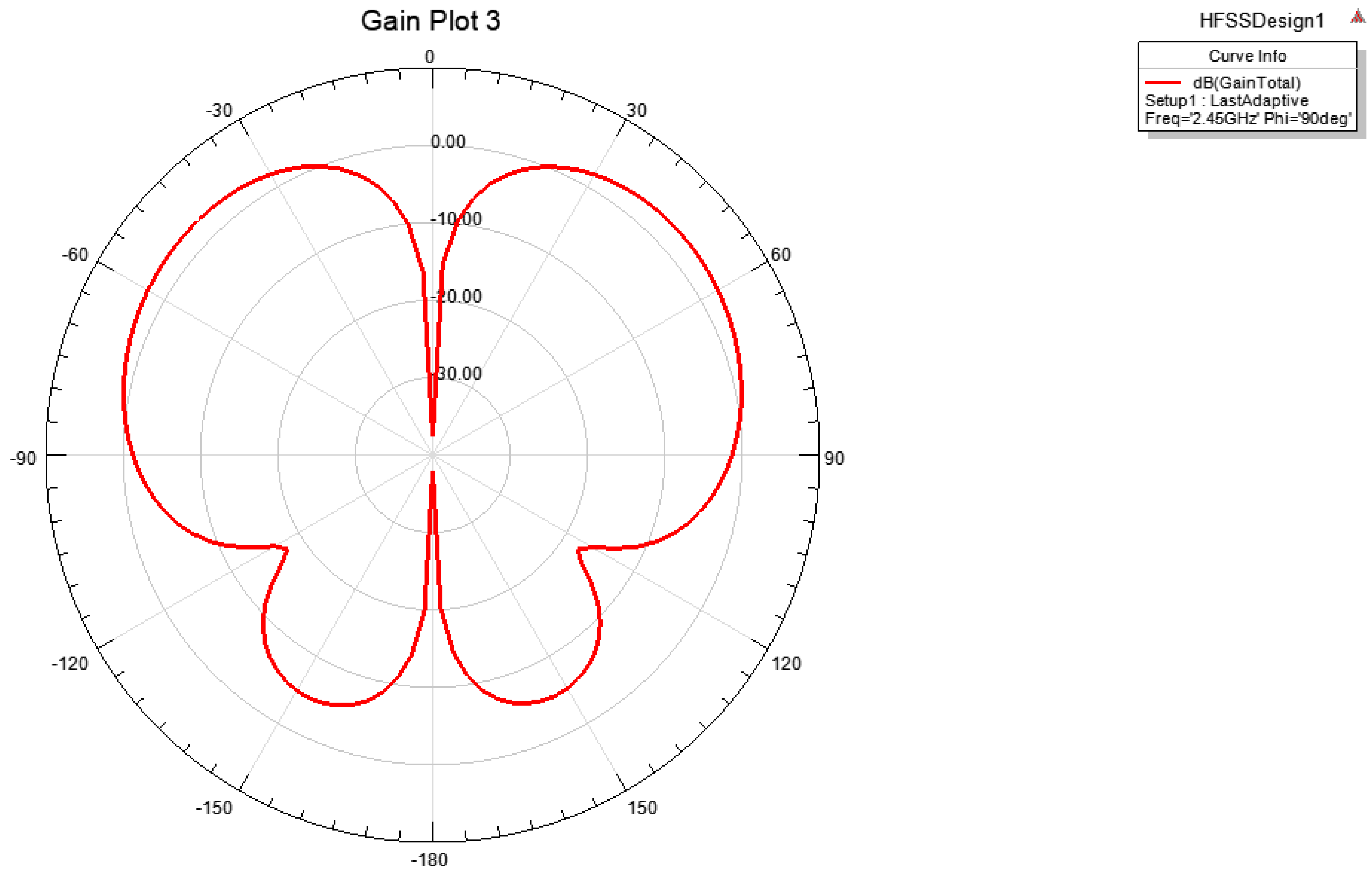
Gain (Far Field report – 3D Polar Plot)



E-Pattern (90derece)



H-Pattern (0 derece)



Dipole Antenna

Dipole Antenna Design

$$\lambda = \frac{c}{f}$$

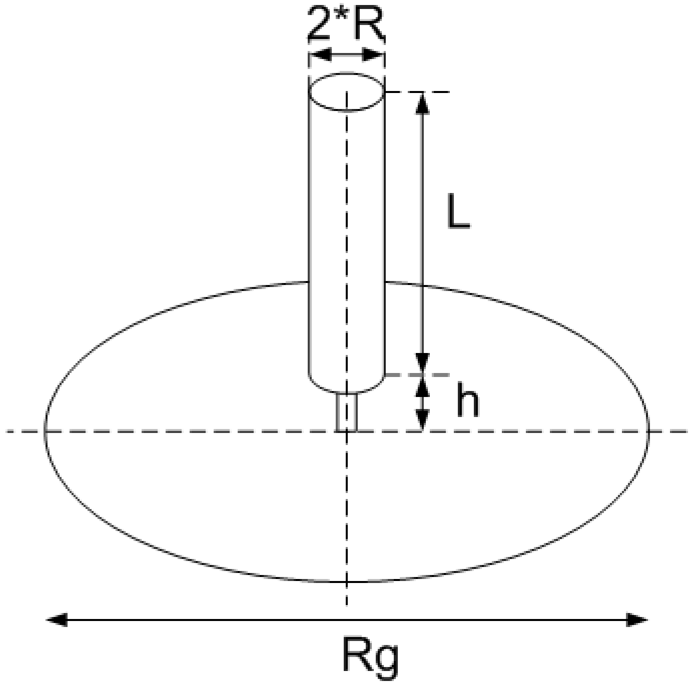
$$L = 0.675\lambda$$

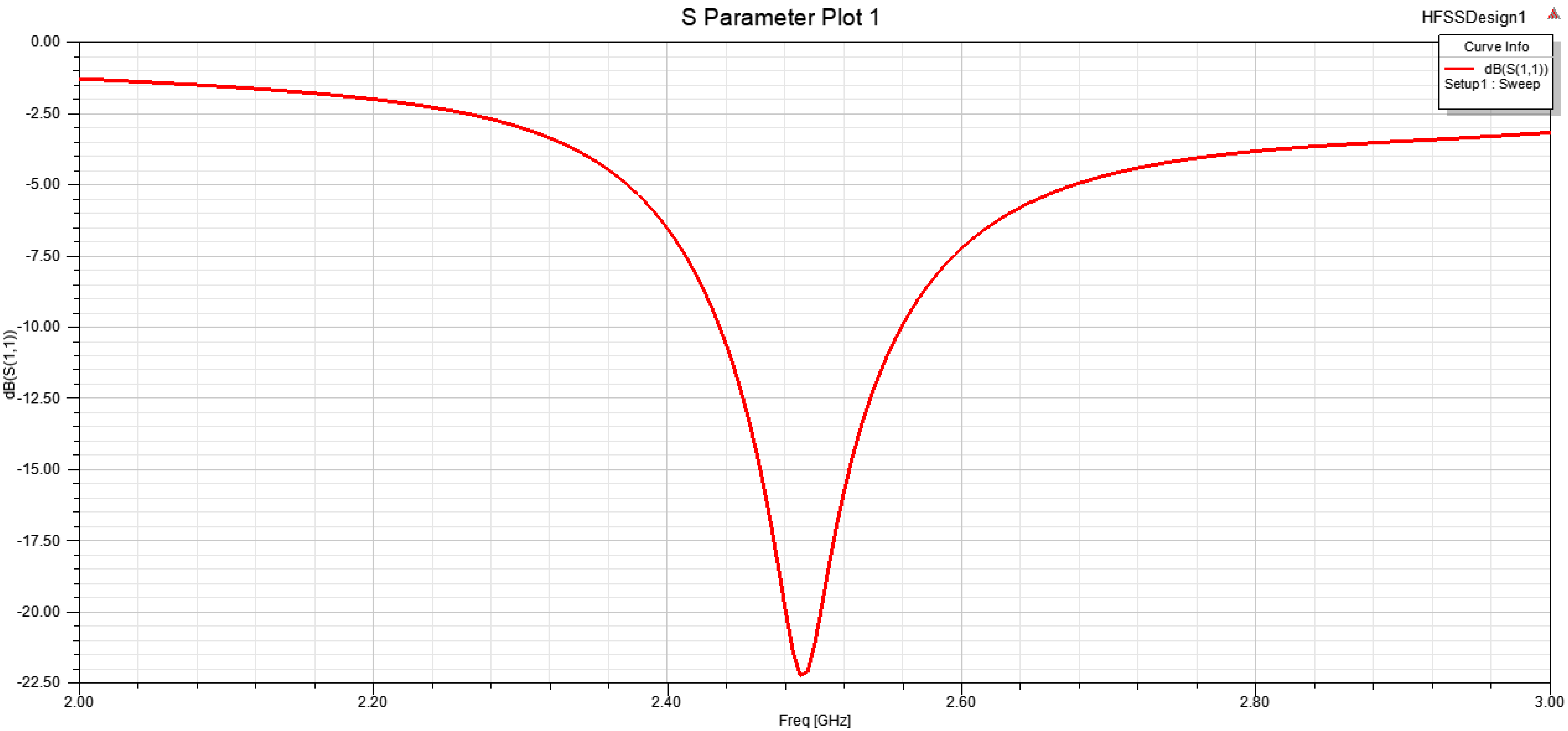
$$R = 0.004\lambda$$

R_g=λ

$$h = 0.02\lambda$$

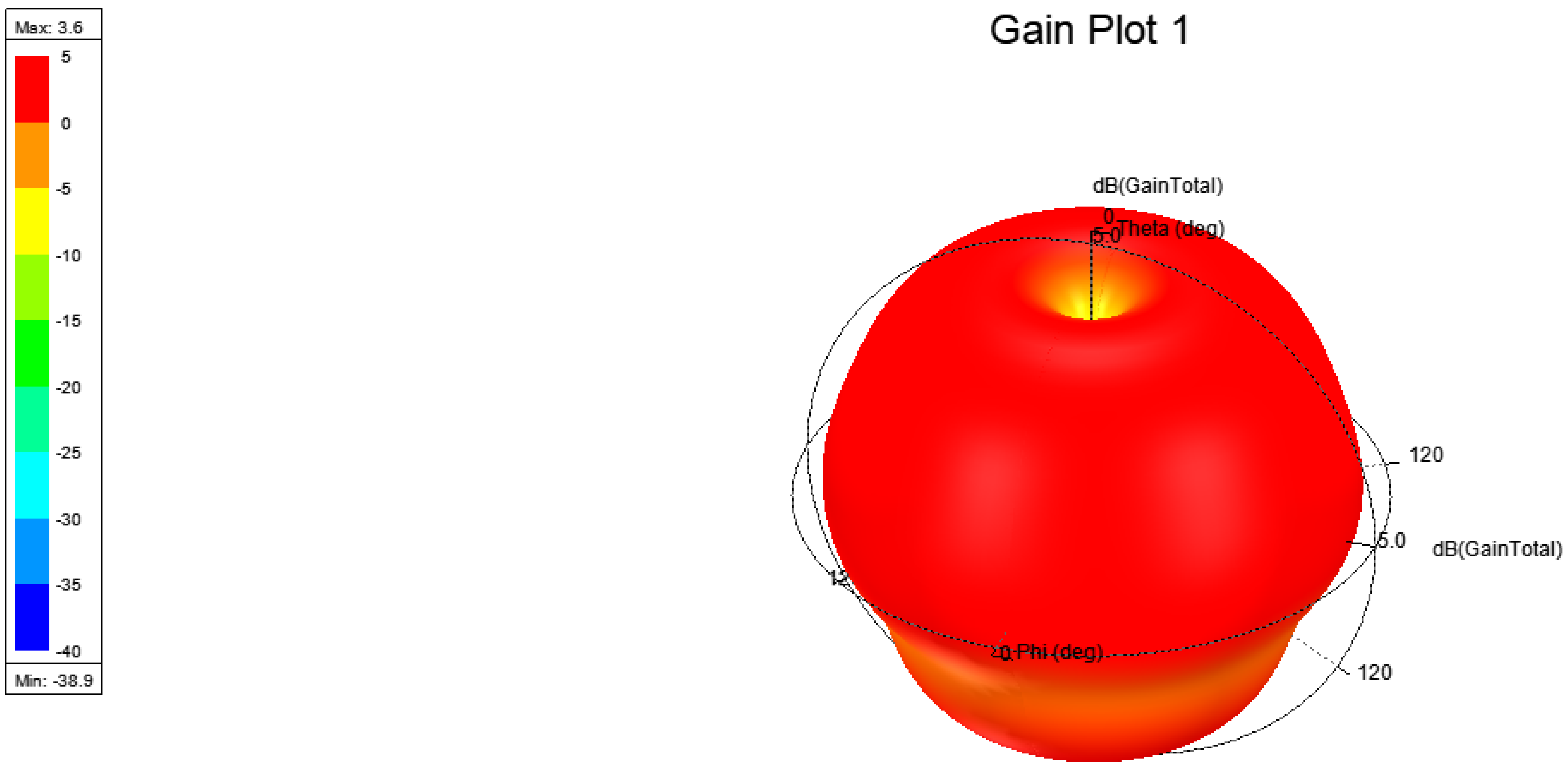
Konnektör çapı 0.01λ alınır.



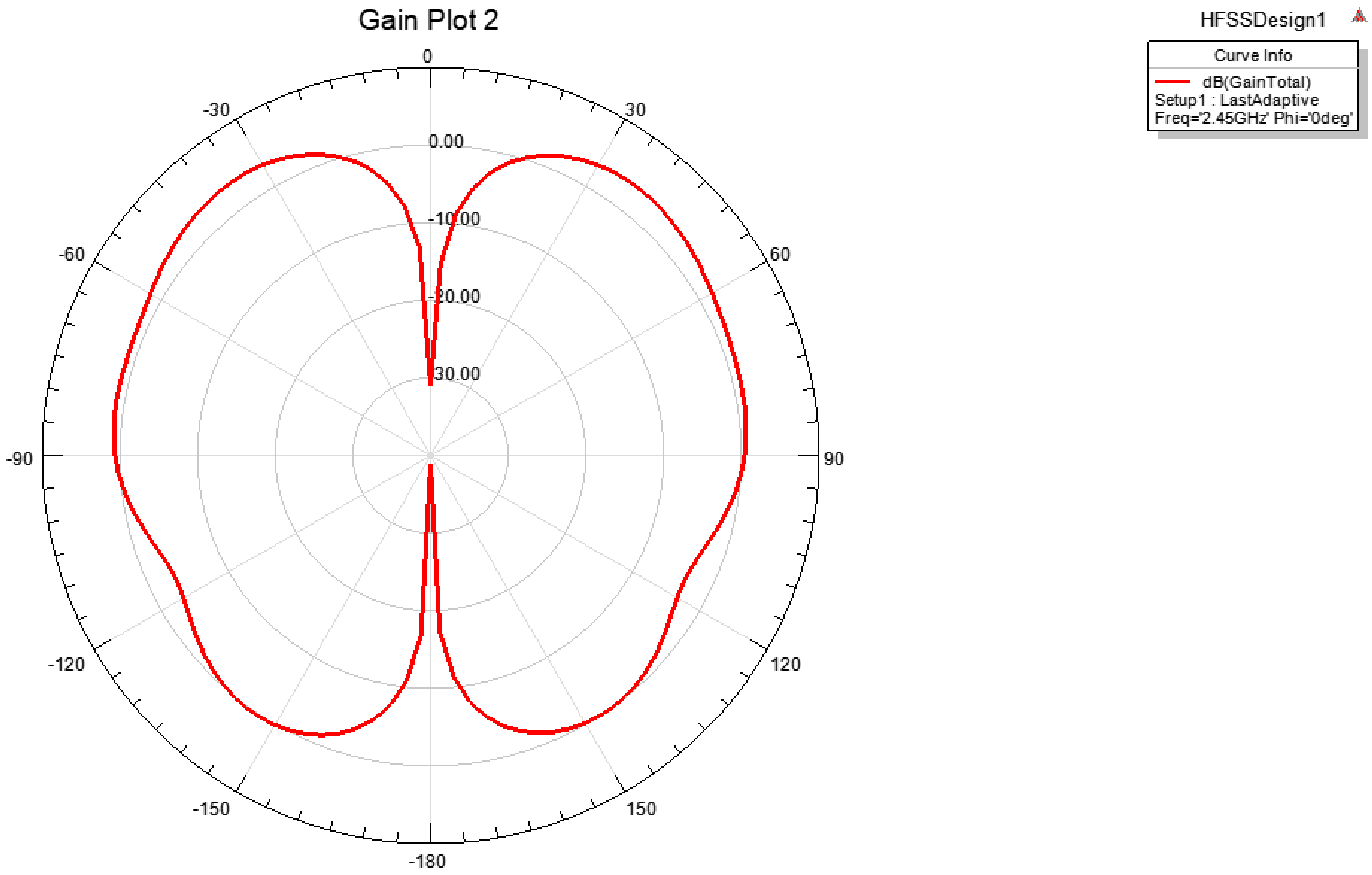


S Parameter Plot 1
HFSSDesign1
Curve Info
dB(S(1,1))
Setup1 : Sweep
0.00
-2.50
-5.00
-7.50
-10.00
-12.50
-15.00
-17.50
-20.00
-22.50
dB(S(1,1))
2.00
2.20
2.40
2.60
2.80
3.00
Freq [GHz]

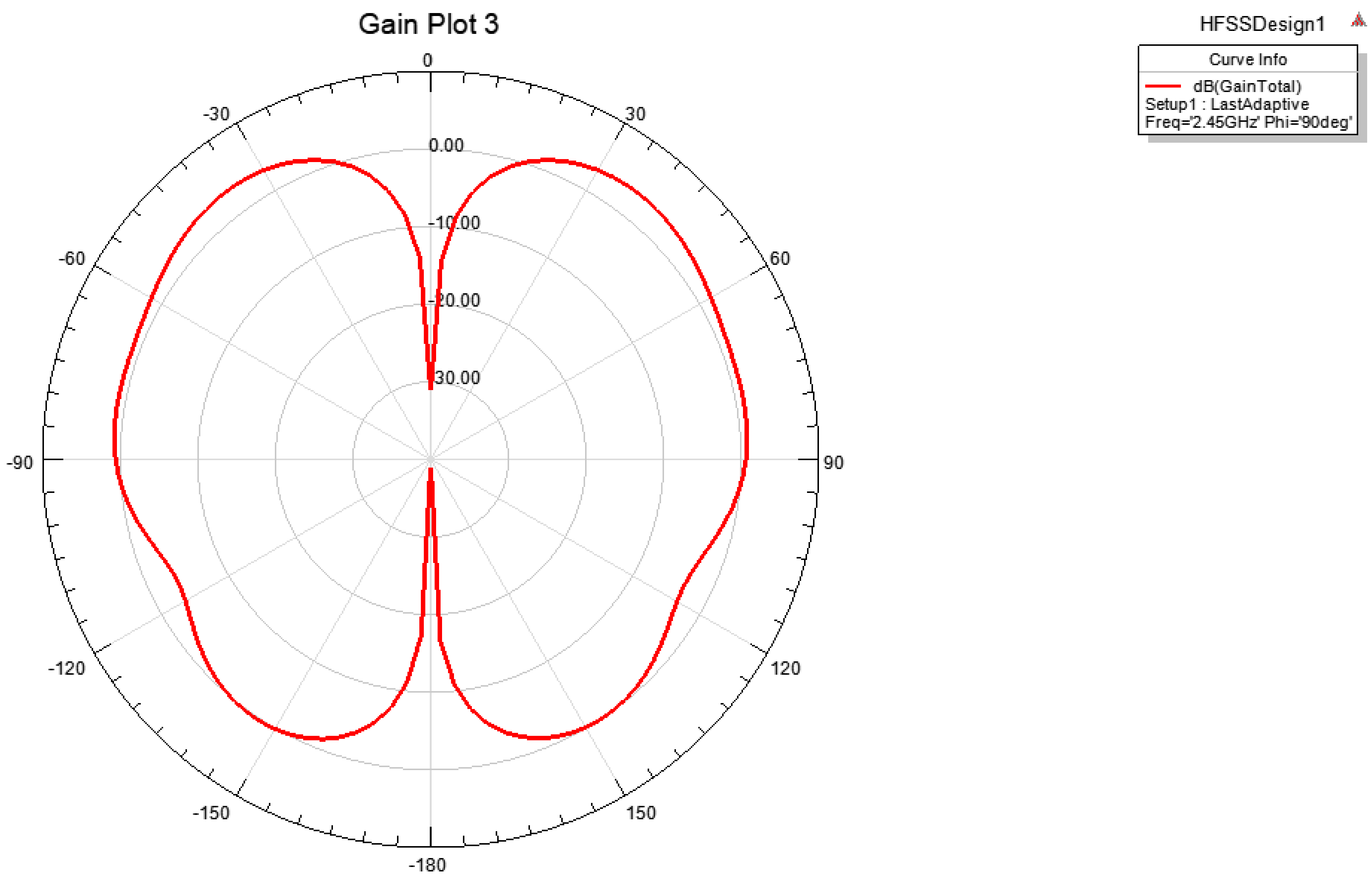
Gain (Far Field report – 3D Polar Plot)



E-Pattern (90derece)



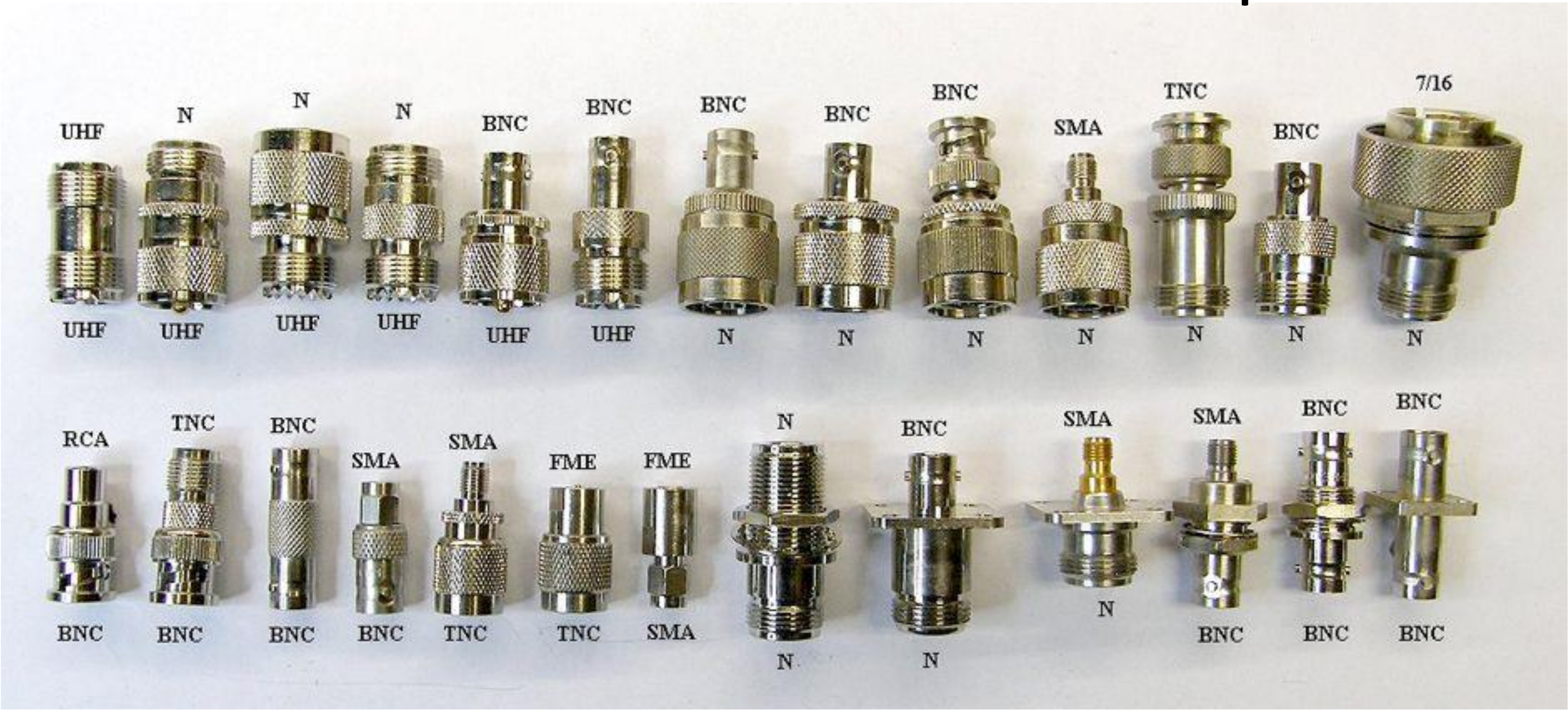
H-Pattern (0derece)



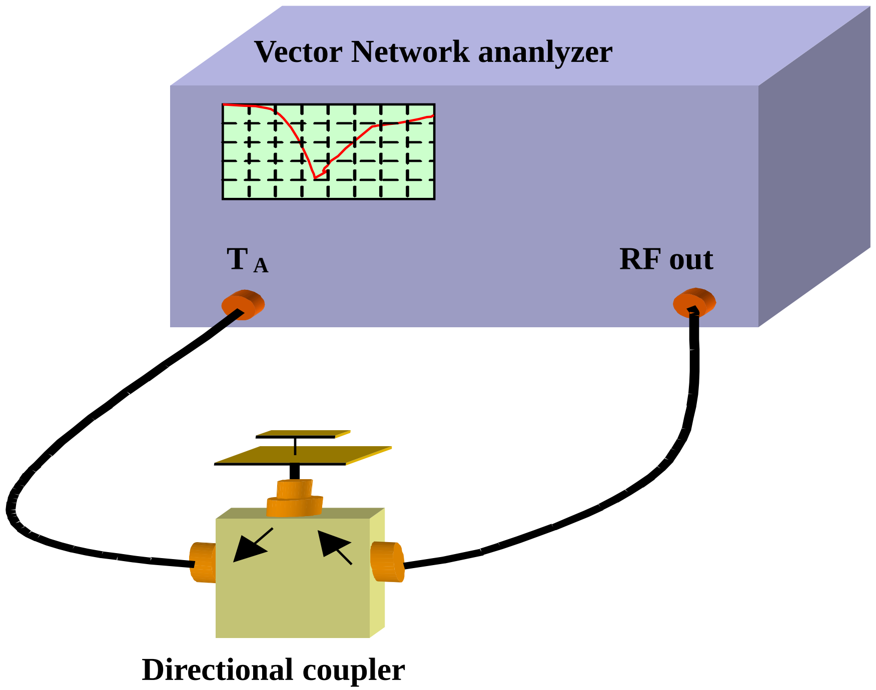
Anten Parametreleri Ölçümü:

Işıma Paterni
S11-Return Loss, VSWR
Gain

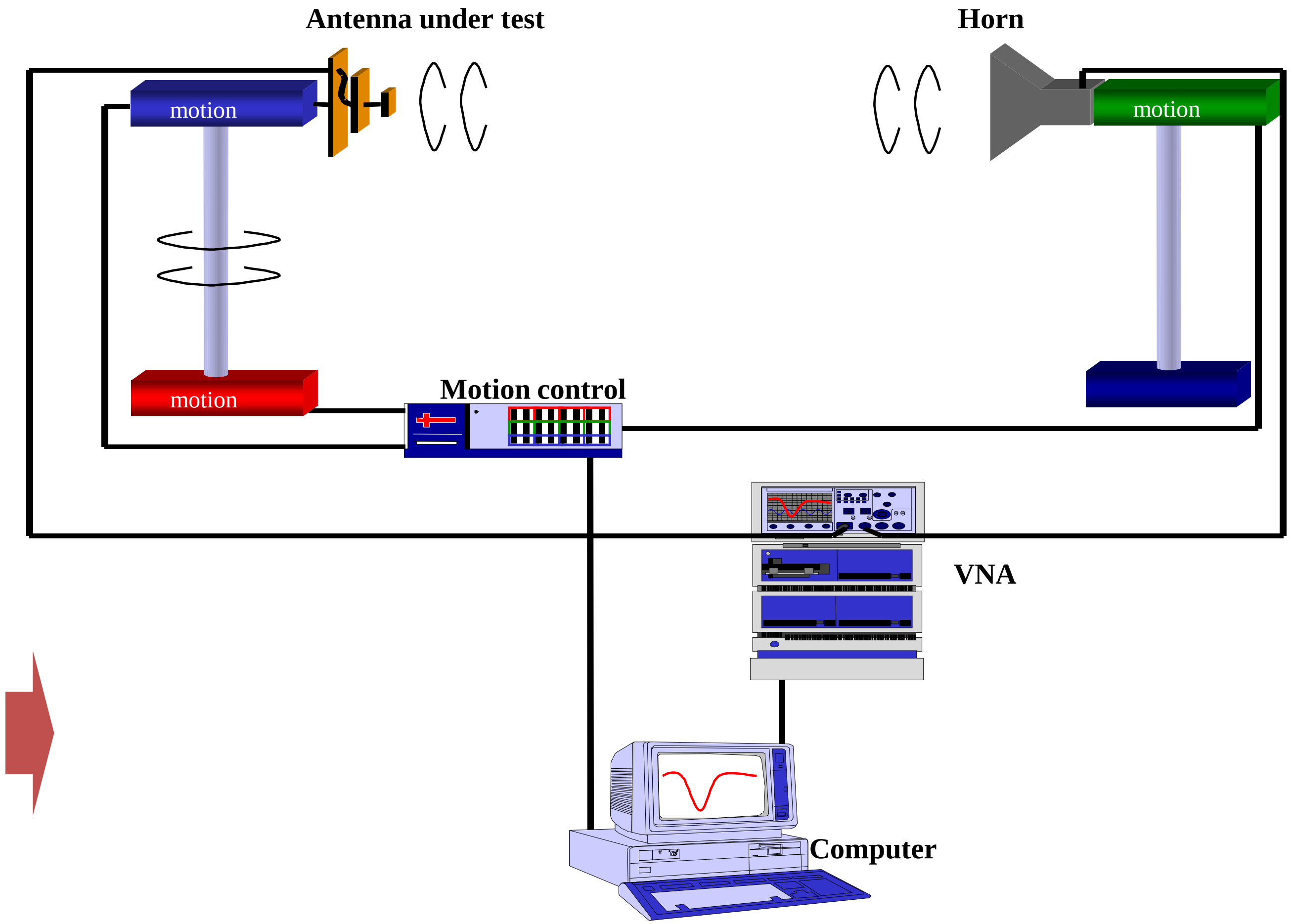
Konnektör Tipleri



Measurement methods

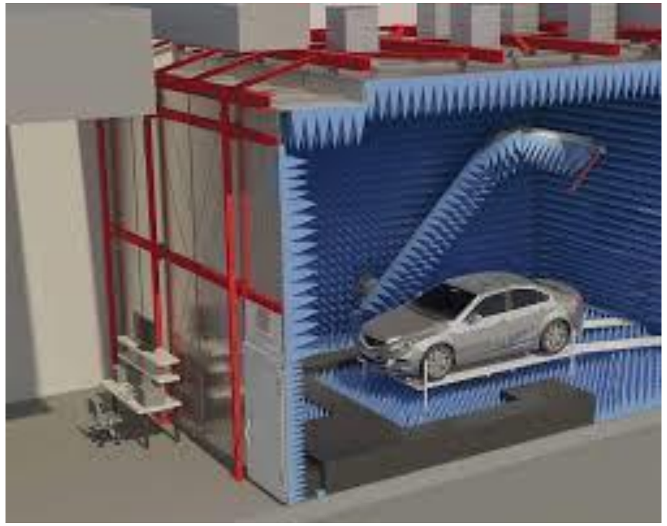


Impedance matching measurements



Radiation measurements

Yansımasız Oda



Radome

- Bu nedenle, anten sistemini havanın bu olumsuz etkilerinden, dış erişim tehditlerinden korumak için radom kullanılır.
- Radom, anten üzerinde olumsuz etkiler yaratan toz, su, su buharı, rüzgar, böcekler, partiküller, güneş radyasyonu, vs.den anteni korur. 250 km/saat rüzgar hızına dayanabilmelidir.
- Radomun iç sıcaklığı -50 – +60°C olması durumunda çalışabilmelidir. Isıtma yapılacaksa tamamen kuru havayla yapılmalıdır. Radom üzerine çok yağış düştüğünde antenin düşeydeki polarizasyonu kaybolur.
- Önemli olan kılıfta kullanılan malzemenin elektromanyetik dalgaların geçişine olabildiğince uygun olmasıdır.
- Bu yapının adı RAdar DOMe (yani radar-kubbe) kelimelerinden türetilmiştir.
- Bu koruyucu kaplama, elektromanyetik dalgaları olabildiğince az yansıtmalı, soğurmalı (absorbtion), kırmalı (diffraction) veya saçmalıdır (scattering) ve geçiş kayıpları yine olabildiğince az olmalıdır.
- Dieltrik malzemede yapılmalıdır. İletken olamaz. Polypropilen
- Bir radomda dalgaların, hem gidiş ve hem de geliş yönündeki zayıflama oranları aynı olmalıdır. Bu nedenle bir „Çift Yönlü Zayıflama" söz konusudur. Bu Çift Yönlü Zayıflama değeri köpüklü bir malzemeden yapılmış bir radomda tipik 0,3 dB civarındadır, yani bu yüksek frekanslı enerjide yaklaşık bir toplam %7 lik kayba karşılık gelir. Radar denklemine göre ise bu yaklaşık %2 lik bir menzil kaybı demektir.
- Uçağın burnunda rüzgarı ilk karşılayan bölge olan radom, radar antenlerinin üzerine yapılan kaplama olarak özetlenebilir. Radom, uçağa aerodinamik bir özellik kazandırır.
- Ayrıca hızlı bir şekilde dönen antenler sayesinde yakındaki personeli kazara çarpmalara karşı korurlar.

Radome

- Uçağın burnunda rüzgarı ilk karşılayan bölge olan radom, radar antenlerinin üzerine yapılan kaplama olarak özetlenebilir. Radom, uçağa aerodinamik bir özellik kazandırır.
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Kaynaklar

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Sincerely,

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