Low dk Thermoplastic Substrate for Broadband Antennas

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Abstract
In high frequency circuit boards PTFE is widely used as a substrate material. It offers very low dielectric constant and low losses. However, it is relatively expensive to fabricate, making the cost of PTFE laminates high. In addition PTFE-based circuit boards are composite materials with glass fiber reinforcement and thus not isotropic. Glass fiber also increases losses compared to raw PTFE.

We have developed a new proprietary thermoplastic substrate especially for high frequency circuit boards. This polyphenylene ether (PPE) based substrate offers a low dielectric constant (dk), 2.55, and low dielectric loss (df), 0.002, in 1 to 5.5 GHz frequency range. It is unfilled, which makes the properties both isotropic and completely homogeneous throughout the substrate. This new material can be processed by typical thermoplastics processing methods, such as film and sheet extrusion and injection molding. Among thermoplastics, PPE is inherently low burning material and it can be easily made flame retardant (V0). However, the addition of flame retardant was found to slightly increase the dielectric loss at high frequencies. This plastic material exhibits a high glass transition temperature, Tg, around 200ºC. This also gives the highest short term use temperature. There is no crosslinked structure to support the substrate above Tg. Processes requiring higher temperatures, such as conventional lead free reflow soldering or wave soldering can not be used.

Because of the very good dielectric properties the material is intended for high frequency applications where the number of required solder connections is limited. One of these is a broadband base station antenna. The performance of this new material as a UMTS/WCDMA antenna for 1.92 – 2.17 GHz frequency band was evaluated with very promising results. First, a patch antenna was designed based on simulations and then the demo antenna was built. The measured performance coincided well with the simulation data. Design of a full size base station array antenna demonstrator is also presented.

Background and Material Development
Polyphenylene ether (PPE) is a polymer which offers an attractive set of properties. The dielectric properties are excellent because of its unpolarity. It exhibits a high glass transition temperature Tg, 217ºC and it is inherently low burning. The good dielectric properties of PPE have been utilized in GETEK laminates and APPE laminates. GETEK laminates are made by adding PPE to crosslinkable epoxy and in APPE PPE molecules take part in the cross-linked structure. E-Glass is used as reinforcement in these grades. These materials are marketed as excellent low dk/df materials for high frequency applications. The typical dk is 3 to 4 and df is 0.002 or lower.

Our approach was to prepare a PPE based laminate by utilizing the thermoplastic nature of PPE. PPE as such is very difficult to process and in order to make it a real thermoplastic resin it needs to be plasticized. Typically it is plasticized by adding polystyrene into the PPE resin. This creates a miscible blend and makes it easily processable by conventional plastics processing methods. This has one drawback, which is the lowering of the Tg. In our approach the proprietary PPE compound has very good processability without a dramatic drop in Tg. Tg remains high, over 200ºC and this PPE material can be injection molded or extruded by conventional plastics processing equipment.

The use of thermoplastic material opens up new possibilities especially in board manufacturing. Long curing times at elevated temperatures are not needed. 3D structures are formed in tens of seconds and square meters of boards in minutes. So the main benefit of using thermoplastic materials is in their manufacturing. Characteristic to all thermoplastics is that you can deform them by applying heat above the Tg or above the melting temperature in case of a crystalline resin. With this thermoplastic PPE the upper most temperature that can be tolerated for short term is the glass transition temperature, 200ºC. Thus this material is not suitable for reflow soldering with lead free solders, and care needs to be taken in other high heat processes. An example of a PPE based PCB is shown in Figure 1.

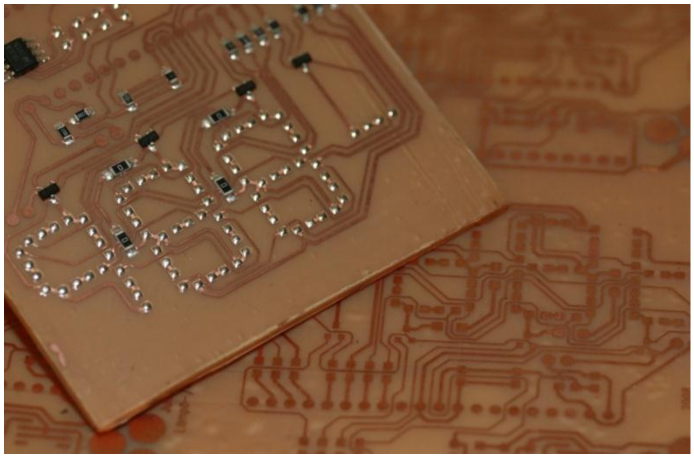

Figure 1. Test boards prepared with conventional PCB technology.

In this study first test bars and plaques were injection molded. Test bars were used to evaluate the mechanical properties of the material and the test plaques were prepared for resonator measurements. The material can be used to make 3D injection molded integrated circuits, such as antenna structures.

After the resonator measurements, a copper clad laminate was produced by pressing together PPE film, glass fiber fabric and copper foil. The pressing cycle took only a few minutes, because only softening of the material is needed and time consuming curing / crosslinking reactions do not take place. Glass fiber fabric is known to increase the dk and df and this change was also measured. The reason of using GF was to fix the thickness of the laminate to the right level. This manufacturing method does not fully utilize the thermoplastic nature of the PPE based resin. In optimal production method there are no GF needed, and the result is an unfilled copper clad laminate with dk 2.55 and df <0.002. This will also yield a fully isotropic material, where the dielectric properties are absolutely constant throughout the material, even in a micrometer scale. This can be seen as an additional advantage over the glass fiber reinforced laminates.

The dielectric properties of the test laminate with GF were evaluated at 1 GHz by a material analyzer. The values dk=2.8 and df=0.002 were used as starting points for antenna design and simulation. Furthermore a test antenna was prepared by conventional PCB manufacturing process and the performance was measured.

The UMTS/WCDMA patch antenna is a high frequency application where radiator elements can be made out of double sided copper clad laminates. There are no components attached to these boards, only the coaxial feed connection needs to be established. From PCB technology point of view these radiator elements are very simple, but from the material point of view very demanding. The dielectric properties of these boards need to be constant over all possible conditions. Most importantly, dissipation factor needs to be as low as possible in order to minimize the loss of antenna power into the dielectric material. Low permittivity is also an advantage because the 50 ohm feed line widths are wider resulting in lower conductor losses. From material side PTFE based laminates are the best available materials for this application, but their drawback is the very high material cost. Lower cost alternatives for PTFE are in the market, and they exhibit very good performance, however their cost is this rather high. We see a good market opportunity for PPE based thermoplastic material in antennas. Two material compositions were tested as shown in Table 1. The main difference between the two materials is in their burning characteristics. PPE-LL (low loss) was not flame retardant and PPE-V0 was made to be inherently flame retardant (V0 in 3 mm thickness). The addition of flame retardant caused the dielectric constant to increase slightly and also the dissipation factor increased. Otherwise the properties of the two tested grades were practically the same.

Table 1. Material properties of PPE based thermoplastic antenna substrate.

	Standard	Unit	PPE-LL	PPE-V0
Dielectric Constant	IPC-TM650 2.5.5.9		2.55	2.6
Dissipation Factor	IPC-TM650 2.5.5.9		0.001	0.002
Flame Retardancy	UL94		N/A	V0
CTE (x, y, z)		ppm/°C	50	50
Tg	IPC-TM650 2.4.25	°C	207	197
Volume Resistivity	IPC-TM650 2.5.17.1	MΩ*cm	$2x10^{8}$	$2x10^{8}$
Surface Resistivity	IPC-TM650 2.5.17.1	MΩ	$2x10^{8}$	$2x10^{8}$
Copper Peel Strength	IPC-TM650 2.4.8	N/mm	1	1
Water Absorption	IPC-TM650 2.6.2.1	%	0.4	0.4
Specific Gravity	ASTM D792	g/cm3	1.06	1.06
Tensile Modulus	ISO 527	MPa	2300	2300
Tensile Strength	ISO 527	MPa	60	55
Flexural Modulus	ISO 178	MPa	2200	2200
Dimensional Stability	150°C/2h	%	<0.2	<0.2

Resonator Measurements

Dielectric properties of the proposed new material have been measured by using TM_{010} cavity resonators at VTT. A circular cylindrical resonator with the TM_{010} mode is used in material measurements. The resonance frequencies and the quality factors of the cavity resonator must be known with (f_0, Q_0) and without (fs_0,Qs_0) dielectric material (Fig.2). The reflection coefficient of the resonator is measured with small frequency steps by using a vector network analyzer to define the resonance frequency and the relevant cavity quality factor (Q-value) (Fig.3). The dielectric constant of the material (dk) and dissipation factor (df) are calculated from f_0, Q_0, fs_0,Qs_0 and volume of the material [1]. Volume of the material must be known very accurately. The dielectric material sample to be tested can be in the shape of a rod or a plate.

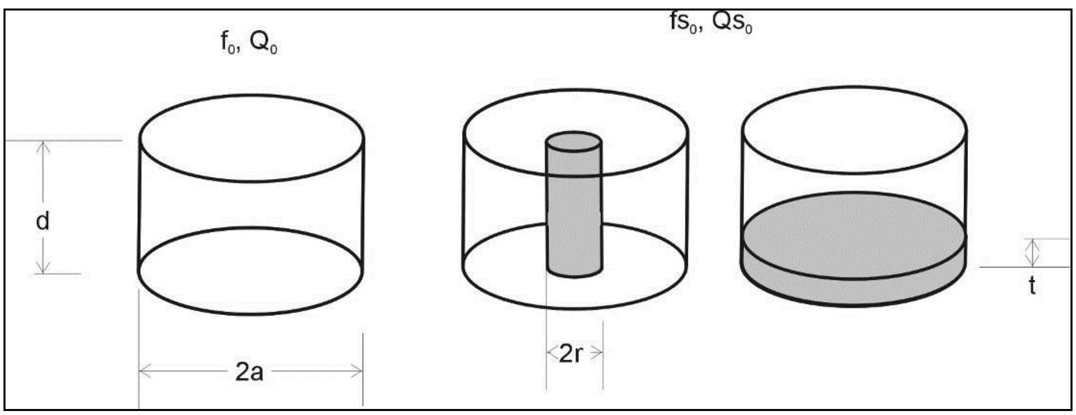

Figure 2 Empty, dielectric rod loaded and dielectric plate loaded cavity resonator.

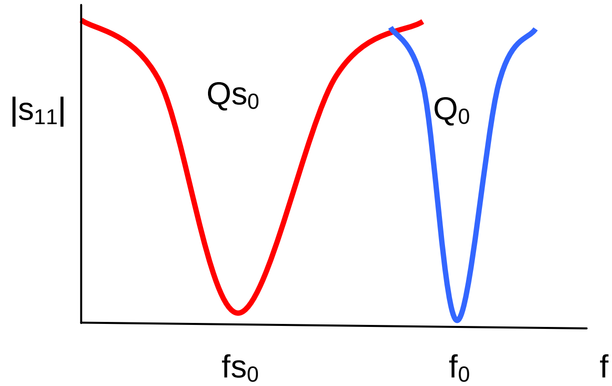

Figure 3. Measured impedance characteristics of the material loaded and empty cavity.

Material measurements were done with two resonators at 2 GHz and 5.5 GHz (Fig.4). The two different material samples were nominated as PPE-LL and PPE-V0 (with flame retardant). Both test materials were first injection molded to test plaques and then machined to the exact dimensions. For 2 GHz measurements, two test samples were machined as a Ø112mm disc with a thickness of 2 mm and a 100*100mm² slab with a thickness of 4 mm. For 5.5 GHz tests, the test samples were Ø40mm discs with thicknesses of 2 mm and 4 mm. Permittivity and loss tangent were calculated from the measurements and are tabulated in Table 2.

Figure 4. Pictures of used resonators (Left: 5.5 GHz resonator, Right: 2 GHz half-split resonator).

Table 2. Measured material characteristics

Sample	Frequency [GHz]	Measured thickness [mm]	dk	Error thickness +/- 0.05mm	Error thickness +/- 0.1mm	df	Error thickness +/- 0.05mm	Error thickness +/- 0.1mm
				dk err +/-%	dk err +/-%		df err +/-%	df err +/-%
PPE-LL	2	2	2.53	4	9	0.0012	13	21
PPE-LL	2	4	2.55	2	4	0.0012	6	10
PPE-LL	5.5	2	2.55	4	8	0.0022	9	16
PPE-LL	5.5	4	2.53	2	3	0.0019	6	8
PPE-V0	2	2	2.60	4	9	0.0020	13	21
PPE-V0	2	4	2.61	2	4	0.0020	6	10
PPE-V0	5.5	2	2.56	4	8	0.0028	9	16
PPE-V0	5.5	4	2.54	2	3	0.0025	6	8

Test vehicle design and characterization

The proximity-coupled microstrip patch antenna was selected for the test vehicle because of its wideband performance and simple construction [2-4]. Specifications for the design were set as follows: S11 < –10 dB, frequency band 1.92–2.17 GHz, gain > 8 dBi. Commercial high-power base station antennas have a higher matching requirement (S11 < - 14dB) which requires the use of multiple stacked patches. A design with a single radiating patch was opted here for simplicity. Design work was done in Zeland IE3D simulator which is based on the Method of Moments (MoM). The construction of the proximity-coupled patch antenna is shown in Figure 5. The reflecting ground plane is optional and was not used in the prototype antenna. Simulated input matching is below –10 dB between 1.9–2.2 GHz, and simulated peak gain is 8.5 dBi at 2.0 GHz.

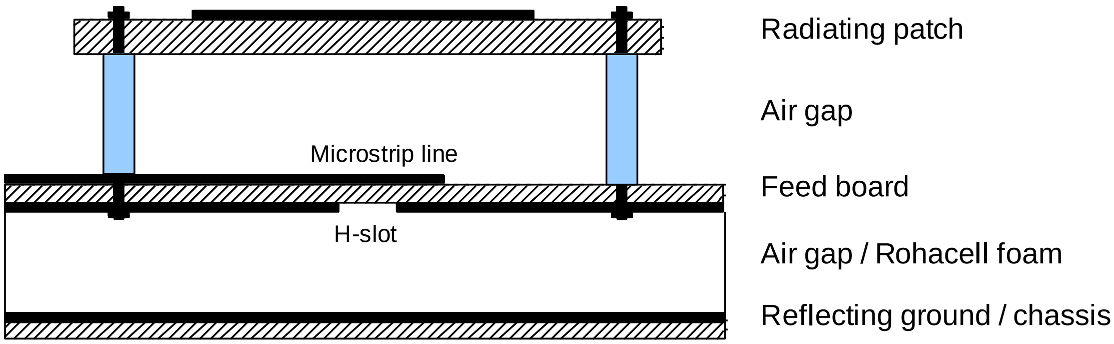

Figure 5. Proximity-coupled antenna construction.

The prototype antenna was manufactured in-house at VTT using regular PCB processing facilities. Assembly was done by using plastic spacers and nylon screws & nuts. Size of the antenna including ground plane is 120 x 120 mm2. The antenna uses the glass-fiber reinforced laminate.

Input matching and radiation patterns of the test antenna have been measured in VTT's large anechoic chamber. The antenna is mounted on a rotating mast for the radiation pattern measurement (Fig.6). The distance between the transmitting antenna-under-test (AUT) and the receiving antenna is 10 meters. Measured input matching is shown in Fig. 7 for two air gap heights (11 mm and 12 mm) and shows that the specifications are met.

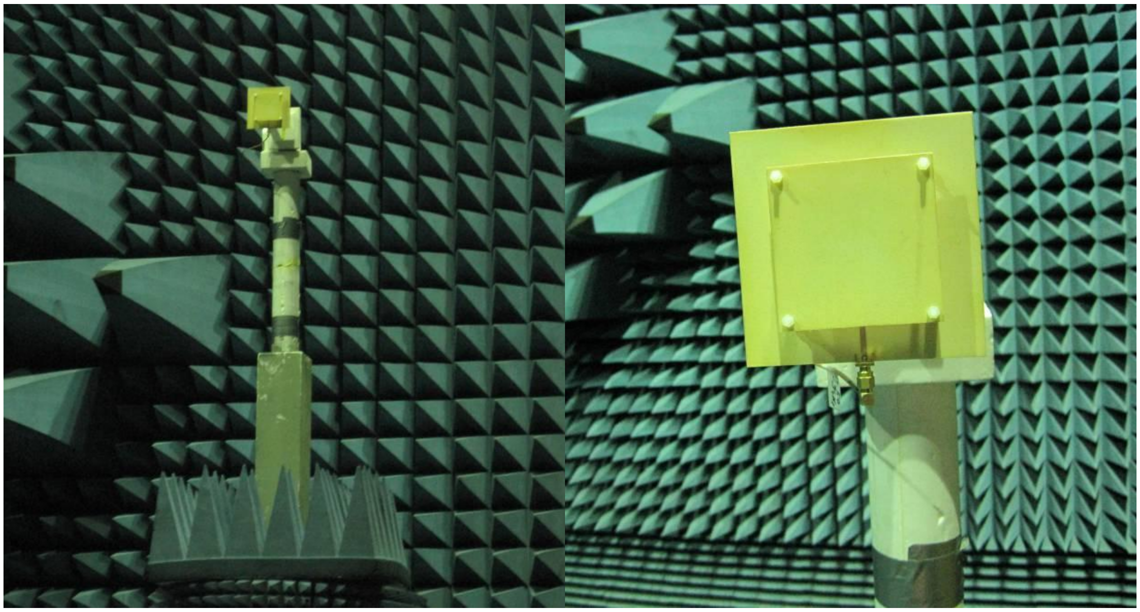

Figure 6. Radiation pattern measurements in an anechoic chamber at VTT.

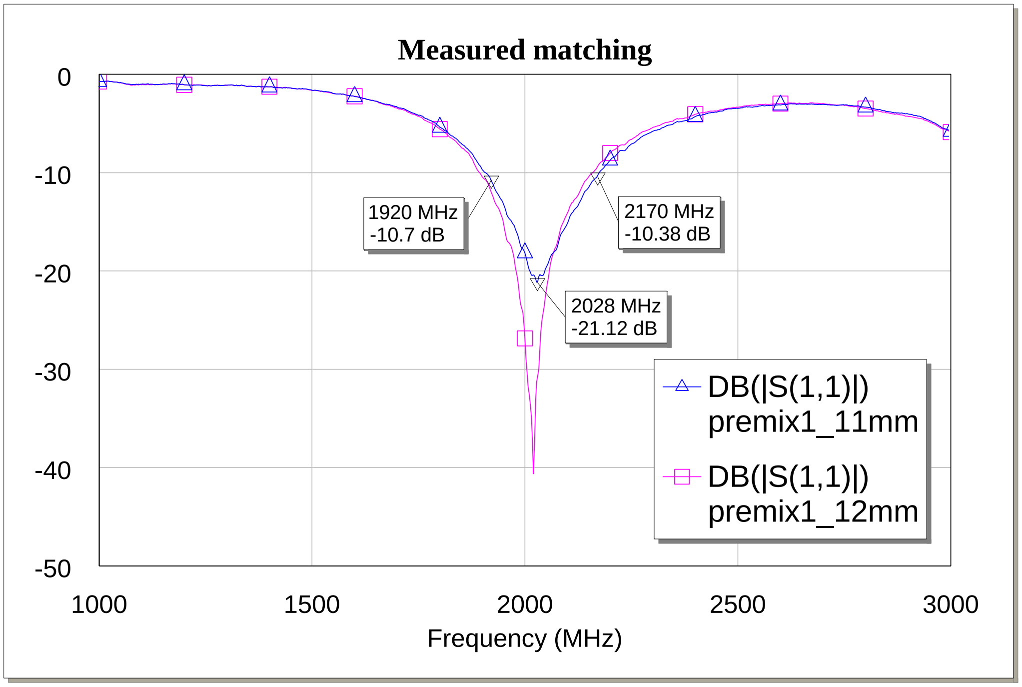

Figure 7. Measured input matching of the test antenna with two air gap heights.

The measured horizontal radiation patterns of the test antenna are shown in Fig. 8. Peak gain is 9.5 dBi at 2.11 GHz. Half power beam widths are between 60–70 degrees. The back lobe at +/-180 degs is quite high because there microstrip ground plane is quite small and there is no metal plane / chassis behind the antenna. The front-to-back ratio can be increased easily to 20 dB or more by adding a large reflecting ground plane like shown in Fig. 5.

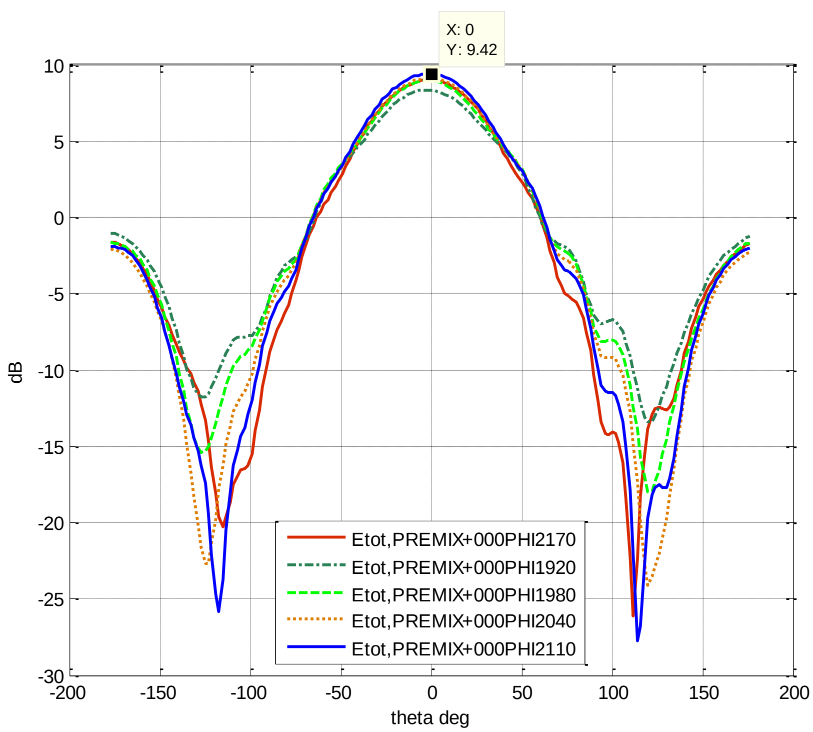

Figure 8. Measured horizontal radiation patterns.

The high measured peak gain shows that the proposed PPE material has very low dielectric losses and is very suitable for making large antenna feed networks for base station antennas. In order to prove the suitability of the proposed material for real antenna applications, a set of full-sized (1 meter class) base station antenna demonstrators on different materials have been designed. The antenna panels consist of eight vertically stacked antenna elements similar to the one shown in Fig. 6. The simulation results show that by using the proposed PPE material for the feed network the antenna gain can be improved substantially. Table 3 shows the comparison results between some common antenna substrate materials. All feed networks and antenna elements were fully optimized for the material in question. The Premix PPE antenna panel design from the simulator is shown in Fig. 9. The corporate feed network uses Wilkinson-type power dividers. A SMA coaxial connector is mounted on the side. The designed antenna panels are under manufacturing, and test results will be presented in the conference.

Table 3. Comparison of different antenna substrate materials for the 8-element antenna panel.

Laminate	dk	df	antenna gain [dBi]
Premix PPE	2.55	0.002	17
Rogers RO4350B	3.48	0.004	16
Arlon 25FR	3.48	0.004	16
Taconic RF35	3.58	0.0035	16.3
Generic FR-4	4.2	0.017	13

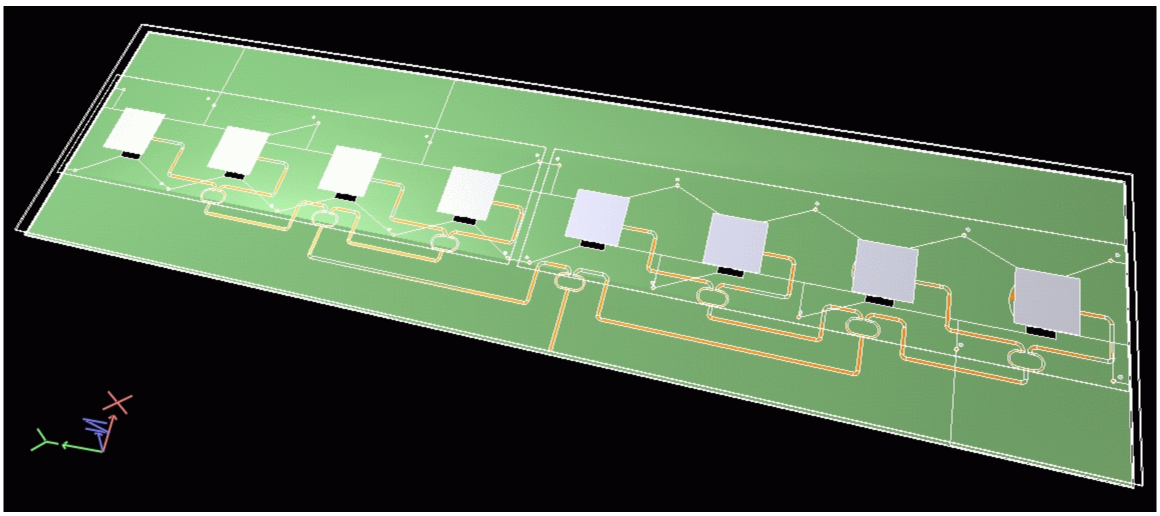

Figure 9. Designed 8-element base station antenna panel.

Conclusions

A new PPE based thermoplastic PCB material has been developed. It has a high Tg together with excellent dielectric properties. In this study two different grades were evaluated, one with an extremely low dielectric loss and one with flame retardant. Test boards of this PPE based material have been manufactured by using standard PCB manufacturing methods.

Material characterization was done at 2 GHz and 5.5 GHz with cavity resonators. Low dielectric constant and low losses make the material very suitable for base station antenna arrays. A prototype single antenna element for the UMTS/WCDMA band has been designed, manufactured and tested. The results compare well with simulations. The antenna element has a peak gain of 9.5 dBi at 2 GHz. Full-size base station antenna panels have also been designed and are currently in manufacturing. The simulation results show that the proposed PPE substrate material is superior to many commercial antenna grade materials.

The proposed thermoplastic material can also be used to mold radomes for high performance radar and telecom antennas. The dielectric properties are superior to commonly used polycarbonate and ABS plastics.

References

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[2] W.S.T. Rowe, R.B. Waterhouse, "Investigation of proximity coupled antenna structures", *2003 IEEE AP-S Int. Symp. Digest*, Vol. 2, pp. 904–907, June 2003

[3] S.Y. Ke, "Broadband proximity-coupled microstrip antennas with an H-shaped slot in the ground plane", *2002 IEEE AP-S Int. Symp. Digest*, Vol. 2, pp. 530–533, June 2002

[4] J. Säily, "Proximity-coupled and Dual-polarized Microstrip Patch Antenna for WCDMA Base Station Arrays", 2006 *Proc. Asia Pacific Microwave Conference*, pp. 2086–2089, Dec. 2006

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LET´S MAKE A GOOD MIX

SMART PLASTICS

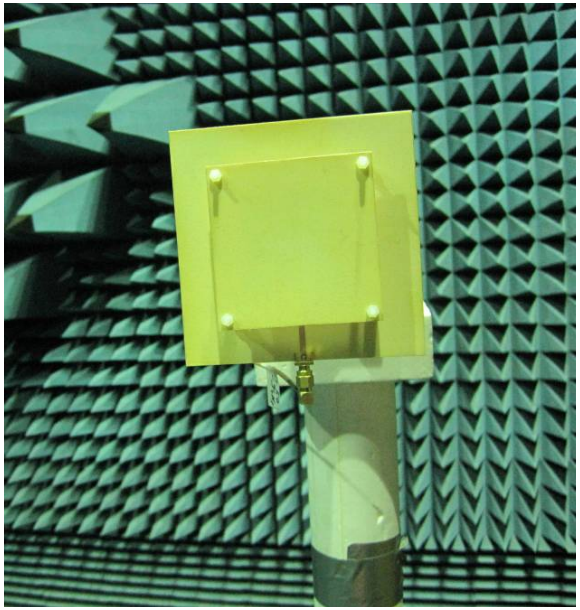
FOR ELECTRONICS

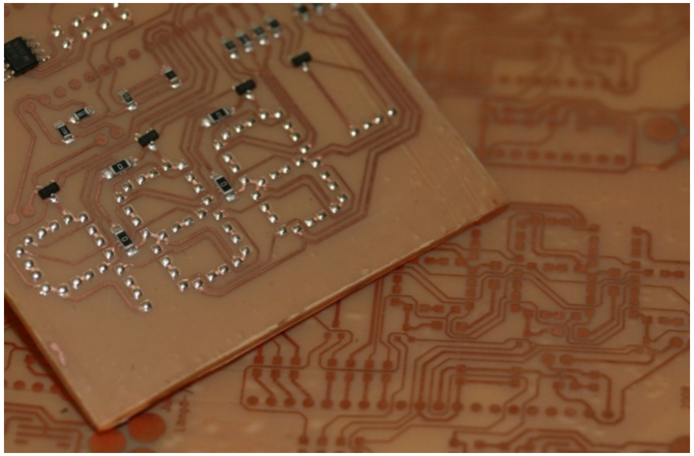
 

Unique Material Solutions for High Frequency Applications

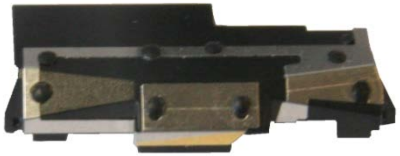
Outline

- Background
- Objective
- Material development
- Resonator Measurements
- Test Vehicle Design and Characterization
- Conclusions





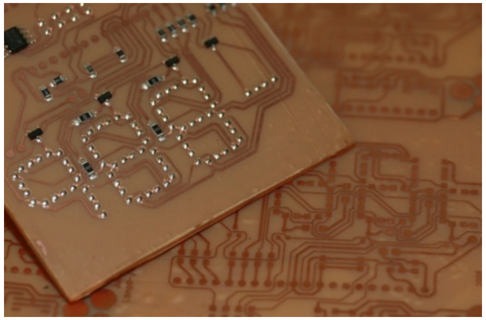
Typical High Frequency Applications



Material requirements in HF applications

- Low signal loss / Low dissipation factor (Df)
- Stable and controlled dielectric constant over frequency
- Homogenous material
- Inert to ambient conditions
- Easy to manufacture

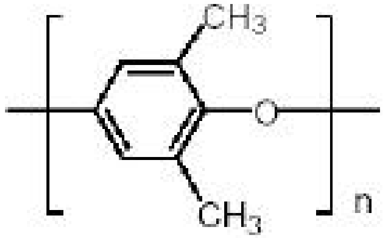
Objective



I. To develop a new PCB material with excellent dielectric properties

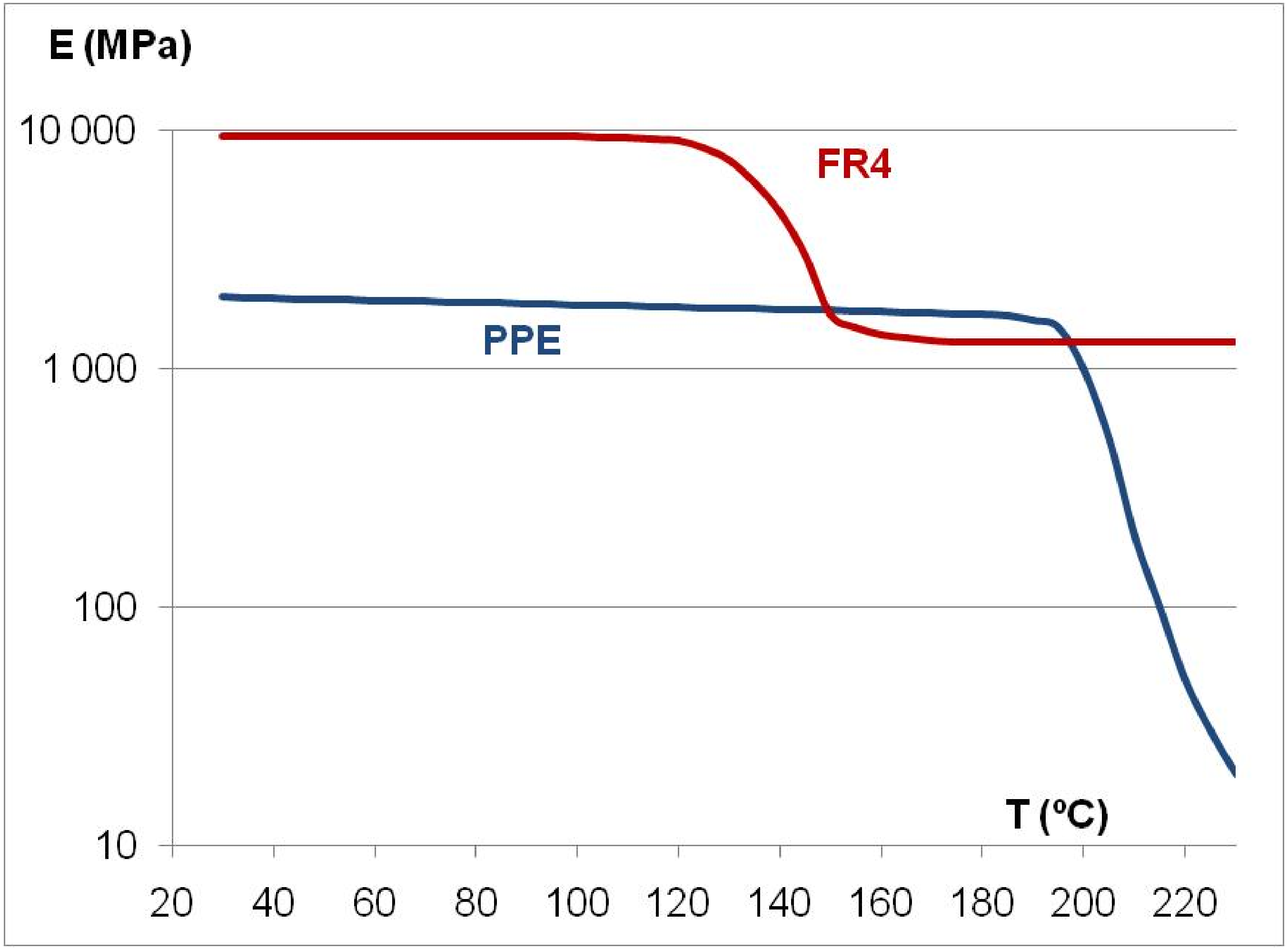
II. To evaluate its performance as UMTS/WCDMA antenna substrate

Unique PPE material composition



- Low dissipation factor (0.001)
- Controlled dielectric constant (2.55)
- Unfilled material with 100% homogenity
- Low water absorption (0.2%)
- High temperature resistance (Tg ~ 200° C, HDT ~ 185° C)
- Possibility to control dielectric constant per application needs
- Thermoplastic!

Thermoplastic vs. Thermoset



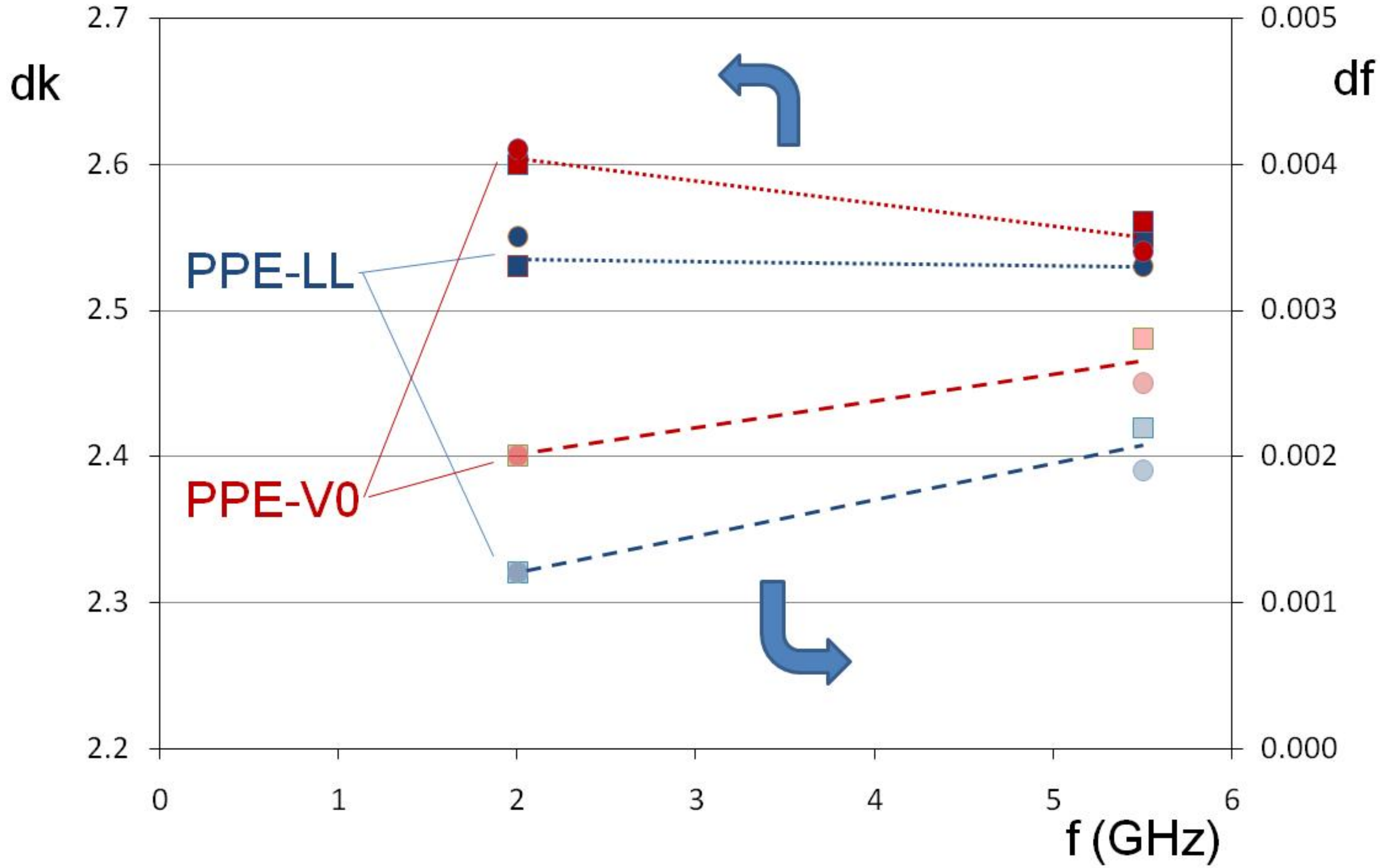
Test Materials

- PPE-LL (Low Loss)
  - dk 2.55, df 0.001 @ 1 GHz
- PPE-V0 (flame retardant)
  - dk 2.60, df 0.002 @ 1 GHz
  - V0 at 3 mm thickness

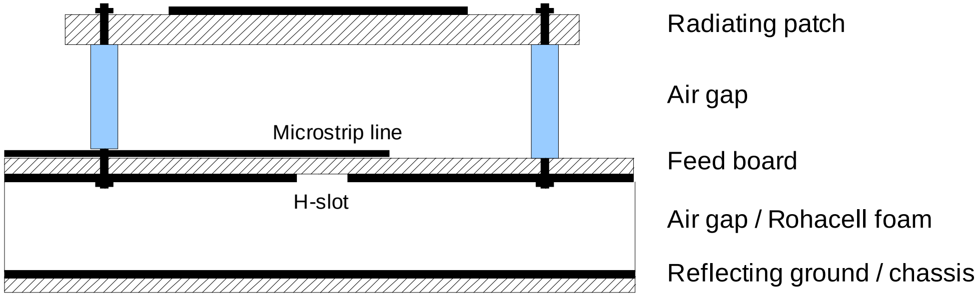
- Glass fiber fabric (1080) filled laminate
  - dk 2.8, df 0.002 @ 1 GHz

Resonators 2 and 5.5 GHz

Dielectric Properties



Test Vehicle Design and Simulation



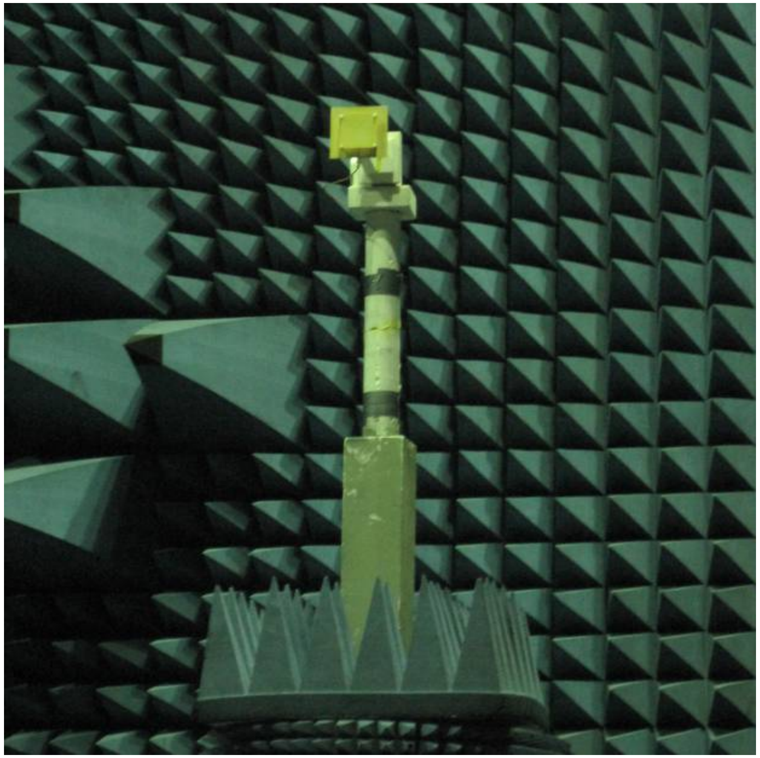
<u>Specs for Design</u>

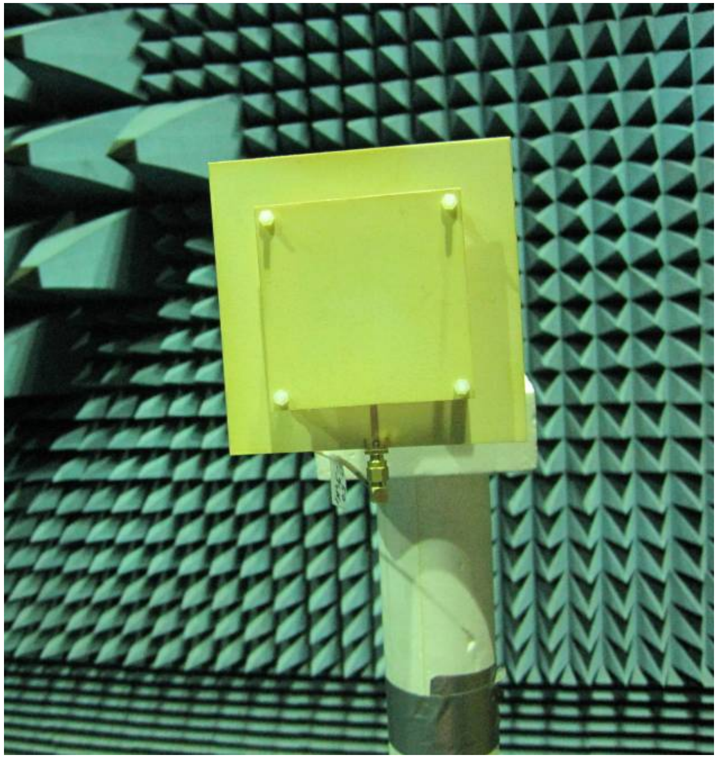
- S11 < -10 dB
- 1.92 – 2.17 GHz band
- Gain > 8 dBi

<u>Simulation results</u>

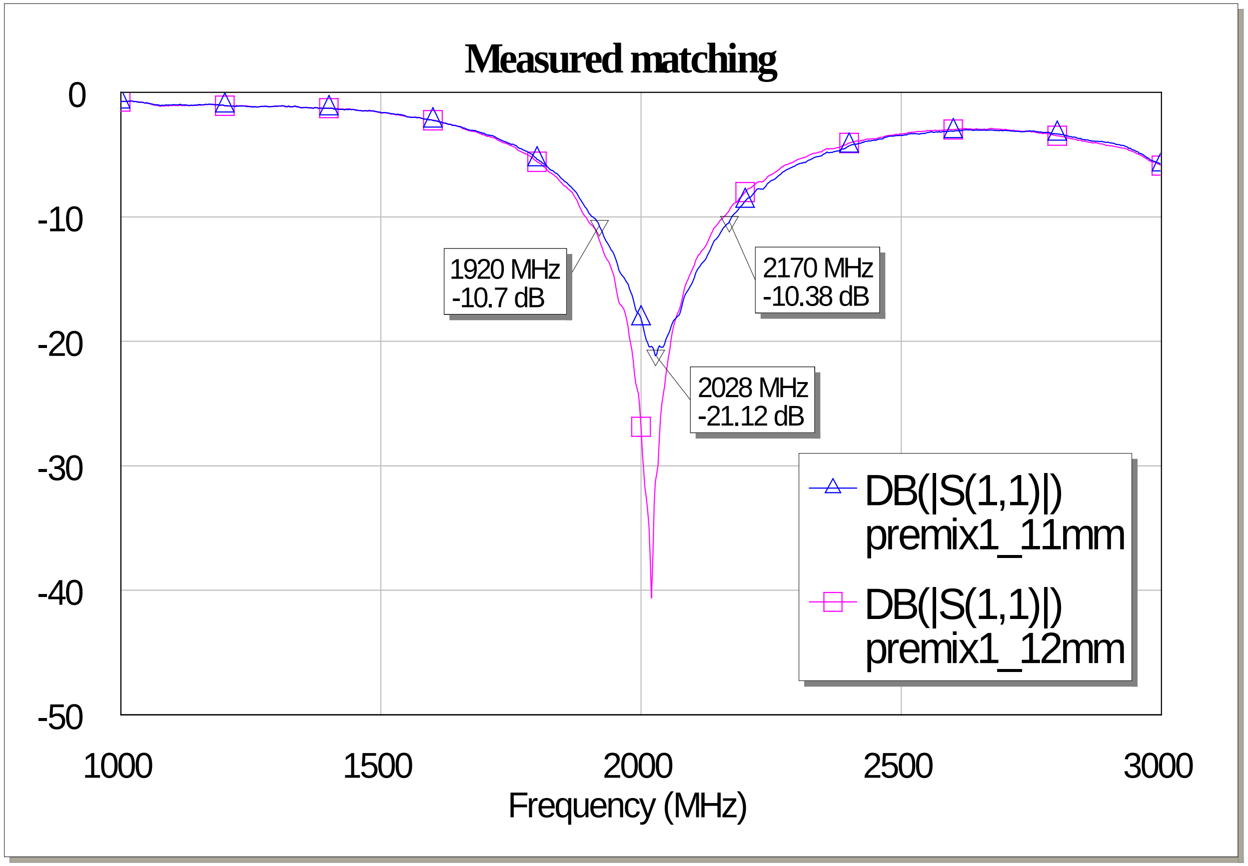
- S11 < -10 dB
- 1.9 – 2.2 GHz band
- Gain = 8.5 dBi @ 2.0 GHz

Radiation Pattern Measurements in Anechoic Chamber at VTT

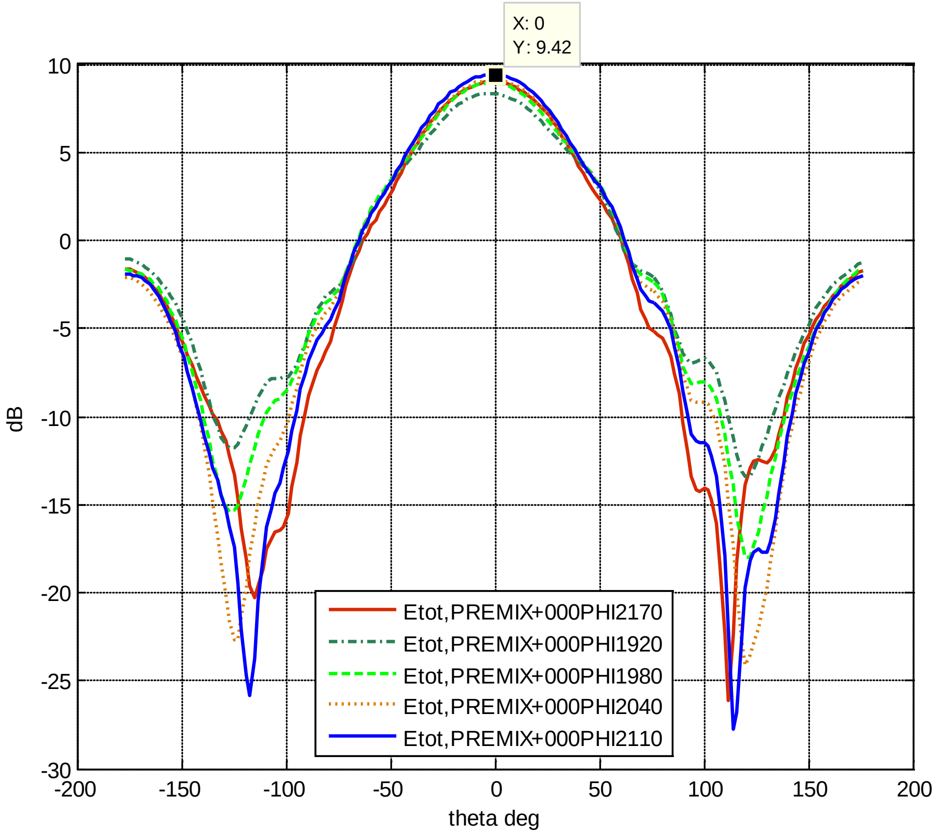




Measured Input Matching of the Test Antenna with Two Air Gap Heights



Measured Horizontal Radiation Patterns



- Peak gain 9.5 dBi at 2.11 GHz
- Half power beamwidth ~ 60 - 70º
- Back lobe at ±180º can be decreased by adding a large reflecting ground plane

Designed 8-Element Base Station Antenna Panel

Laminate	dk	df	antenna gain [dBi]
Premix PPE	2.55	0.002	17
Rogers RO4350B	3.48	0.004	16
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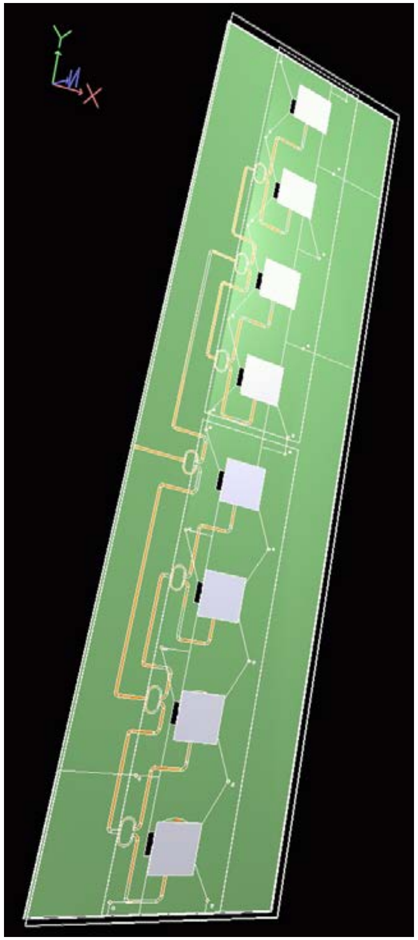

Optimal Feed Line Widths

- – Low permittivity is advantageous for telecom antenna substrates
- – 50 ohm feed line widths are wider
- – Lower conductor losses in large feed networks

  - Dk = 2.16 / Df = 0.001 (Rogers RT/Duroid 5880)
    - – line width 3.0 mm → loss 0.007 dB/cm
  - Dk = 2.55 / Df = 0.002 (Premix PPE)
    - – line width 2.8 mm → loss = 0.009 dB/cm
  - Dk = 3.5 / Df = 0.004 (Rogers RO4350B)
    - – line width 2.2 mm → loss = 0.017 dB/cm

Conclusions

- New PPE based thermoplastic PCB laminate has been developed
- Prototype single antenna element for UMTS/WCDMA was designed, manufactured and tested
- PPE substrate is superior to many commercial antenna grade materials in antenna performance