The Quest for 100dB Isolation in Mixed-Signal ASICs

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Summary

- The Problem: **Isolation**
- Nature of the problem: **Not simple**
- Many ways to solve the problem
- One solution: **Faraday Cages**

- The Problem: **Isolation**
  - We need to provide good isolation, sometimes exceeding 100dB, among circuits that co-exist on a single die.
  - Thermal and magnetic isolation are not irrelevant, but they are beyond the scope of this presentation.

- Nature of the problem: **Not Simple**
  - Ultimately, there are nontrivial tradeoffs and it remains necessary to apply good engineering judgement.

- Many ways to solve the problem:
  - Dis-integrate
  - Relax spec
  - Exploit cyclostationarity (Move the noise to another timeslot)
  - Low-ρ substrate with *zero* impedance ground
  - High-ρ substrate with integrated Faraday cages

- One Solution: **Faraday Cages**
  - Adopt new circuit and layout techniques that allow us to integrate Faraday cages around each element that requires isolation.

Concepts

- Substrate Noise
- Faraday Cage
- Cyclostationary Noise

Substrate Noise

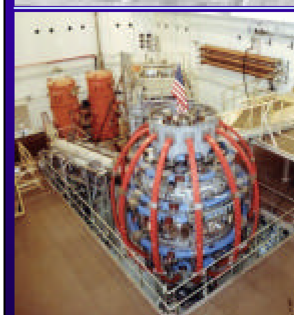
<--- Useful reference (Kluwer, 2001)

Substrates are distributed RC networks (unless you are unlucky enough to get latchup or other disasters that involve active devices).

The RC networks are complex, hard to characterize, and generally intractable.

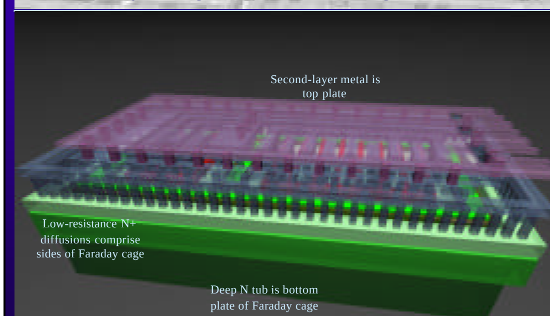
Because they couple circuits that were supposed to be isolated, they introduce correlated or uncorrelated noise.

Faraday Cage



Faraday Shield (or Faraday Cage): An electrostatic shield named after its inventor Michael Faraday. It is made by placing conductive material (often aluminum or copper) around some device and connecting that material to ground. The better the conductor (in other words, the less resistance it has) the better shield it will be. The braided wire around the conductor(s) in audio cable is an example of a Faraday Shield. They are also used in transformer designs (to prevent capacitance between the primary and secondary windings), and the most sensitive electronics on circuit boards, in which case they are often deployed as a hard aluminum cage around said components.

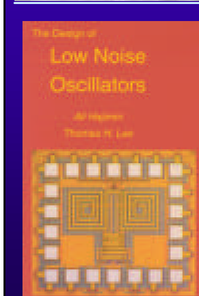
Faraday Cage, containing oscillator



Cyclostationary Noise

- Cyclostationarity
  - Definition: having a periodically time-varying power spectrum
- Example (from Hajimiri and Lee):
  - "… due to the periodically changing operation points of the active devices in the oscillator, many of the noise sources have a periodically changing power spectrum; they are cyclostationary."

Cyclostationary Noise



Hajimiri and Lee (Kluwer, 1999) is an excellent reference. Although this concept is most commonly applied to oscillators, it pertains to a wide class of circuits.

Isolation Requirements

- Monolithic radios (GPS, Bluetooth)
  - Microvolt input signals
  - Large amount of on-chip logic
- MEMs and MEMs drivers
  - 100v output swing is common
  - Analog processing on same chip
  - On-chip sensors with very low signal amplitude
- Ultrasound signal processors
  - Input signal magnitude is swept from volts to millivolts
  - Required SNR exceeds 100dB

Magnitude of the Problem

- (Xu, 2001). Substrate noise is ~ -10 dBm. This is several orders of magnitude higher than the -130 dBm signal present at the input of her monolithic GPS receiver chip.

CMOS Processes

- Bulk, high-ρ substrate
- Epi, on low-ρ substrate
- High-ρ substrate with low-ρ buried layer

CMOS Processes

- Bulk, high-ρ
  - ubiquitous (TSMC, etc.)

CMOS Processes

- Epi, on low-ρ substrate
  - widely available as option (TSMC, etc.)
  - *de rigueur* in some high performance variants (eg. IBM, ST)

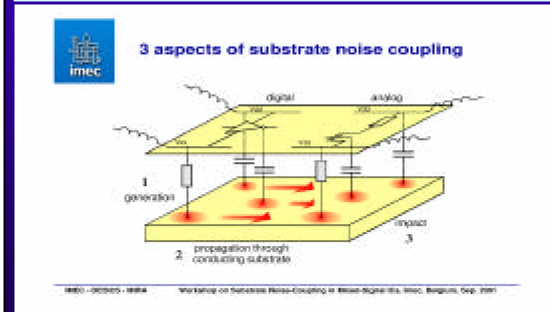
CMOS Processes

- High-ρ substrate with low-ρ buried layer
  - Growing availability, driven by RF BICMOS
    - IBM
    - ST
    - XFAB
  - HV CMOS
    - Alcatel
    - XFAB

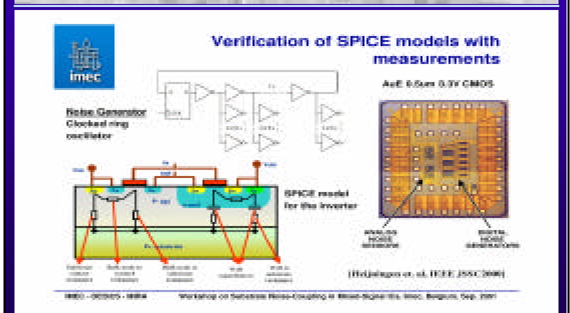
Case Histories: Low-ρ Substrate

- Badaroglu
- Yanntek

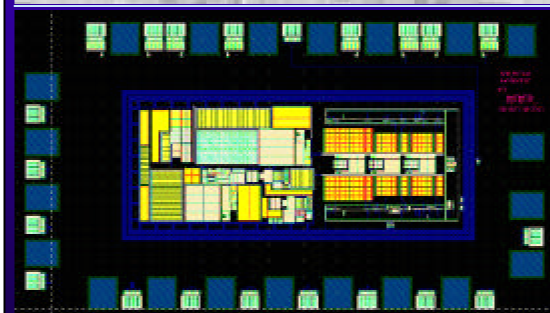
Badaroglu



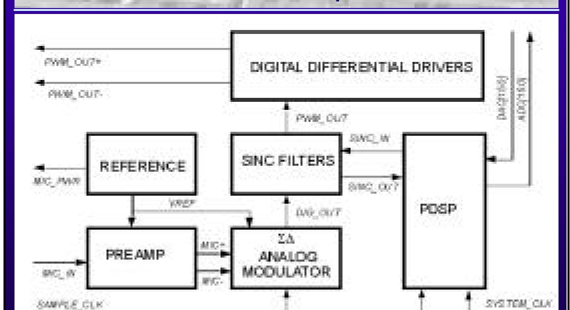
Badaroglu



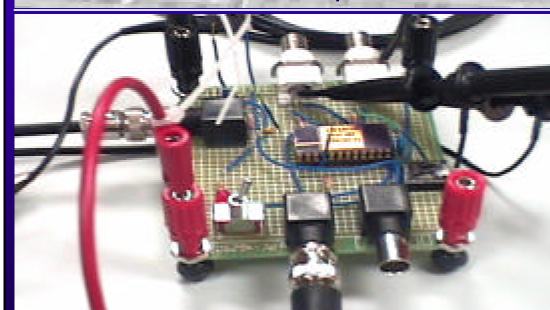
Our ΣΔ converter, low-ρ substrate



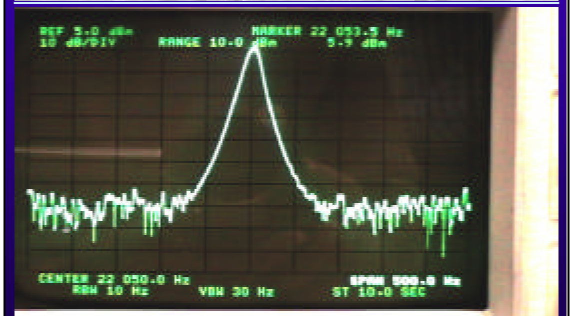
ΣΔ converter, low-ρ substrate



ΣΔ converter, low-ρ substrate



ΣΔ converter, low-ρ substrate



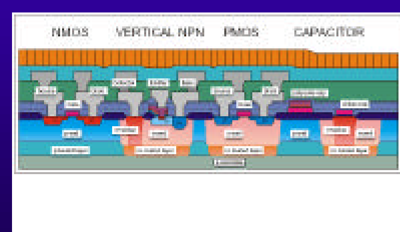
Case Histories: High-ρ Substrate

- Yanntek: Ultrasound chip (Hilbert)
- Su: test chip, at Stanford
  - Su, et al "Experimental Results and Modeling Techniques in Mixed-Signal Integrated Circuits" JSSC v 28 no 4 April 93 p420+.

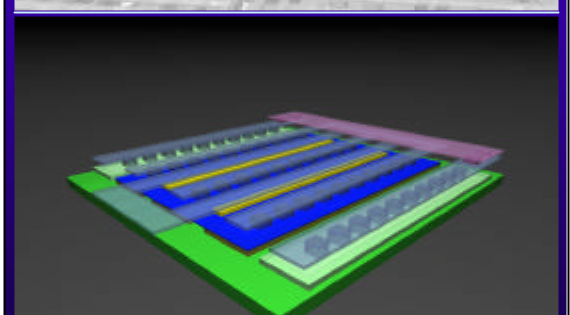
Case Histories: High-ρ Substrate

- Hilbert is a TGA for an ultrasound system
- Built in XFAB 0.6u BICMOS
- Modest isolation requirements (< 100dB)

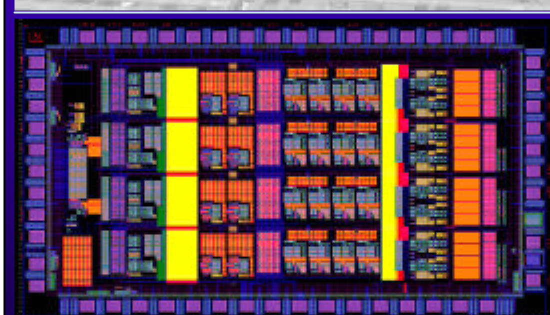
XFAB Process, used for Hilbert

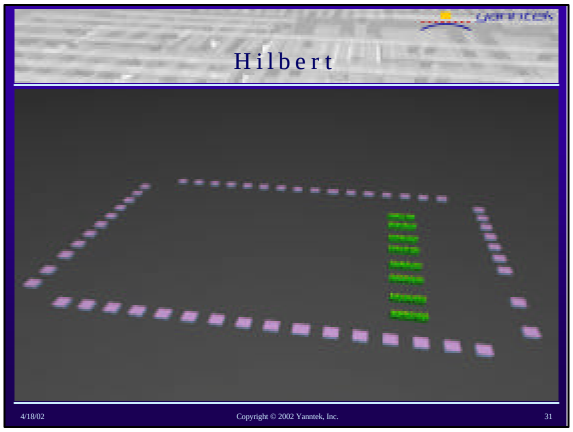


Hilbert



Hilbert




Hilbert
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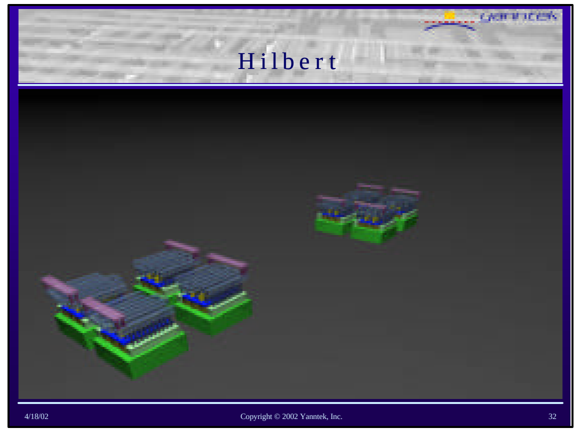
Hilbert
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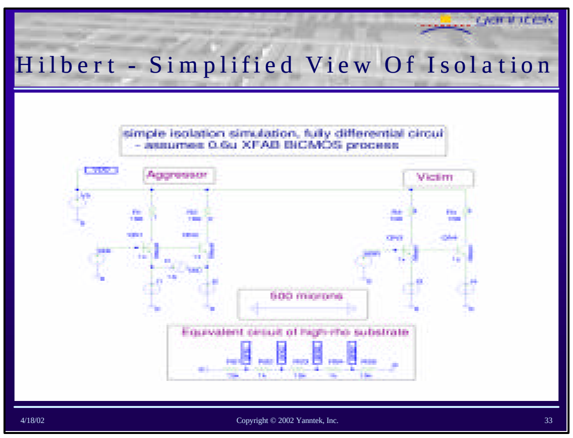
Hilbert - Simplified View Of Isolation
simple isolation simulation, fully differential circuit
- assumes 0.6u XFAB BiCMOS process
Aggressor
Victim
500 microns
Equivalent circuit of high-rho substrate
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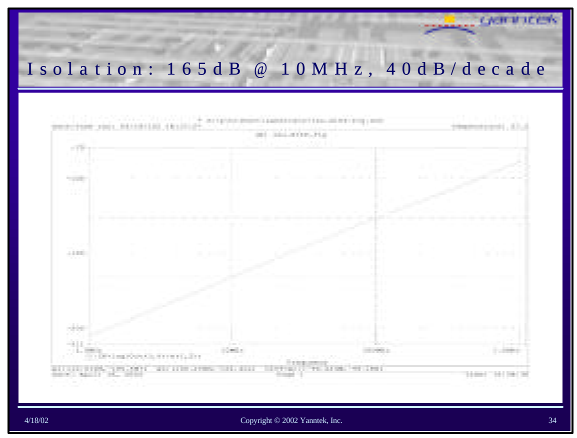
Isolation: 165dB @ 10MHz, 40dB/decade
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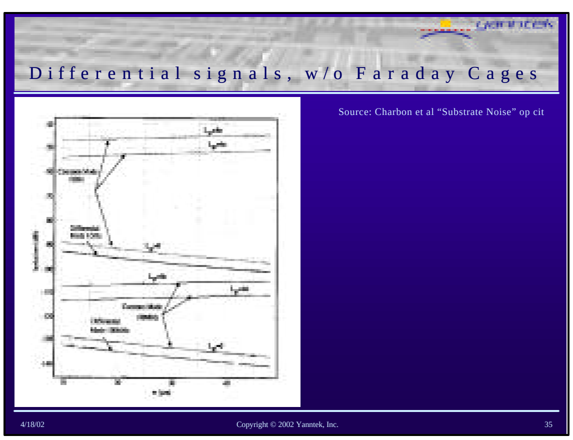
Differential signals, w/o Faraday Cages
Source: Charbon et al "Substrate Noise" op cit
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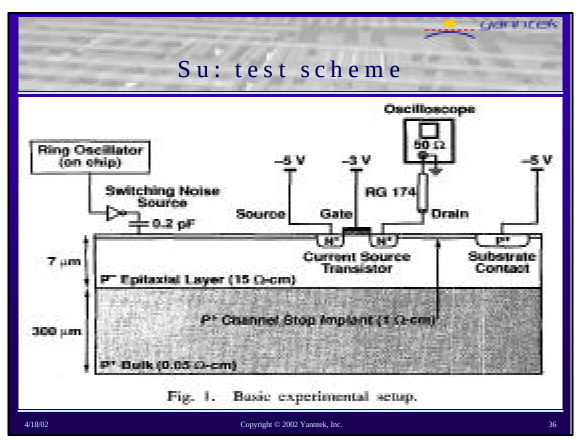
Su: test scheme
Oscilloscope
50 Ω
Ring Oscillator
(on chip)
−5 V
−3 V
−5 V
Switching Noise
Source
RG 174
0.2 pF
Source
Gate
Drain
7 μm
Current Source
Transistor
Substrate
Contact
P⁻ Epitaxial Layer (15 Ω-cm)
P⁺ Channel Stop Implant (1 Ω-cm)
300 μm
P⁺ Bulk (0.05 Ω-cm)
Fig. 1. Basic experimental setup.
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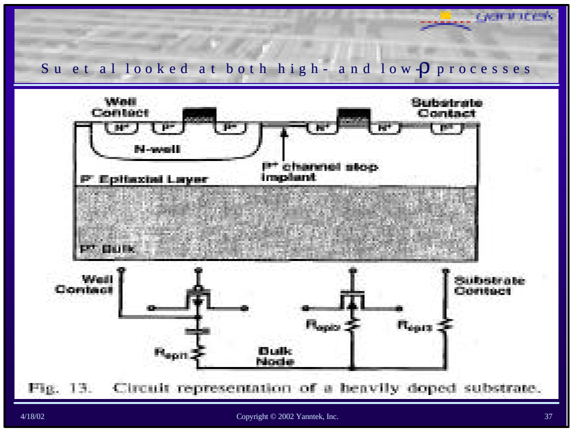
Su et al looked at both high- and low-ρ processes
Well Contact
Substrate Contact
N-well
P⁺ channel stop implant
P⁻ Epitaxial Layer
P⁺ Bulk
Well Contact
Substrate Contact
Bulk Node
Fig. 13. Circuit representation of a heavily doped substrate.
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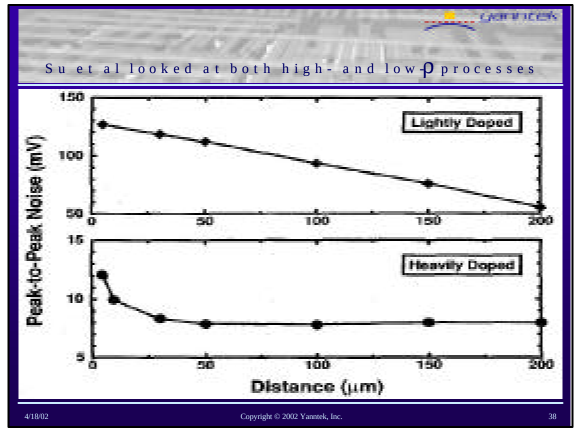
Su et al looked at both high- and low-ρ processes
Peak-to-Peak Noise (mV)
Lightly Doped
Heavily Doped
Distance (μm)
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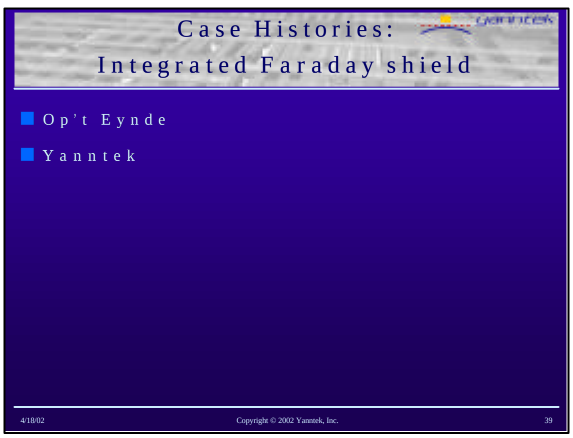
Case Histories:
Integrated Faraday shield
Op't Eynde
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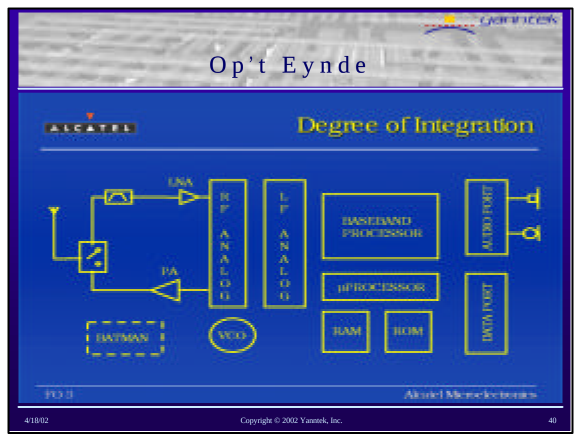
Op't Eynde
ALCATEL
Degree of Integration
LNA
PA
RF ANALOG
LF ANALOG
BASEBAND PROCESSOR
μPROCESSOR
RAM
ROM
AUDIO PORT
DATA PORT
BATMAN
VCO
Alcatel Microelectronics
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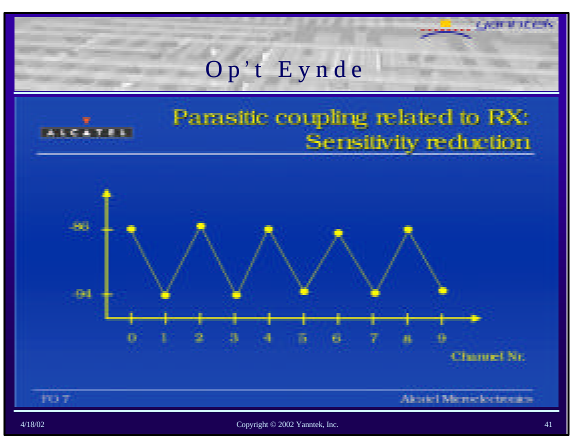
Op't Eynde
ALCATEL
Parasitic coupling related to RX:
Sensitivity reduction
-86
-94
0 1 2 3 4 5 6 7 8 9
Channel Nr.
Alcatel Microelectronics
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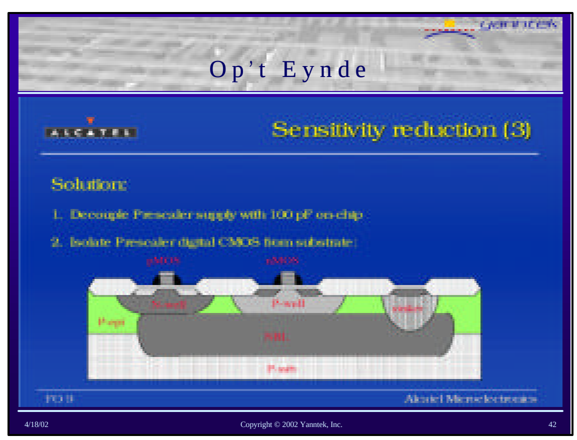
Op't Eynde
ALCATEL
Sensitivity reduction (3)
Solution:
1. Decouple Prescaler supply with 100 pF on-chip
2. Isolate Prescaler digital CMOS from substrate:
Alcatel Microelectronics
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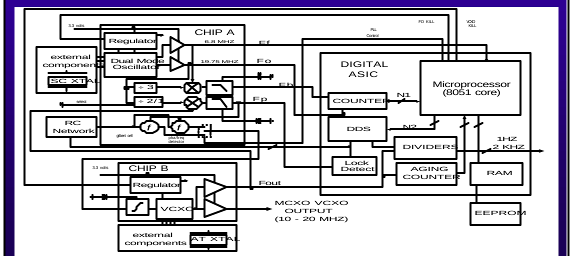
Our Immediate Problem

- Extreme-stability clock
  - achieve atomic-clock performance at smaller power and size



Conclusion

- > 100dB isolation is readily achieved, under some circumstances.
- Faraday cages are effective, and they can be used to suppress noise at either the aggressor or victim location

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