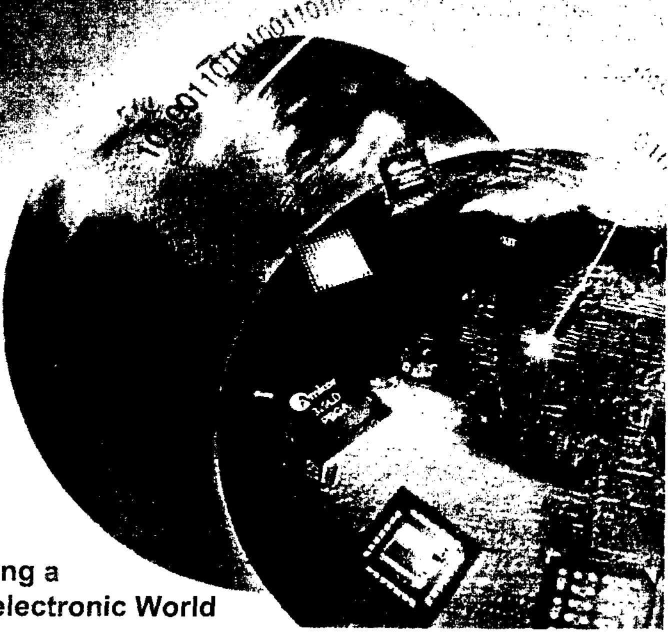
Technologies for RF System in Package (SIP)

Doug Mathews
(Amkor Technology / USA)

Embedded Passives, RF Functional Blocks, and Shields

Michael P. Gaynor
RF Technical Director



Amkor Technology

Enabling a
Microelectronic World

Outline

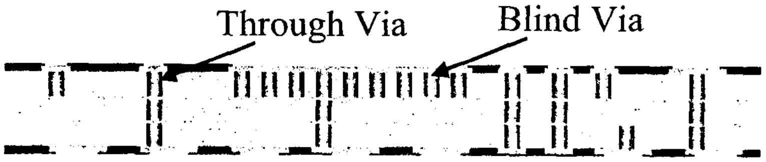
- **Embedded RF Functions in Laminate**
  - Justification
  - Filters and BALUNs results
  - Statistical Study results
  - Summary
- **Embedded RF Functions in LTCC**
  - Justification
  - Diplexer, BALUNs, Filters results
- **Embedded Passives**
  - Justification
  - Issues
- **Embedded Shields**
  - Justification
  - Measured Results
- **Summary**

2.4GHz Laminate RF Functional Library

- **Why Embedded?**
  - Cost
    - Reduced component and assembly cost more than compensates slight substrate cost increase
    - Standardize Substrate for leveraging volume
  - Routing
    - More area for die, routing, and other components
  - Package Height Restrictions
    - Ceramic RF Functional Block Components are typically 1mm in height
- **Why a library?**
  - Basic filters and baluns are common to WLAN/PAN
  - Reduced development time
    - Usually customized to customers configuration
    - Parasitics and via placement can impact performance
  - Lower development costs

Preferred Substrate Construction

- **Getek ® RF Substrate**
  - May also use BT-MG
    - Variance may be higher due to temperature and humidity effects
  - ε_r =3.95, loss δ=.010
- **2 Core Construction**
  - Blind Vias between layers 1-2, 3-4
  - Through vias 1-4
  - Nominal thickness .510 mm
- ***Suitable for***
  - Controlled impedance lines, resonant structures, BALUNs, filters, couplers, matching circuitry, ground planes, thermal planes
  - Frequencies to 6 GHz



Nominal Thickness=.510mm ε_r=3.95
Loss Tan=.01 Blind Vias 1-2, 3-4 Through Vias 1-4

Today's Filtering Solutions

Bluetooth

DEA322448BT-2005

- Ceramic Bandpass Filter
- LTCC construction
- Height typically >1mm
- Cost typically $.20-.33

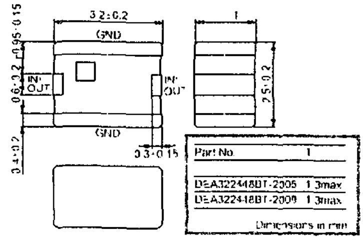
Band Pass Filters
Shielded

FEATURES

- Compact low profile and light weight.
- Low insertion loss, high attenuation
- Shielded type.

SHAPES AND DIMENSIONS

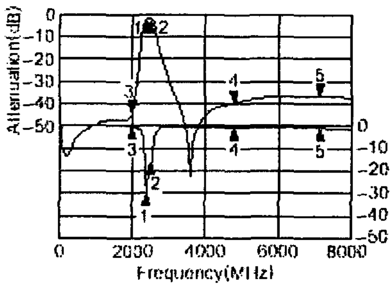
DEA321897BT-2001/DEA322448BT-2005/DEA322448BT-20



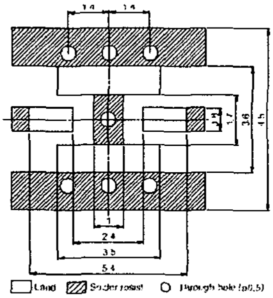
Part No.	1
DEA322448BT-2005	1.3max
DEA322448BT-2009	1.3max

Dimensions in mm

1: 2400.0MHz, –2.2740dB 4: 4800.0MHz, –39.798
2: 2497.0MHz, –2.1410dB 5: 7200.0MHz, –36.603
3: 1990.0MHz, –43.860dB



From TDK Datasheet



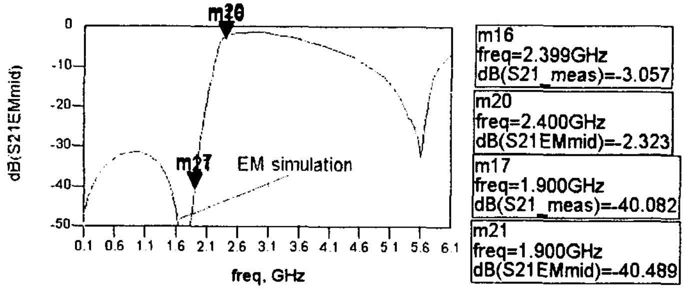
High Pass Filters as Alternative

- **Protects Receiver from main threats of Cellular**
  - GSM, DCS/PCS, CDMA Mobile TX (1980MHz)
- **Attenuates harmonics of the transmitter**
  - 10-15dB depending upon architecture if in the transmit path
  - Also protects receiver from 802.11a systems
- **Addition of Notch Structure**
  - For higher selectivity requirements for GSM (>30dB)
- **Alternative filter designs**
  - Where proximity of cellular is not a major concern
    - Bluetooth mouse for example (1m separation opposed to 1mm)
  - Where insertion loss is critical
    - Selectivity and Insertion Loss tradeoff
- **Embedded in 4 layer substrate**
  - saving top layer area
- **Eliminates costly component**

40dB Selectivity Filter

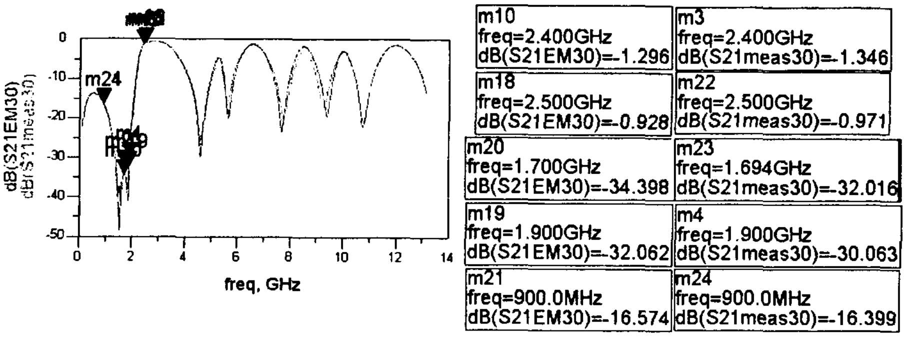
- 40dB at DCS/PCS
- 30dB at GSM
- 2.5dB IL typical In-band
- 15dB at 5.8GHz, IEEE 802.11a band
- Used where rejection is a must and overall RX Noise Figure can be sacrificed

HPF Module Circuit:
EM Simulation versus Measurement



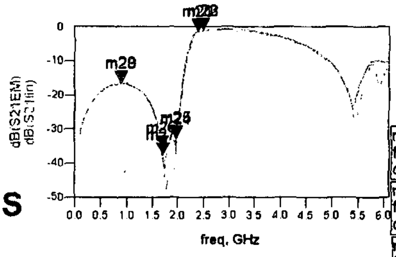
30dB Selectivity Filters

- 30dB at DCS/PCS, 16dB at GSM
- ~10dB at 5.8GHz , IEEE 802.11a band
- 1.35dB in-band IL
- Adequate protection to DCS/PCS Mobile TX that may be incorporated in same unit
- 0.27dB lower loss than filter with 30dB rejection to 1.98GHz, base station PCS TX or Mobile PCS RX



30dB Selectivity Filters

- 30dB DCS/PCS Base Station TX/Mobile RX
- 17dB GSM
- 10dB @ 5.8GHz
- 1.5dB IL
- Provide 30dB protection to PCS base station TX, Mobile RX at cost of 0.27dB Insertion Loss



m21
freq=2.400GHz
dB(S21lin)=-1.415

m20
freq=2.400GHz
dB(S21EM)=-1.574

m22
freq=2.500GHz
dB(S21lin)=-1.177

m23
freq=2.500GHz
dB(S21EM)=-1.171

m24
freq=1.980GHz
dB(S21lin)=-33.022

m25
freq=1.980GHz
dB(S21EM)=-32.659

m26
freq=1.700GHz
dB(S21lin)=-35.671

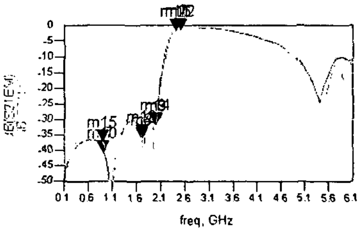
m27
freq=1.700GHz
dB(S21EM)=-37.758

m28
freq=900.0MHz
dB(S21lin)=-16.838

m29
freq=900.0MHz
dB(S21EM)=-16.722

Improved GSM Selectivity at cost of 0.3dB Insertion Loss

- +3 passive components
- 30dB DCS/PCS
- >32dB GSM
- 1.8dB In band IL



m1
freq=2.400GHz
dB(S21lin)=-1.588

m2
freq=2.400GHz
dB(S21EM)=-1.723

m11
freq=2.400GHz
dB(S21meas)=-1.760

m5
freq=2.500GHz
dB(S21lin)=-1.355

m6
freq=2.500GHz
dB(S21EM)=-1.559

m12
freq=2.500GHz
dB(S21meas)=-1.422

m4
freq=1.700GHz
dB(S21lin)=-36.383

m8
freq=1.700GHz
dB(S21EM)=-36.198

m13
freq=1.700GHz
dB(S21meas)=-35.241

m3
freq=1.980GHz
dB(S21lin)=-31.883

m9
freq=1.980GHz
dB(S21EM)=-31.479

m14
freq=1.981GHz
dB(S21meas)=-31.563

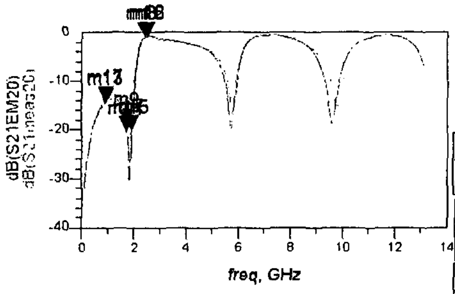
m7
freq=900.0MHz
dB(S21lin)=-40.484

m10
freq=900.0MHz
dB(S21EM)=-40.506

m15
freq=900.0MHz
dB(S21meas)=-37.034

20dB Selectivity Filter

- <1 dB Insertion Loss
- 18-20dB Selectivity DCS/PCS
- 14dB GSM
- Stand alone application



m11
freq=2.400GHz
dB(S21EM20)=-0.868

m8
freq=2.400GHz
dB(S21meas20)=-0.915

m12
freq=2.500GHz
dB(S21EM20)=-0.662

m16
freq=2.500GHz
dB(S21meas20)=-0.911

m14
freq=1.700GHz
dB(S21EM20)=-20.334

m9
freq=1.700GHz
dB(S21meas20)=-18.635

m15
freq=1.900GHz
dB(S21EM20)=-20.164

m7
freq=1.900GHz
dB(S21meas20)=-19.929

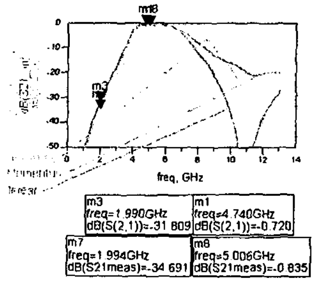
m13
freq=900.0MHz
dB(S21EM20)=-14.496

m17
freq=900.0MHz
dB(S21meas20)=-13.981

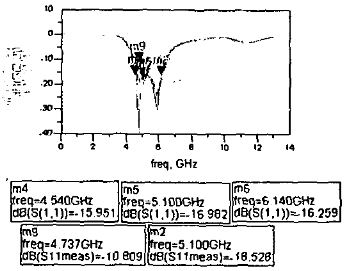
Embedded 5.7GHz Bandpass Filter

BANDPASS FILTER VERSION 1
MOMENTUM, LINEAR, AND MEASURED

INSERTION LOSS

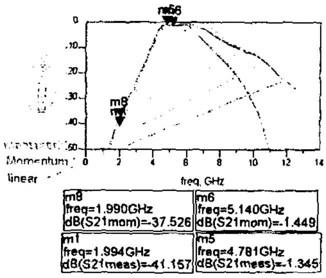


RETURN LOSS

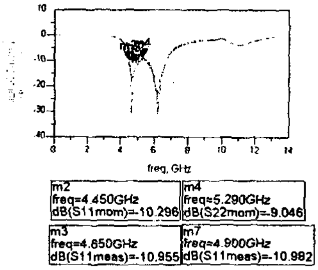


BANDPASS FILTER VERSION 2
MOMENTUM AND LINEAR

INSERTION LOSS

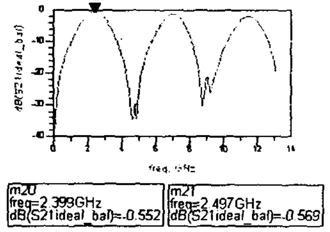


RETURN LOSS

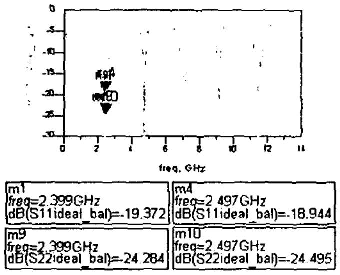


Substrate Baluns

50 Ohm BALANCED
INSERTION LOSS

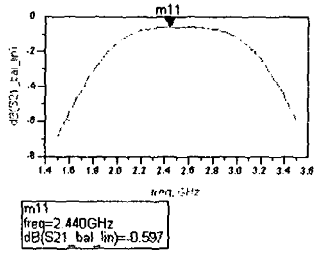


50 Ohm BALANCED
RETURN LOSS

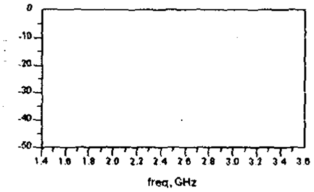


- **High Z and Low Z Designs**
  - Configurable to your needs
  - Low Z Stripline
    - Up to 100ohms balanced
    - 3 layers required
  - High Z broadside coupled
    - 4 layers required
- **Under Die Substrate Design**
  - Takes advantage of die area
- **Same substrate construction as filters**

200 Ohm BALANCED
INSERTION LOSS



200 Ohm BALANCED
RETURN LOSS



Statistical Variation Study Underway

- **OBJECTIVES:**
  - Determine the electrical variance of the functions
    - Across an Individual Panel
    - Across Panels within a Substrate Lot
    - Across Substrate Lot Dates (3 lots/ base material)
    - Across Material Lots
    - Across Base Material
    - Across 2 vendors
- **Utilizing Getek and BT-MG**
  - Correlate Performance to Substrate Construction
    - Will cross section applicable functions
    - Utilize measured electrical data (dielectric constant, loss tanget) of base material if available

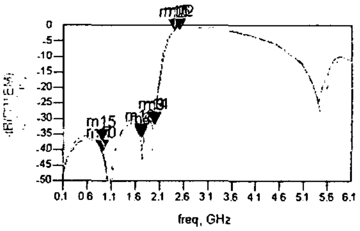
---

Filter Statistical Analysis

- **Material mechanical limits taken as 6 sigma values**
- **Material electrical properties and component value limits taken as 3 sigma values**
- **Statistical Analysis done on linear filter model**
- **10,000 trials**

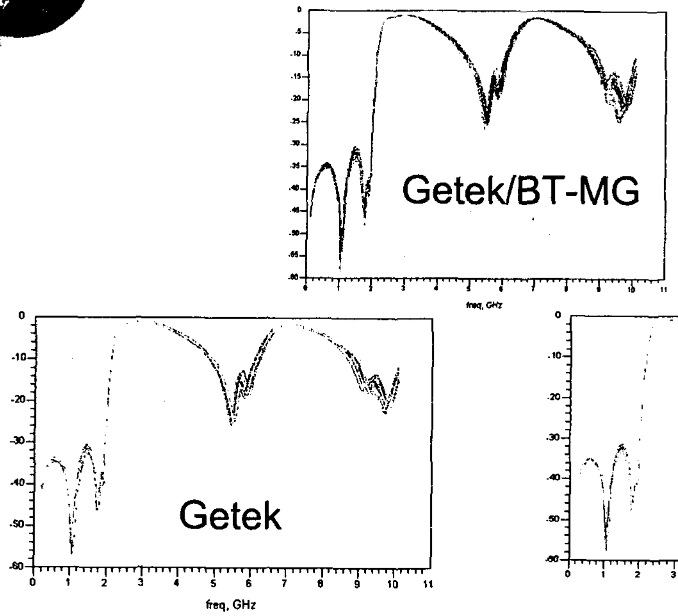
Variable	Sigma σ	1 Sigma Std Dev
Line Width	6	± 2.2µm
Core Thickness	6	± .11 mils
Prepreg Thickness	6	± .15 mils
Copper Thickness Layers 1,4	6	± 1.7µm
Copper Thickness Layers 2,3	6	± .3µm
Permittivity	3	± .03
Loss Tangent	3	± .00006
Cap value <5pf	3	± .08pF
Cap value >5pf	3	± .16pF

*based on vendor supplied variances for indicated Sigma value



```
m1                      m2                      m11
freq=2.400GHz           freq=2 400GHz           freq=2 400GHz
dB(S21lin)=-1 588       dB(S21EM)=-1.723        dB(S21meas)=-1.760
m5                      m6                      m12
freq=2.500GHz           freq=2.500GHz           freq=2.500GHz
dB(S21lin)=-1 355       dB(S21EM)=-1.559        dB(S21meas)=-1 422
m4                      m8                      m13
freq=1 700GHz           freq=1 700GHz           freq=1.700GHz
dB(S21lin)=-36 383      dB(S21EM)=-36.198       dB(S21meas)=-35.241
m3                      m9                      m14
freq=1 980GHz           freq=1 980GHz           freq=1 981GHz
dB(S21lin)=-31.883      dB(S21EM)=-31.479       dB(S21meas)=-31.563
m7                      m10                     m15
freq=900.0MHz           freq=900.0MHz           freq=900 0MHz
dB(S21lin)=-40.484      dB(S21EM)=-40.506       dB(S21meas)=-37 034
```

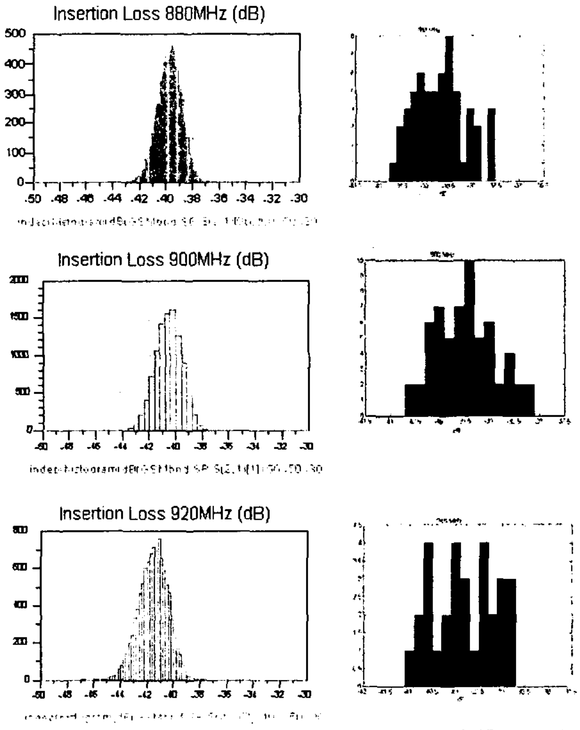
Example Data: Laminate Embedded Filter Attenuation/Insertion Loss



In Band Insertion Loss 1.47dB-1.86dB over all materials/lots

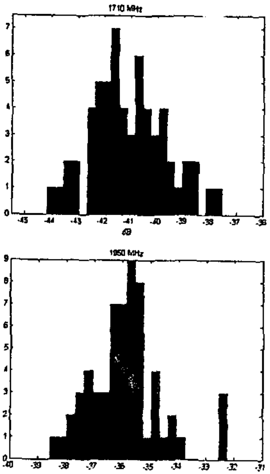
GSM Insertion Loss

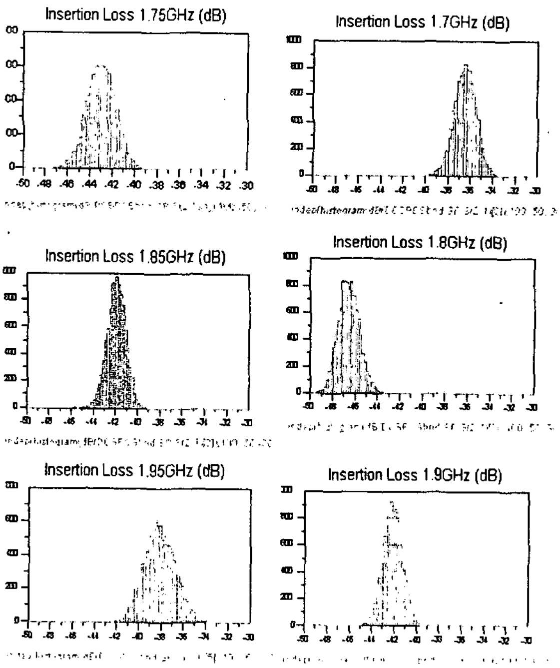
- **Good margin to 32dB specification**



DCS/PCS Insertion Loss

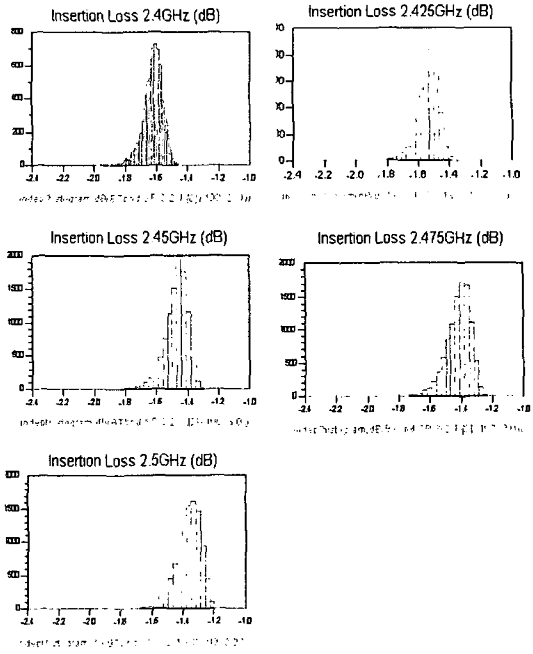
- Wider Variation, spread, at endpoints (1.7GHz and 1.95GHz)
- Still adequate margin to 30dB requirement at endpoints

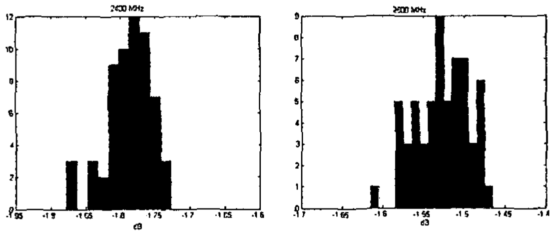




In Band Insertion Loss

- Possible Small yield loss to 1.9dB Insertion Loss requirement
- 1.9dB Insertion Loss requirement is conservative
  - based on 3.2dB overall I.L. with two antenna switches at their maximum 0.6dB I.L. specification for all trials





Summary: Embedded Laminate RF Functional Blocks

- **Base Library of Laminate Embedded Filters and Baluns developed for 2.4GHz Applications**
  - S-Parameters are provided at connection points
  - Utilizes a low cost 2 core construction
- **Statistical Variation Study in Report Phase**
- **Measurements over variants show solid performance**
- **Filters and Baluns are available for customer use**

2.4GHz LTCC RF Functional Library

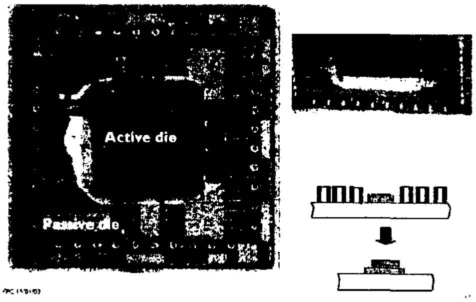
- **Why LTCC?**
  - Cost
    - Reduced cost due to lower height allows for low cost encapsulation
    - Combined functions into one LTCC piece may allow for 2 layer lower cost laminate carrier substrate
    - All LTCC package substrate may be small enough in size to be cost effective with laminate
  - Routing
    - Smaller vias and capture pads with all vias filled allows for tighter routing and lower cost for fine pitch flip chip
  - Package Height Restrictions
    - Lower height 0.48mm nominal compared to 1mm to fit under shield

Other Low Profile Designs

- 5GHz 802.11a BALUNs
- 2.4GHz, 5GHz 802.11 Low Pass Filters
- 2.4GHz, 5GHz 802.11 PIN diode Antenna Switch
- 900MHz, 1800MHz, 1900MHz, GSM/DCS/PCS Low Pass Filters
- 900MHz, 1800MHz, 1900MHz, GSM/DCS/PCS PIN diode Antenna Switch
- 900MHz, 1800MHz, 1900MHz, GSM/DCS/PCS Couplers

Passive Integration Methodologies

- **On die integration**
  - Module/IC partitioning is key
- **IPN (Integrated Passive Networks)**
  - Glass, GaAs, Silicon
- **Discrete Arrays**
  - Silicon
  - Discrete passive arrays
- **Planar Structures**
  - In laminate or LTCC
  - BALUNs, filters, matching structures
  - 2.4GHz Library filters and BALUNs are developed
- **Passives in Substrate**
  - Ceramics buried in laminates
  - LTCC Passives



Philips Silicon IPN for Bluetooth
IWPC Jan 03

Why Embedded Passives?

- **Density**
  - Higher degree of integration in same or smaller area
  - Enables shorter IC to passive conductor paths

- **Cost**
  - Lower cost through less assembly process and smaller package
    - Highly dependent on embedded component density
    - Highly dependent on application
      - RF critical matching or filtering component difficult at this time
      - Large value wider tolerance bypass components a good fit

- **Reliability**
  - Fewer soldered components under overmold should be more reliable
  - Proven technology for board flexing without embedded passive cracking

Technologies for Rigid Substrates

- **Ceramic Filled FR4 resins**
  - Capacitive density: ~2-5pF/cm^2
  - Not useful for packaging applications

- **Thick Film Ceramic**
  - Capacitive Density: ~50nF/cm^2
  - Screened and fired thick film paste
  - Useful for 100pF to 10nF as bypass capacitors

- **Thin Film**
  - Capacitive Density: 10nF/cm^2 and 200nF/cm^2
  - Submicron film process
  - Punch through issue?
  - In early development stages

- **Silicon**
  - Capacitive Density: up to 15nF/cm^2
  - Good for smaller value capacitors
  - Localized array of capacitors may have routing issues

Embedded Passive Challenges

- **Immature Infrastructure**
  - Materials and processes in development
  - Design tools do not exist or are immature
  - Need to identify/test "known good passive inner layers"?
  - Unknown yields and reliablity
  - Acceptable tolerances? (depending on application/function of passive)

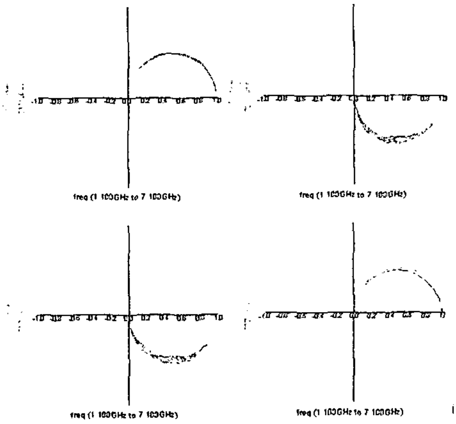
- **Cost**
  - Embedded capacitor density of ~6/cm2 is currently required to offset Material and process cost
    - This assumes no package/substrate shrink
    - This is at todays current pricing without high volume cost reduction

---

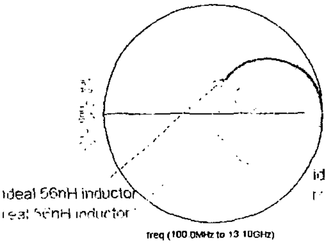
Ideal, Discrete, and Embedded Passives

- **Linear models and circuit theory use ideal components**
- **Real components and embedded components differ from ideal**
- **Linear models simulate quickly and allow for quick optimization**

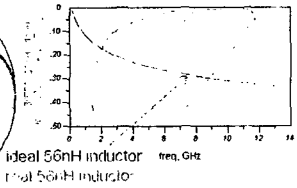
IDEAL, DISCRETE, AND EMBEDDED INDUCTORS



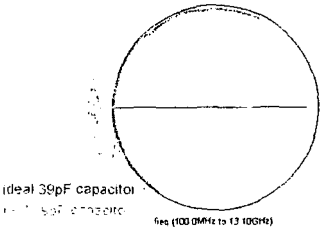
SERIES 56nH S11
REAL VERSUS IDEAL



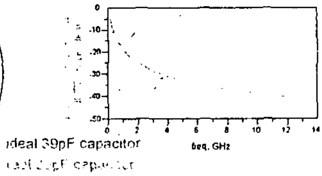
INSERTION LOSS 56nH
REAL VERSUS IDEAL



SHUNT 39pF S11
REAL VERSUS IDEAL



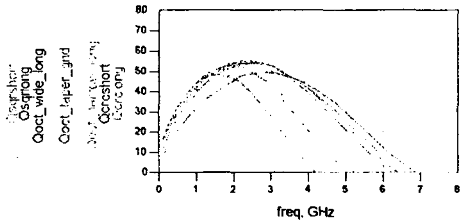
INSERTION LOSS 39pF in
shunt REAL VERSUS IDEAL

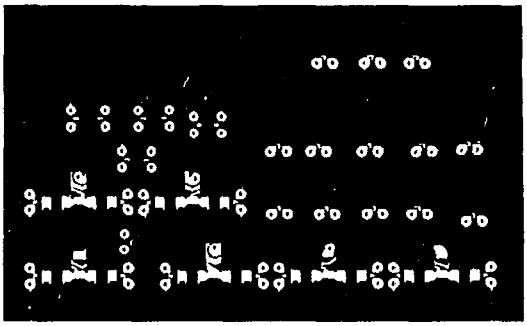


Inductor Geometry

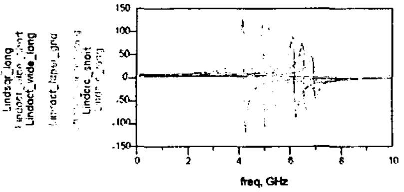
- **In addition, geometry affects *inductors:***

Inductor Q





Inductance



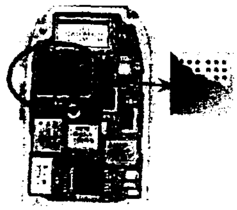
Inductance

freq	.. rc long	...c short	...t taper	...per gnd	...w long	...w short	...de long	...e short	...qr long	.. r short
830.1M...	5.811	4.507	3.587	3.824	5.705	4.391	2.504	1.434	6.969	3.974
842.5M...	5.839	4.525	3.597	3.833	5.733	4.404	2.511	1.439	7.007	3.987
854.9M...	5.820	4.512	3.583	3.821	5.708	4.395	2.506	1.435	6.984	3.975
867.2M...	5.790	4.483	3.557	3.800	5.678	4.367	2.483	1.417	6.954	3.946
879.6M...	5.804	4.491	3.573	3.810	5.691	4.377	2.489	1.423	6.973	3.951
892.0M...	5.843	4.524	3.601	3.835	5.733	4.408	2.510	1.432	7.029	3.981
904.4M...	5.865	4.531	3.612	3.847	5.753	4.422	2.520	1.434	7.054	3.998
916.8M...	5.821	4.504	3.583	3.825	5.713	4.390	2.500	1.428	7.004	3.971
929.1M...	5.810	4.487	3.574	3.811	5.698	4.375	2.494	1.426	6.983	3.960
941.5M...	5.843	4.515	3.585	3.824	5.722	4.397	2.499	1.433	7.025	3.976
953.9M...	5.882	4.545	3.604	3.849	5.763	4.422	2.514	1.438	7.082	3.995
966.2M...	5.861	4.524	3.596	3.835	5.741	4.408	2.506	1.430	7.058	3.978
978.6M...	5.829	4.500	3.578	3.812	5.714	4.384	2.493	1.419	7.030	3.956
991.0M...	5.841	4.511	3.583	3.822	5.728	4.392	2.502	1.424	7.039	3.972
1.003GHz	5.888	4.542	3.613	3.851	5.771	4.427	2.520	1.436	7.099	4.000
1.016GHz	5.901	4.551	3.616	3.857	5.789	4.432	2.524	1.437	7.116	4.011
1.028GHz	5.869	4.523	3.584	3.830	5.742	4.401	2.503	1.429	7.076	3.985
1.040GHz	5.854	4.513	3.576	3.821	5.736	4.390	2.499	1.423	7.064	3.968
1.053GHz	5.884	4.533	3.590	3.836	5.760	4.410	2.509	1.428	7.106	3.986
1.065GHz	5.920	4.556	3.617	3.858	5.798	4.435	2.521	1.433	7.162	4.006
1.078GHz	5.906	4.544	3.613	3.851	5.783	4.425	2.516	1.430	7.142	3.996
1.090GHz	5.880	4.524	3.593	3.836	5.759	4.405	2.507	1.423	7.115	3.980
1.102GHz	5.887	4.526	3.596	3.837	5.765	4.405	2.505	1.423	7.122	3.987
1.115GHz	5.936	4.561	3.619	3.864	5.809	4.440	2.524	1.438	7.181	4.016
1.127GHz	5.946	4.575	3.625	3.871	5.823	4.446	2.532	1.437	7.200	4.019
1.139GHz	5.914	4.544	3.599	3.845	5.784	4.420	2.511	1.428	7.166	3.990
1.152GHz	5.898	4.528	3.595	3.833	5.770	4.404	2.505	1.422	7.152	3.979
1.164GHz	5.933	4.554	3.614	3.855	5.808	4.430	2.519	1.429	7.202	4.000
1.177GHz	5.985	4.584	3.637	3.879	5.851	4.462	2.532	1.434	7.260	4.026
1.189GHz	5.964	4.571	3.630	3.871	5.831	4.447	2.528	1.435	7.244	4.022
1.201GHz	5.932	4.546	3.605	3.845	5.803	4.422	2.509	1.427	7.205	3.998
1.214GHz	5.941	4.556	3.611	3.854	5.611	4.432	2.518	1.429	7.222	4.006

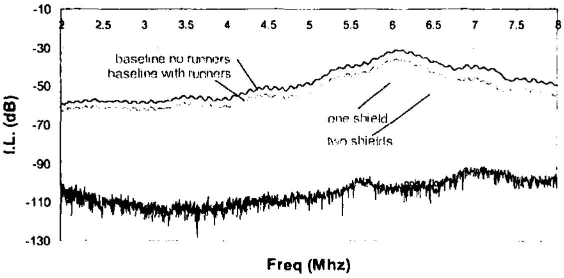
EMBEDDED SHIELDING

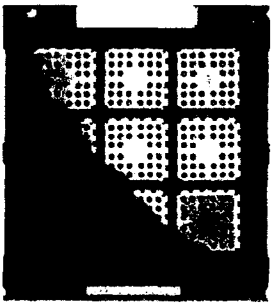
Transfer Molded Integrated Shielding

- **Meets required isolation levels for cell phone applications**
  - near field, 60-70dB Isolation, two shielded compartments
  - Far field performance equal to traditional method
- **Requires less area than traditional shields (.4-.5mm per side)**
- **High volume overmolded process**
- **MSL levels highly dependent upon shield configuration**
- **Process Development Timeline dependent upon customer drive**



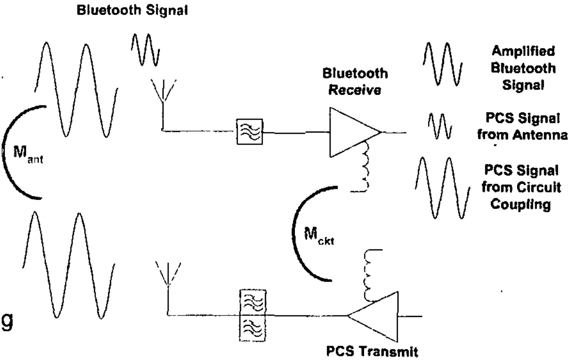
2 Turn Inductor #1 with Large Opening Shield Tabs





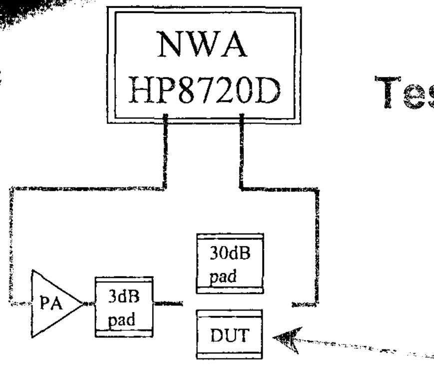
EMBEDDED SHIELDING

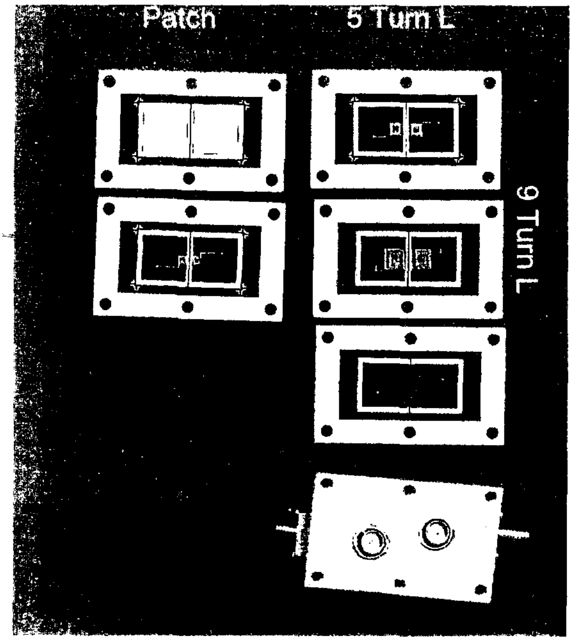
- **Filtering can protect the desired signal from interferers arriving through the antenna**
- **Circuit coupling may degrade either the 2.4GHz receiver or the PCS receiver**
  - May cause a larger noise level in 2.4GHz LNA
  - May enable AGC of PCS receiver if within AGC Bandwidth
    - Typical AGC BW> IF BW
    - May enact up to 30dB of AGC degrading receiver sensitivity
- **Circuit isolation is required to maintain the level achieved by the filters**
- **Careful circuit layout in conjunction with shielding can prevent these issues.**



EMBEDDED SHIELDING

Test Methodology

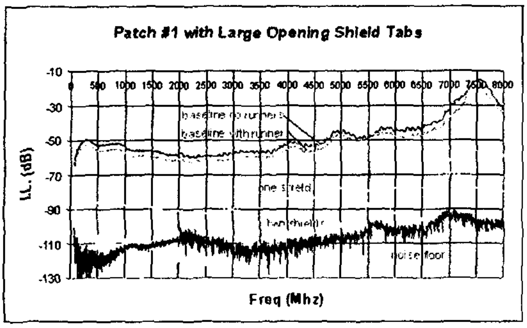


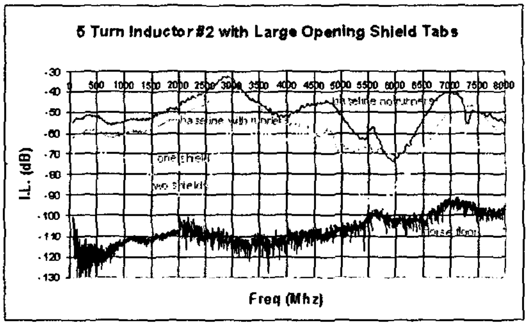


Test Procedure:
1) Calibrate with 30dB pad in place
2) Noise Floor measure with only via substrate
3) Take Baseline S21 measurement of each structure with no shield runners in-between the structures
4) Take Baseline S21 measurement of each structure with shield runners in-between the structures
5) Add one shield over the structure connected to port 1and take S21 measurement
6) Add second shield of same type and take S21 measurement
7) Repeat steps 5 & 6 for 4 of each structure with 3 different shield types and 4 different structures

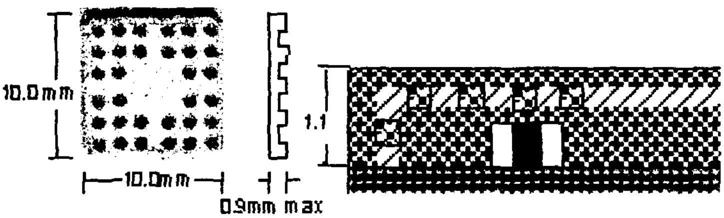
Integrated Shielding

Performance Examples



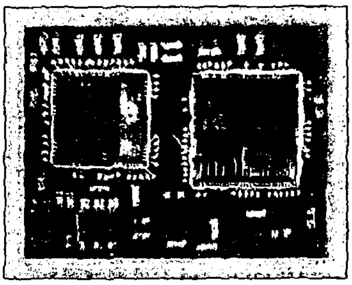


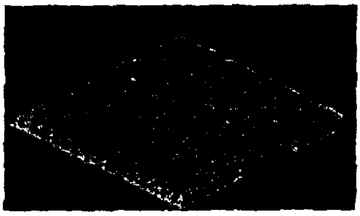
Configurations



Transfer Molded Integrated Shield

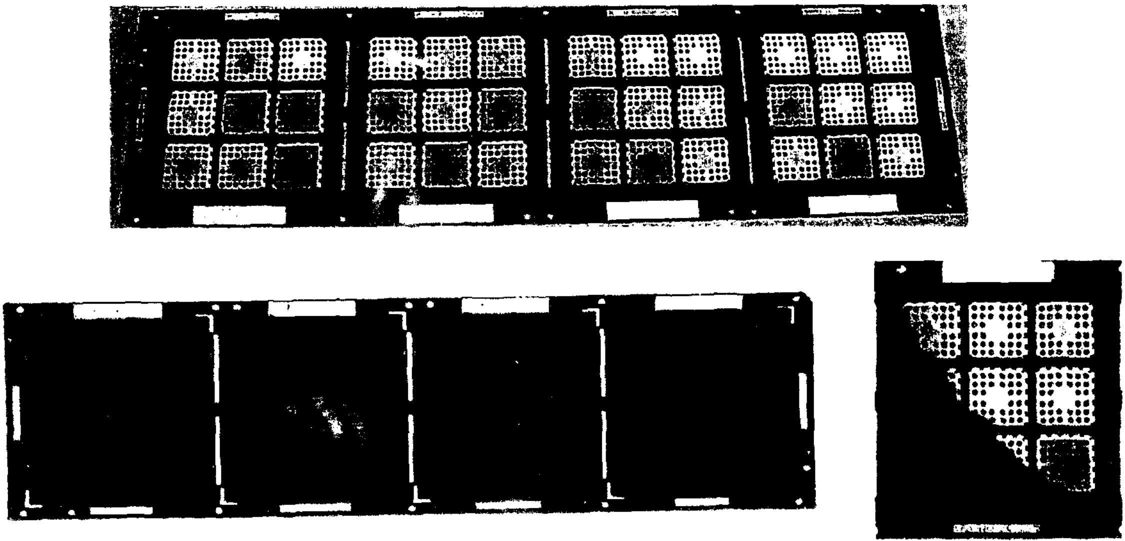
- **Test Vehicle Description**
  - Bluetooth Device (~10x14x1.6mm)
  - Adding grounding ring to layout
    - *Through vias to bottom side to complete shield*
  - Shield concept complete
    - *Drawn shield will be compared to Folded*
- **Test Vehicle will be used for**
  - Process development
  - *Mechanical reliability verification*
  - Development of design rules





EMBEDDED SHIELDING

- After passive and die assembly, shield is attached
- Same Transfer Mold Process
- Same SAW Singulation Process, module may have one or multiple shields with one or multiple compartments



SUMMARY

- Laminate Embedded RF Functions
  - Various Filters, BALUNs, couplers, etc. for Bluetooth, 802.11, and Cellular
- LTCC Embedded RF Functions
  - Various Filters, BALUNs, Diplexers, Antenna Switches, couplers, etc. for Bluetooth, 802.11, and Cellular
- Embedded Passives
  - Various Inductor topologies
    - Performance different than ideal or discrete inductor
    - Must look at inductor performance in overall RF function
  - Working on embedded ceramic capacitors in laminate
- Embedded Shields
  - Program in place to identify and define key design rules