A Low-Power, Radiation-tolerant, RFIC Micro-Transceiver

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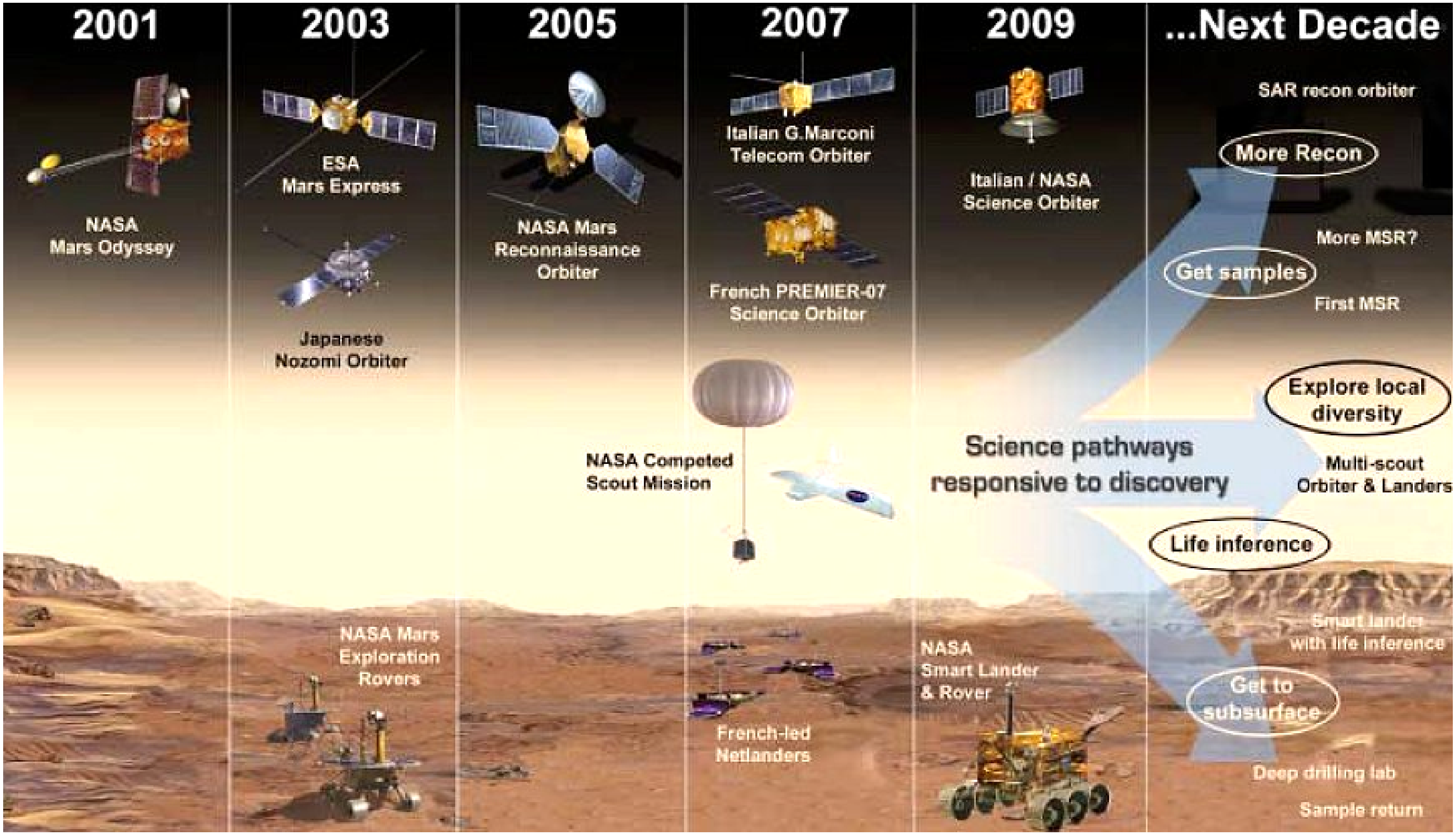
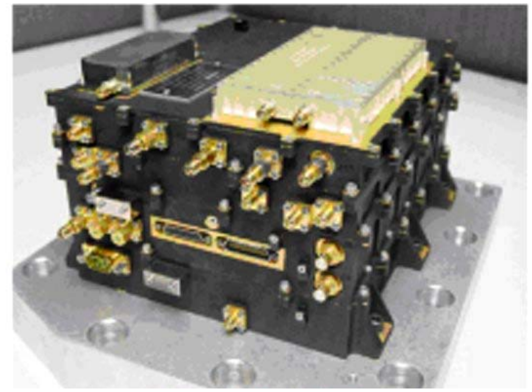
Mars Exploration Timeline



Multimedia courtesy of Caltech's Jet Propulsion Lab and NASA

Problem Statement

Develop a highly-miniaturized, extremely low-mass, low-power UHF Micro-transceiver module for *aerobots*, *microrovers*, *penetrators*, and *small networked landers*.



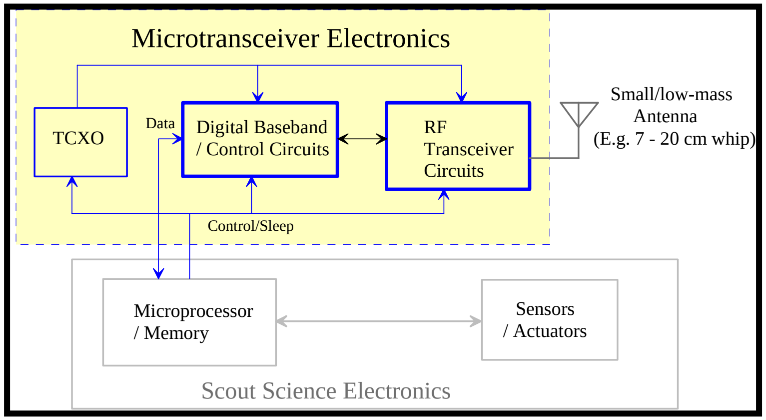
Electra UHF Transceiver
(p/o MRO relay to earth)

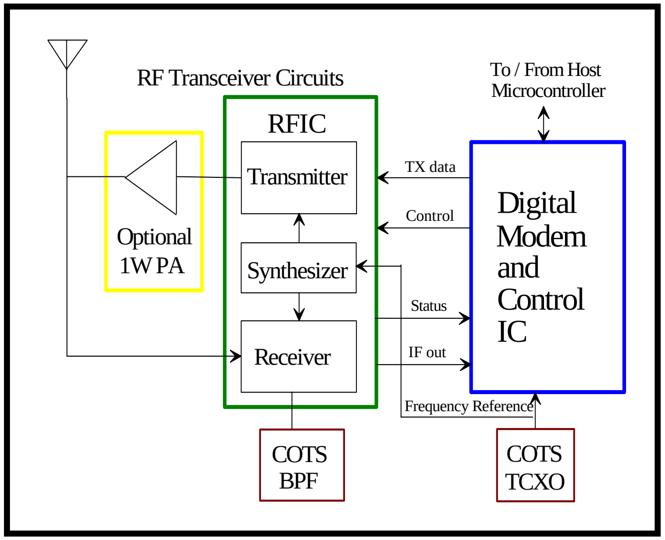
Electra-Interoperable UHF Microtransceiver

Key Challenges, Benefits, and Tradeoffs

- Existing transceivers (e.g. C/TT-505) measure 2000 cm^3, weigh 2 kg, and draw up to 60 Watts on transmit and 6 Watts on receive.
- Target volume and mass of microtransceiver is approximately 5 cm^3 and 5 grams (50 grams) for PC board (metal-housed) form-factor implementations.
- Target power consumption is 50 mW on receive (< 1 mW using sleep mode), and 100 mW / 300 mW / 3 W on transmit for 10 mW / 100 mW / 1 W output.
- Mission tradeoffs include reduced data-volume return at lower transmit powers, half duplex operation, and limited packet handling/formatting, in exchange for one to three orders of magnitude reduction in mass, volume, and power.

Top Level Block Diagrams

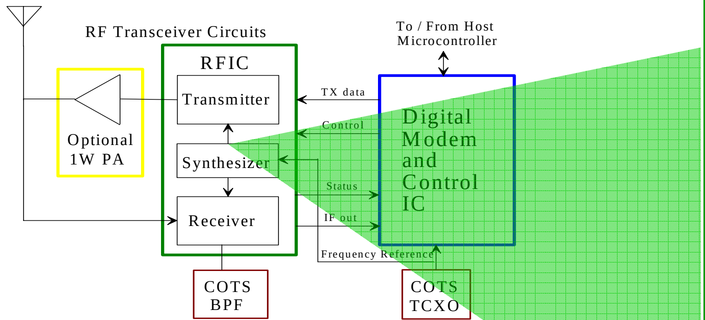




Size/Mass/Power Reduction Techniques

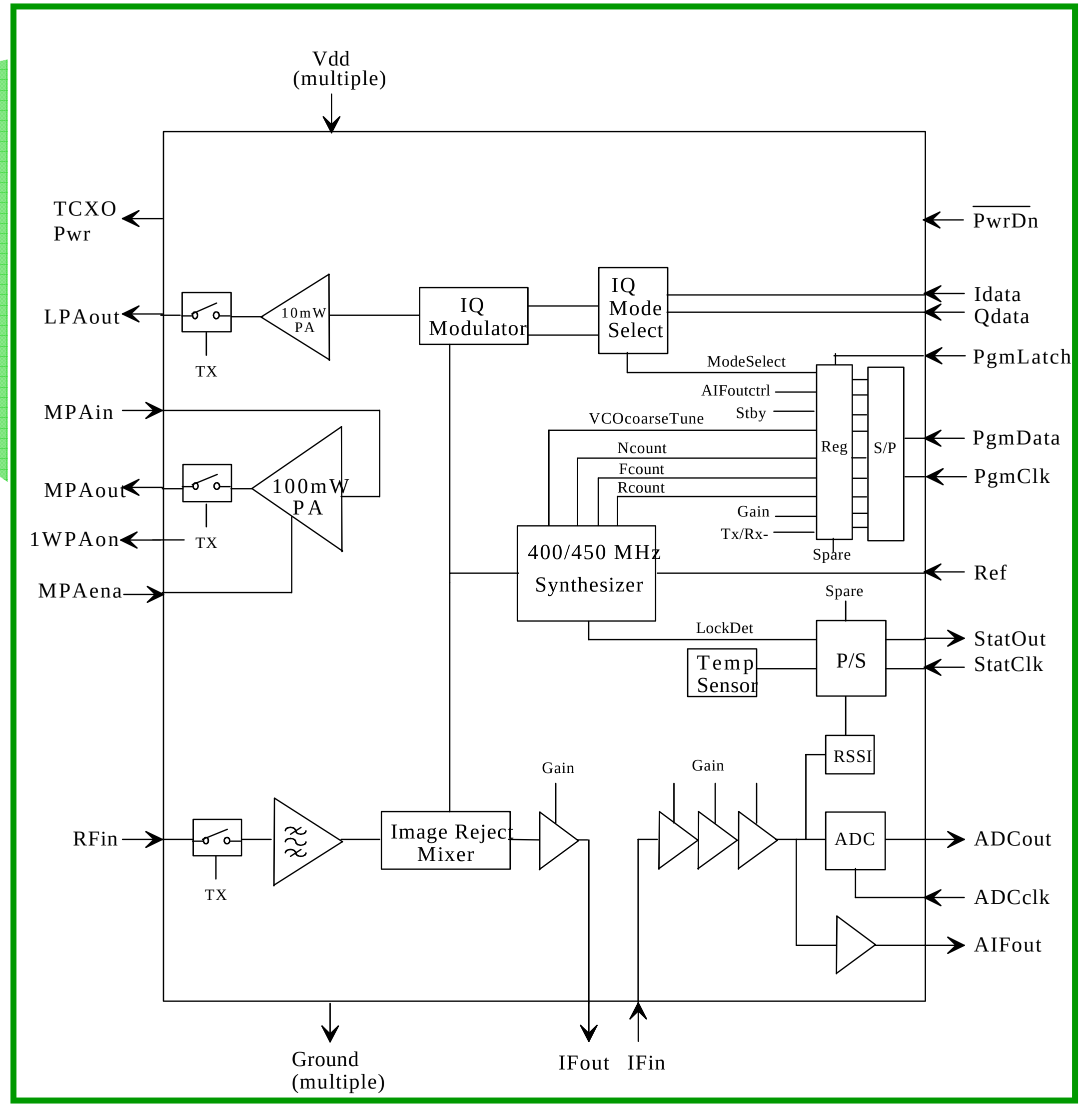
- Design employs a two/three chip solution
- Off-chip components limited to Commercial Off-The-Shelf (COTS) IF filter and TCXO
- RFICs employ full-custom design in Silicon-on-Sapphire process for good RF performance and radiation hardening
- Analog/RF circuits and COTS parts characterized to –100 C to enable operation outside warm-box in some applications
- Digital modem/control circuits designed by JPL will employ low-complexity design techniques and implement subset of Prox-1 space-link protocol
- Higher level protocols will be assumed by host system microcontroller

RFIC Development Technical Approach



RFIC Design Techniques

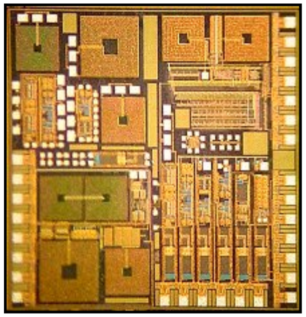
- Proven/robust architectures employed (superhet receiver and direct modulation transmitter)
- New techniques developed for TR switching and integrated watt-level power amp
- Transmitter employs large size, high-Q inductors to achieve good efficiency
- Receive trades off image rejection, IP3, and compression performance for low power
- Half-duplex operation allows transmitter and receiver on same die
- IF sampling allows companion digital modem IC to provide high-quality detection with multiple modulation types



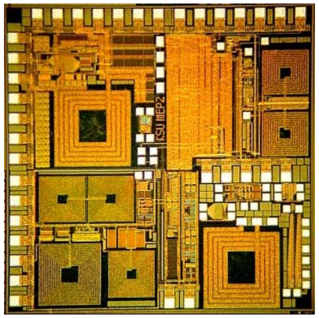
Iterative Prototyping – the key to success

Scheduled Fabrication Runs

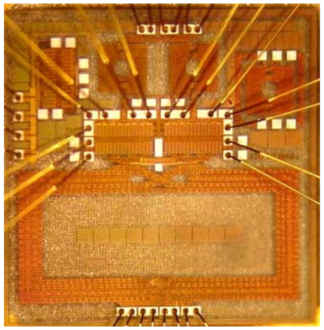
1. RFIC receiver blocks and temp-stable bias circuits	Mar 05	4. Full-transceiver RFIC (100 mW die)	Sep 06
2. 1st RFIC receiver prototype + 100mW PA prototype (+ LNA 2nd spin + SD PLL prototype)	Sep 05	5. Digital receiver and control circuits	Mar 07
3. 1W PA prototype	Mar 06	6. Re-spin as needed	Variable



Fab 1 Receiver
March 2005

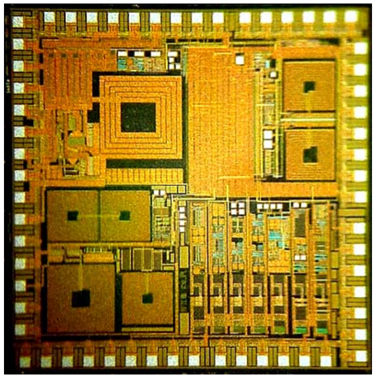


Fab 2 Transmitter
Sept 2005

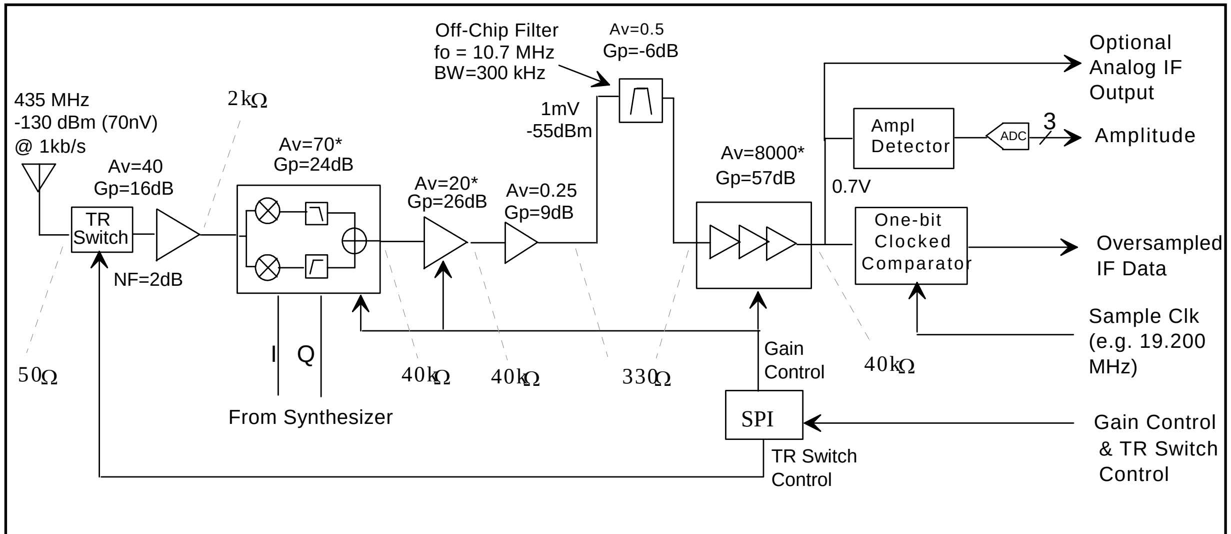


Fab 3 1-Watt PA
March 2006

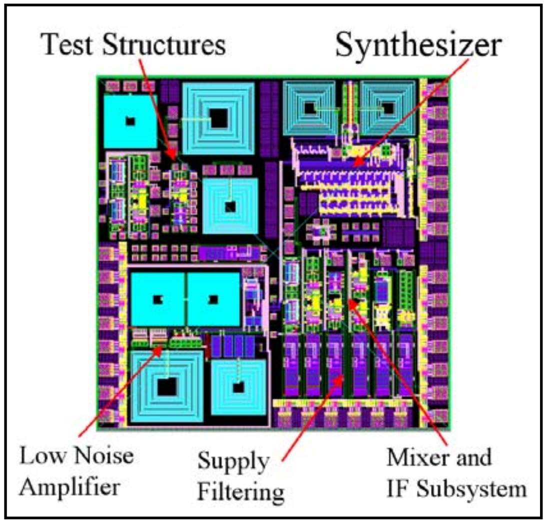
Fab 4 Transceiver
Sept 2006



Fab 1 Receiver Prototype Circuit Design (March 2005)

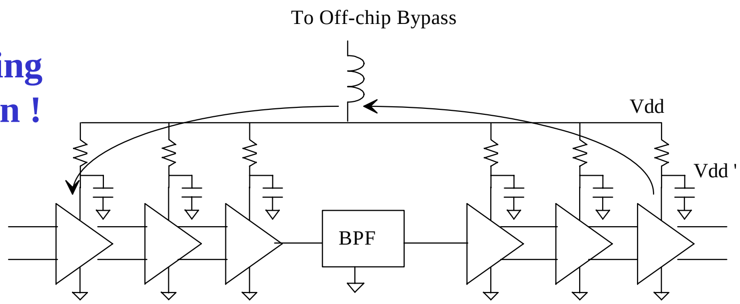


*NOTES: 90 dB of gain control provided in 6dB steps. 15dB excess gain provided by circuits shown.



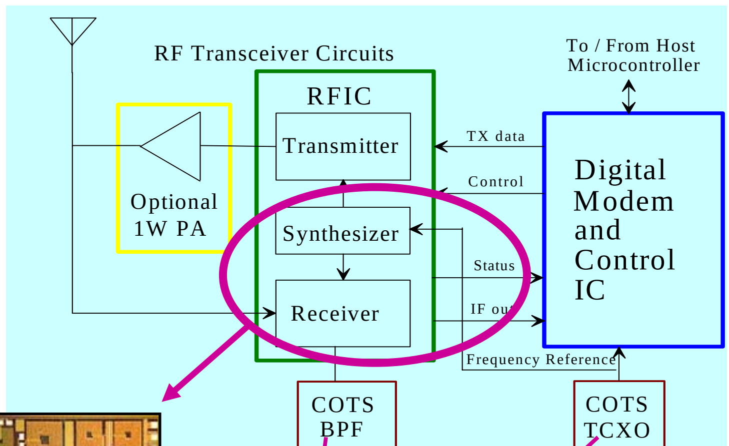
Fab-1 Die Layout

Careful on-chip supply filtering provided in IF amplifier chain !



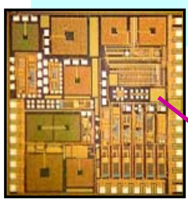
RF Integrated Circuit Development

Fab-1 Receiver Prototype Testing (Summer/Fall 2005)

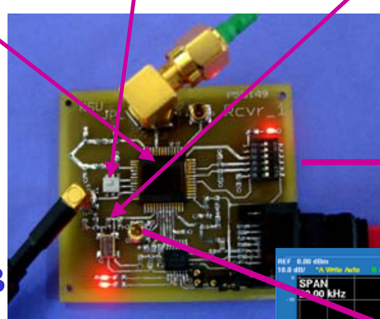


- Successfully tested from RF-in to sampled IF-out
- Low temperature testing showed nominal behavior to –100C with low parametric drift
- Identified areas needing improvement in subsequent fabs to fully meet performance goals:

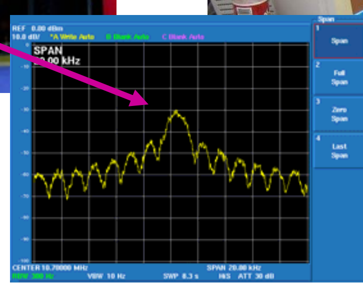
  1. Improve LNA gain to achieve system NF spec
  2. Provide finer tuning steps and reduce spurs



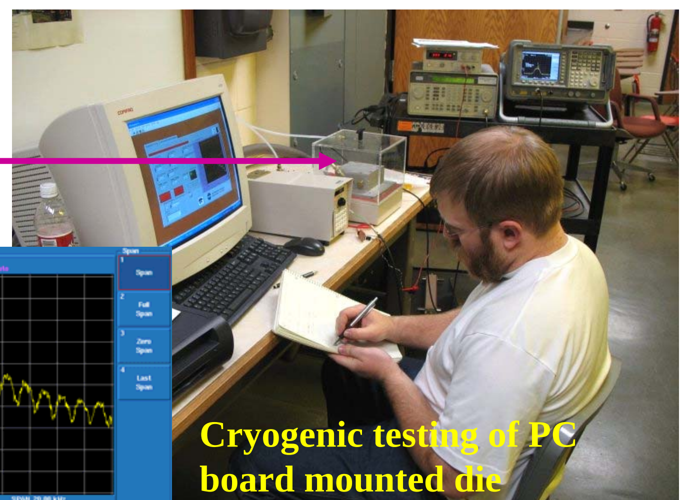
Fab1 die



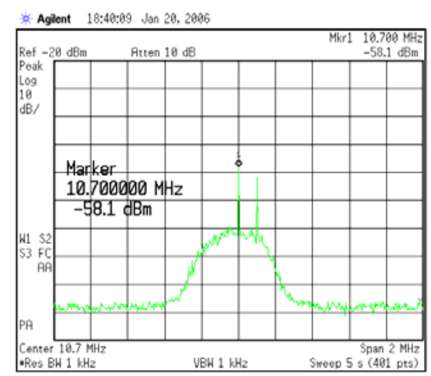
Packaged die on PCB



Spectrum of 1-bit ADC output (1.5 ksps QPSK)

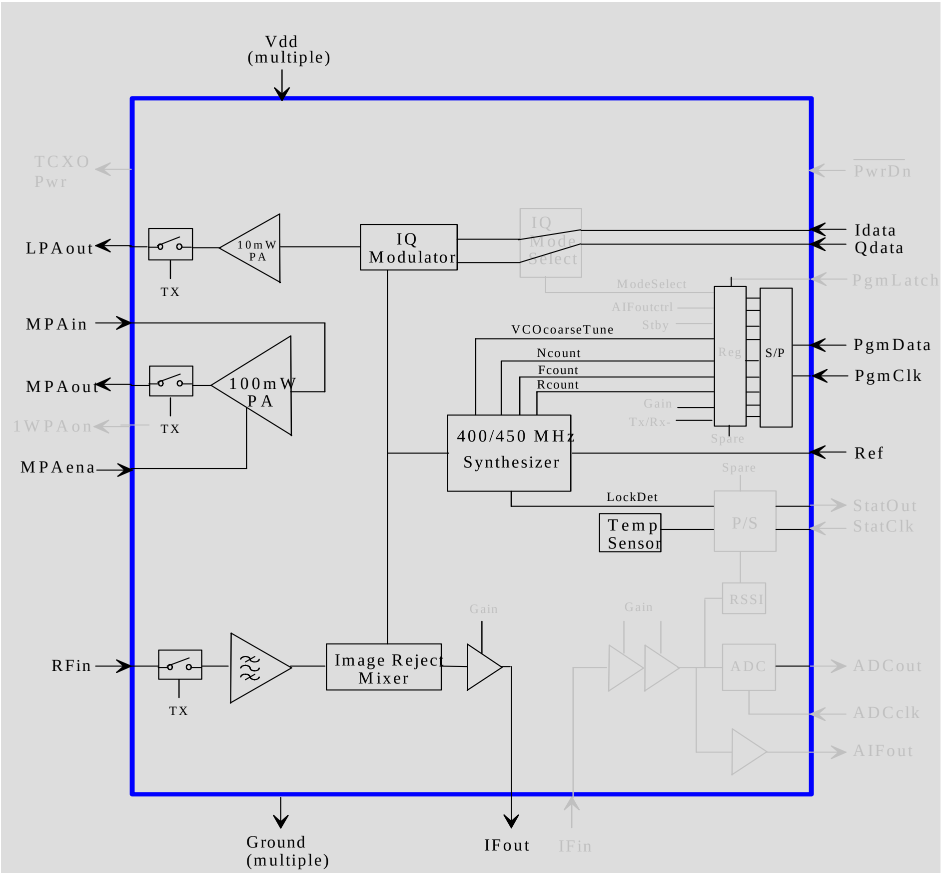


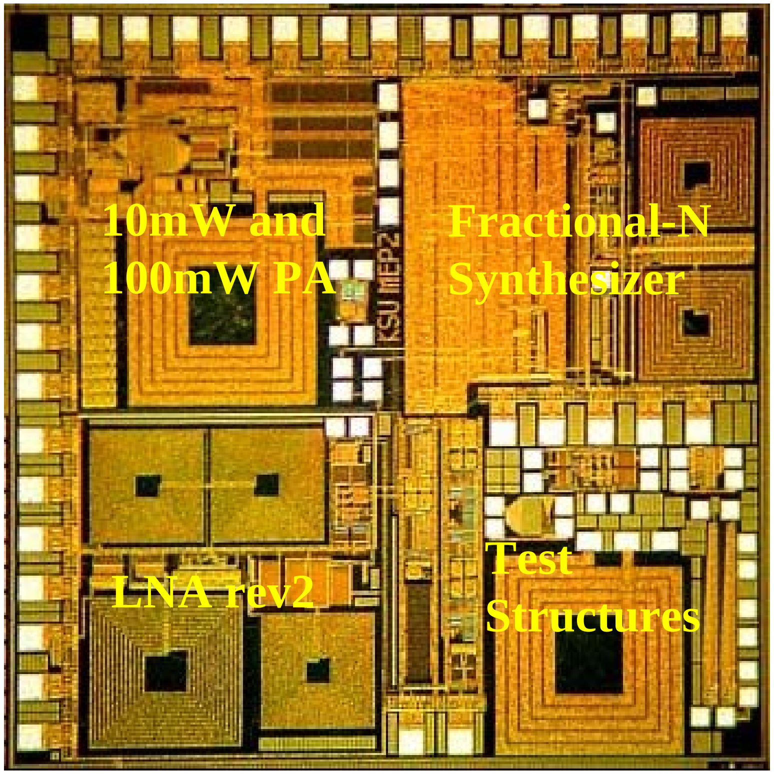
Cryogenic testing of PC board mounted die



IF filter output from +25 C to –100 C with –100 dBm unmodulated carrier.
(reference harmonic spur visible to right)

Fab 2 Transmitter RFIC Circuit Tapeout (March 2006)

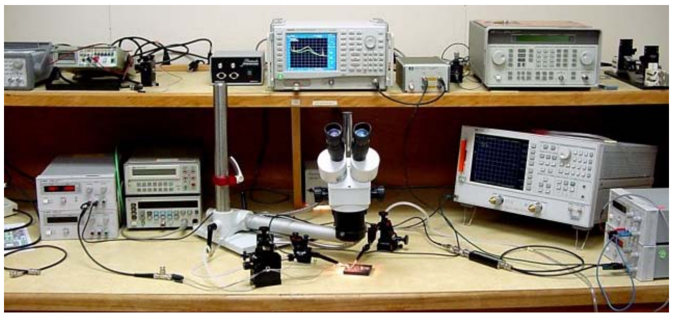




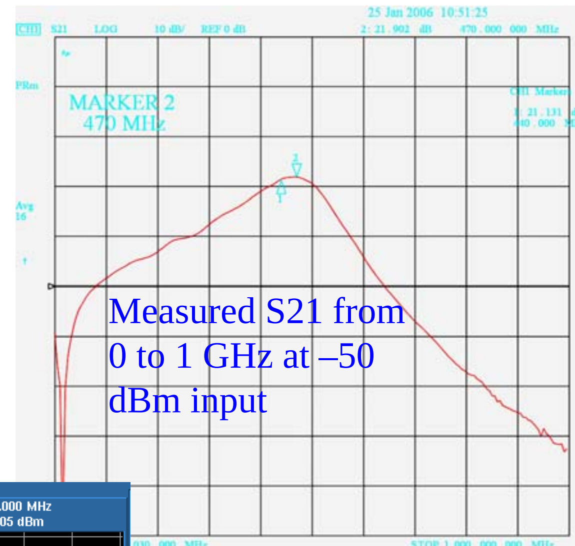
Fab-2 Die Photo

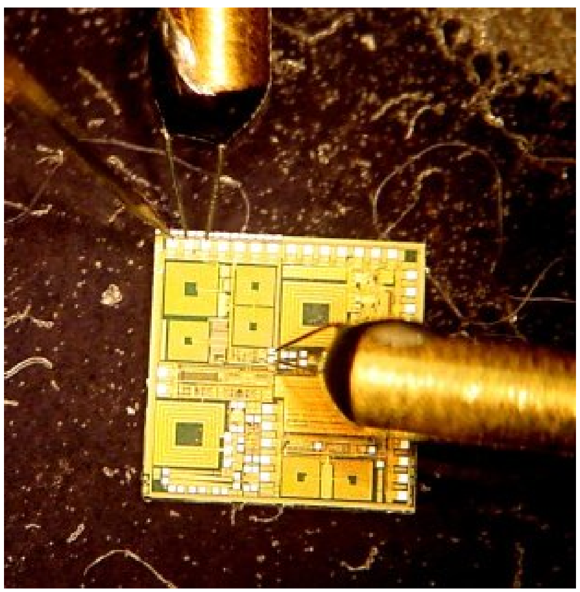
Fab-2 Chip Testing

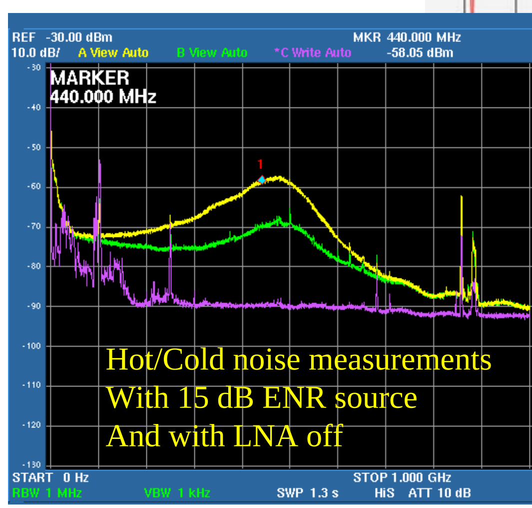
LNA Re-spin Successful ☺



- Gain > 22 dB
- S11 < -10 dB
- Idc = 3 mA (est.)
- 1dBc = -40 dBm





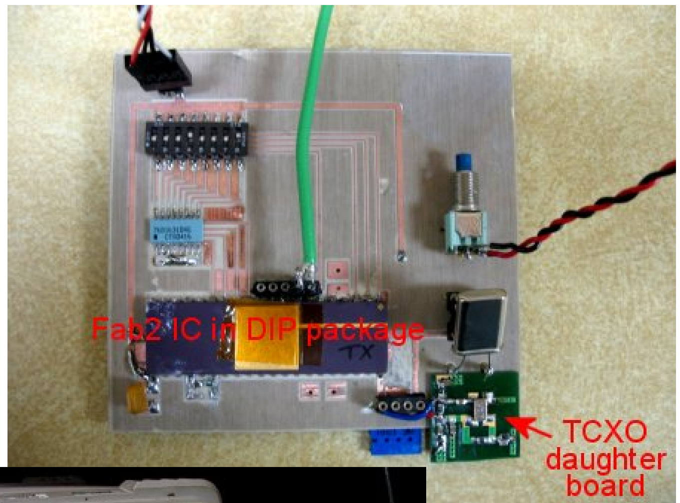


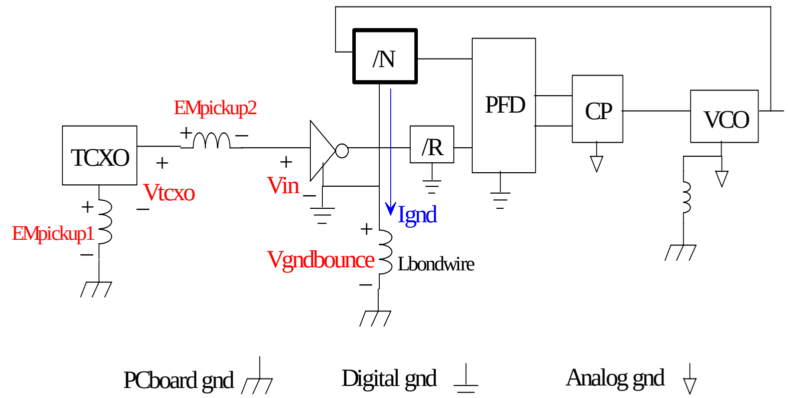
- NF = 3.4 dB at 25C
- Calculated NF < 2.6 dB at –60C

Fab-2 Chip Testing Problems

Phase-lock problems encountered with early PCBs ☹

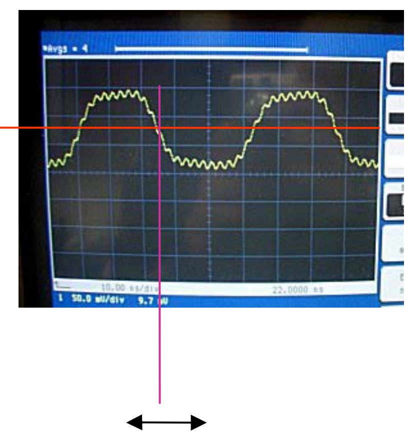
Unlocked spectrum





Vin = Vtcxo - Vgndbounce + (EMpickup1 - Empickup2)

Vin threshold

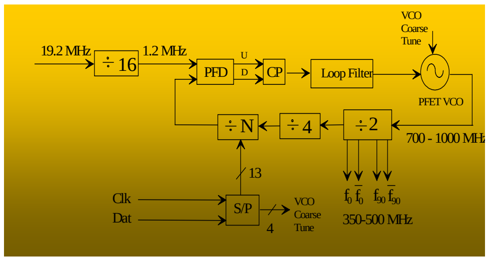


Phase-variation from added 400 MHz signal
⇒Modified feedback in loop
⇒Loss-of-lock

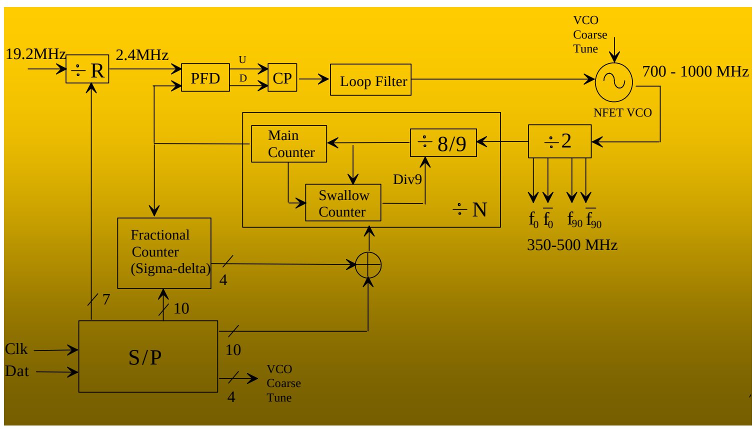
Fab-2 Chip Testing

Fractional-N Synthesizer Operational after PCB mods

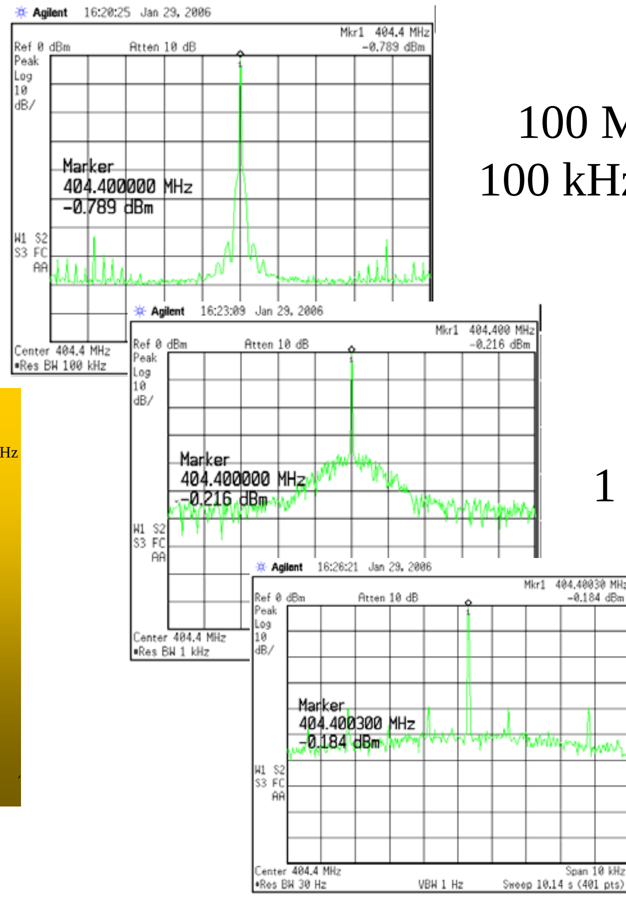
(Phase Noise, Spurs, and Power Consumption Acceptable)



Fab-1 Integer-N Architecture
Tuning step size = 4.8 MHz



Fab-2 Fractional-N Architecture
Tuning step size = 2.34 kHz



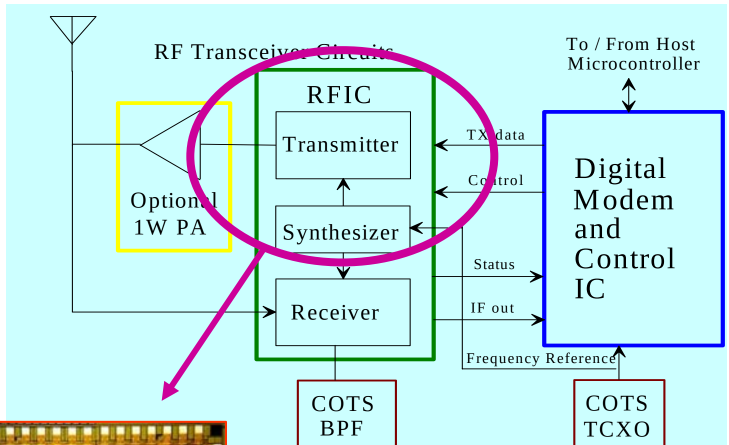
100 MHz Span
100 kHz resolution

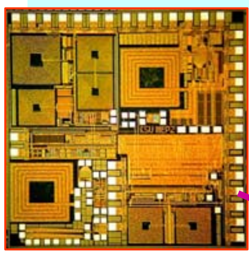
1 MHz Span
1 kHz resolution

10 kHz Span
30 Hz resolution

Fab-2 Chip Testing

Full Transmitter Spectrum and Constellation Tests

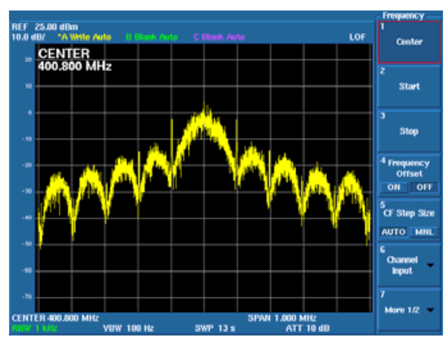




Fab2 die

Packaged die on revised PCB

- All circuits operational and tested to -100 C
- Identified areas needing improvement in subsequent fabs to fully meet performance goals:
  1. *Provide dedicated vdd/gnd pins to TCXO to address PLL locking problems*
  2. *Increase PFD/CP current to allow wider loop bandwidth and reduce phase jitter and EVM*
  3. *Provide dedicated ground on loop filter and more Vdd/Gnd bonds on PA to address constellation EVM problems*

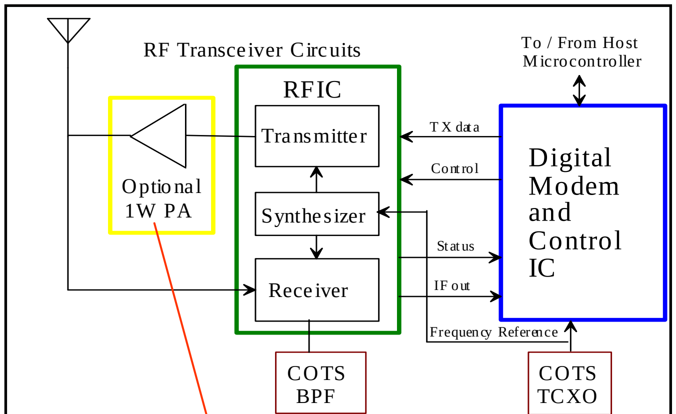


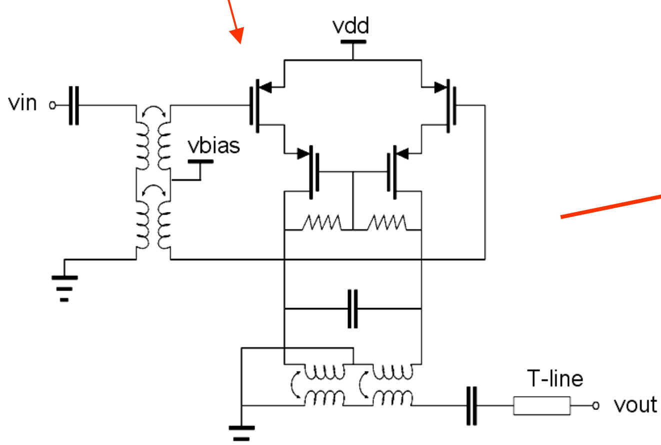
BPSK spectrum

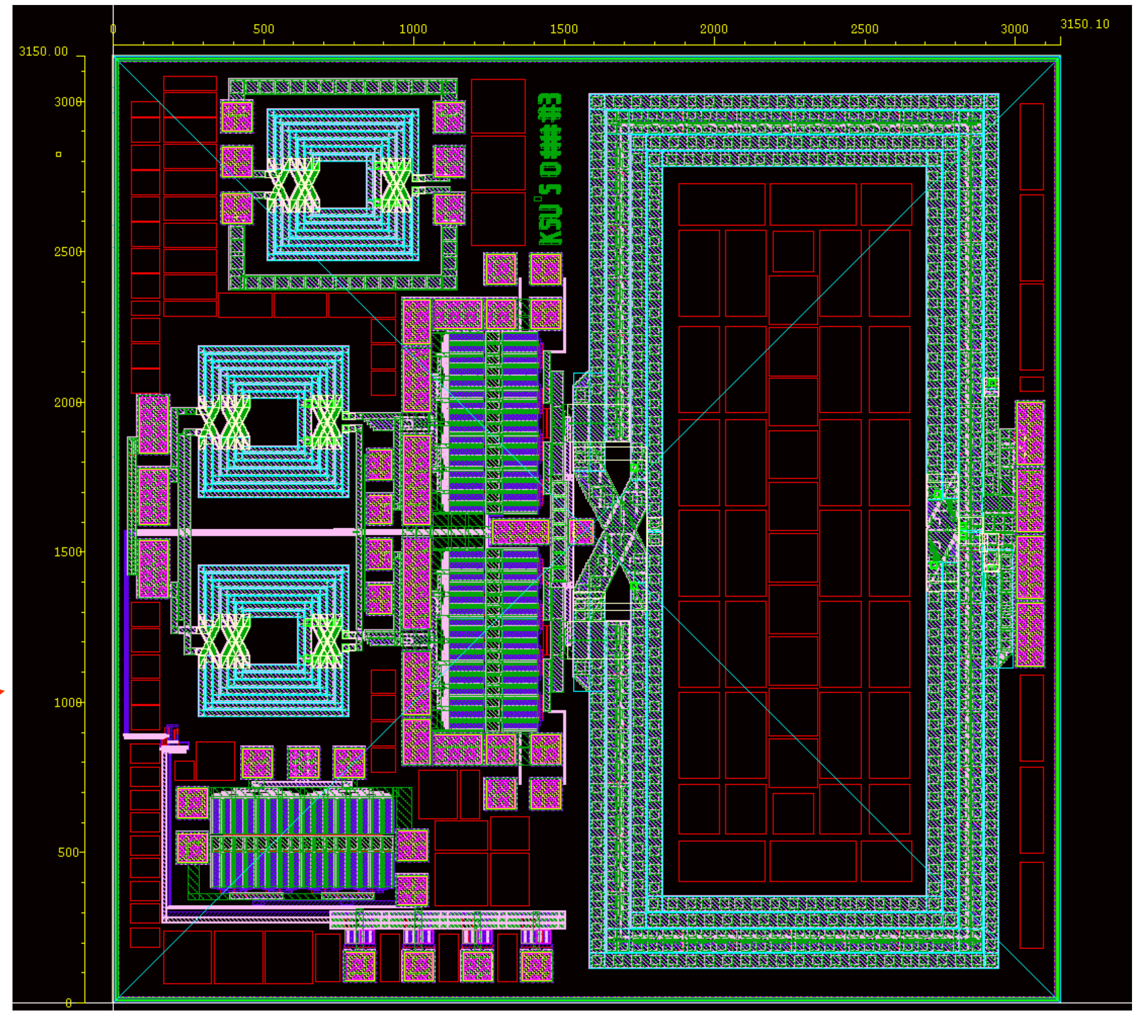
Transmitter signal constellations (1kbps BPSK)

RF Integrated Circuit Development

Fab-3: 1-Watt Transmitter Submitted in March 06



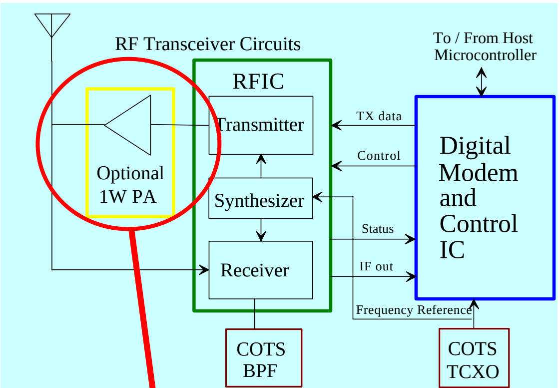




Fab-2 Chip Testing

Fab-3: 1-Watt Power Amplifier Successfully Tested

Microtransceiver Chipset Block Diagram



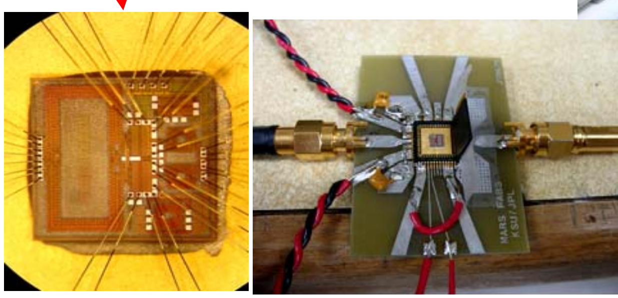
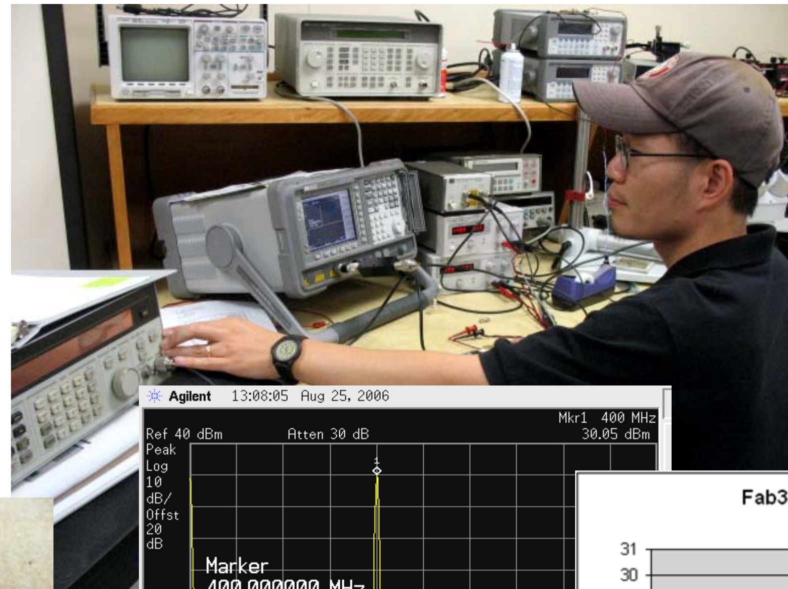
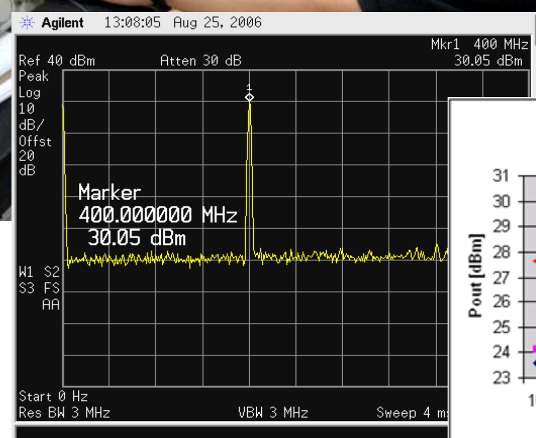


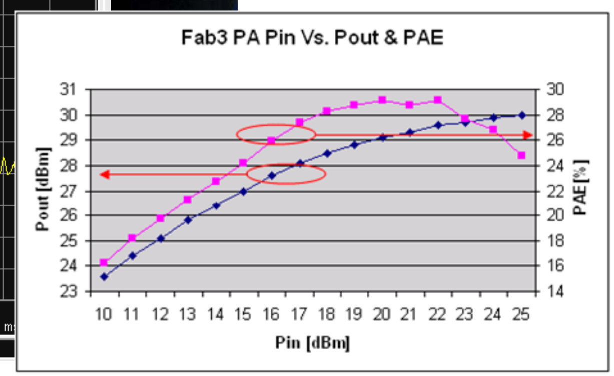
Photo of die mounted in package and package on PCB





Measurment of PA output on spectrum analyzer.

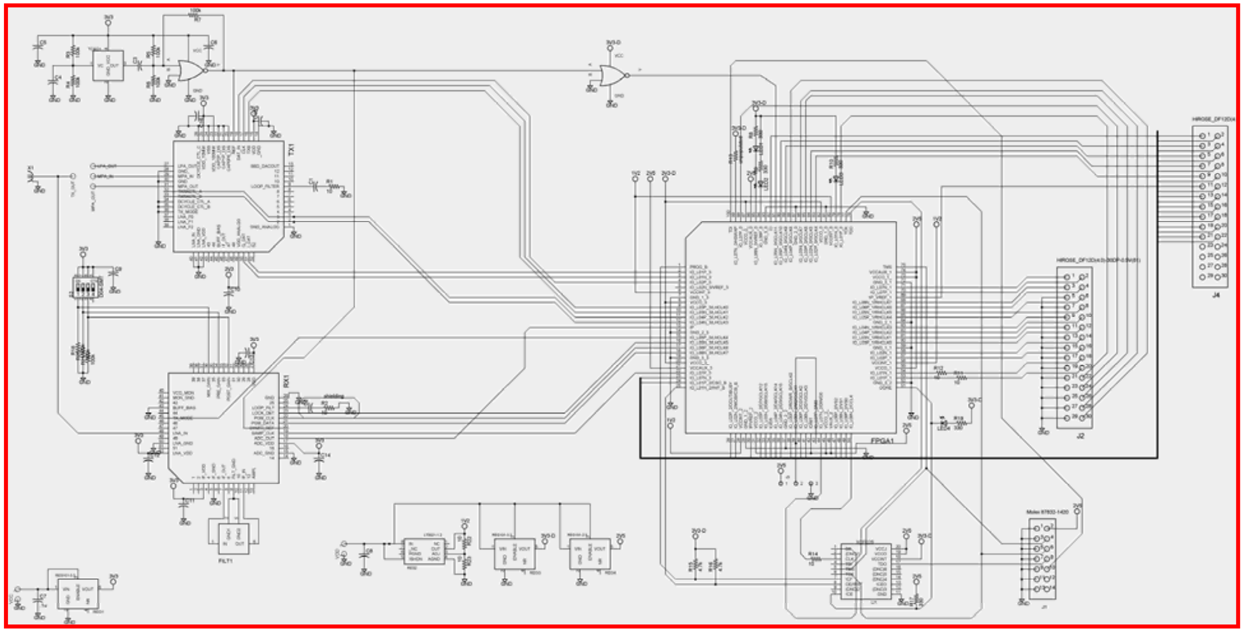
- 20 dB attenuator protects instrument
- Offset of 20 dB added to display
- Accuracy approx +/- 0.5dB
- Meets spec, although some variation between die
- Tested to 4V for safety



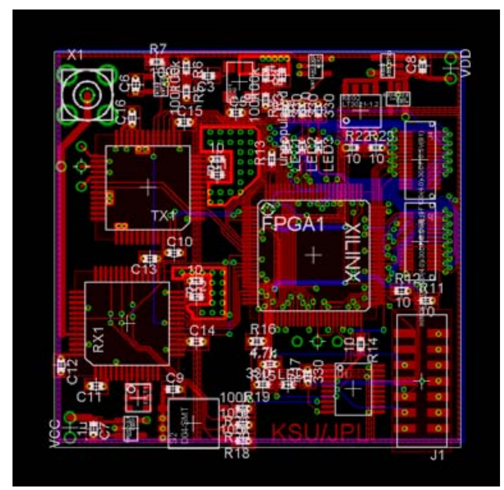
Completes initial development of all major Microtransceiver RFIC prototype circuits.

System-Level Test Vehicle

K-State/JPL Transceiver Integration

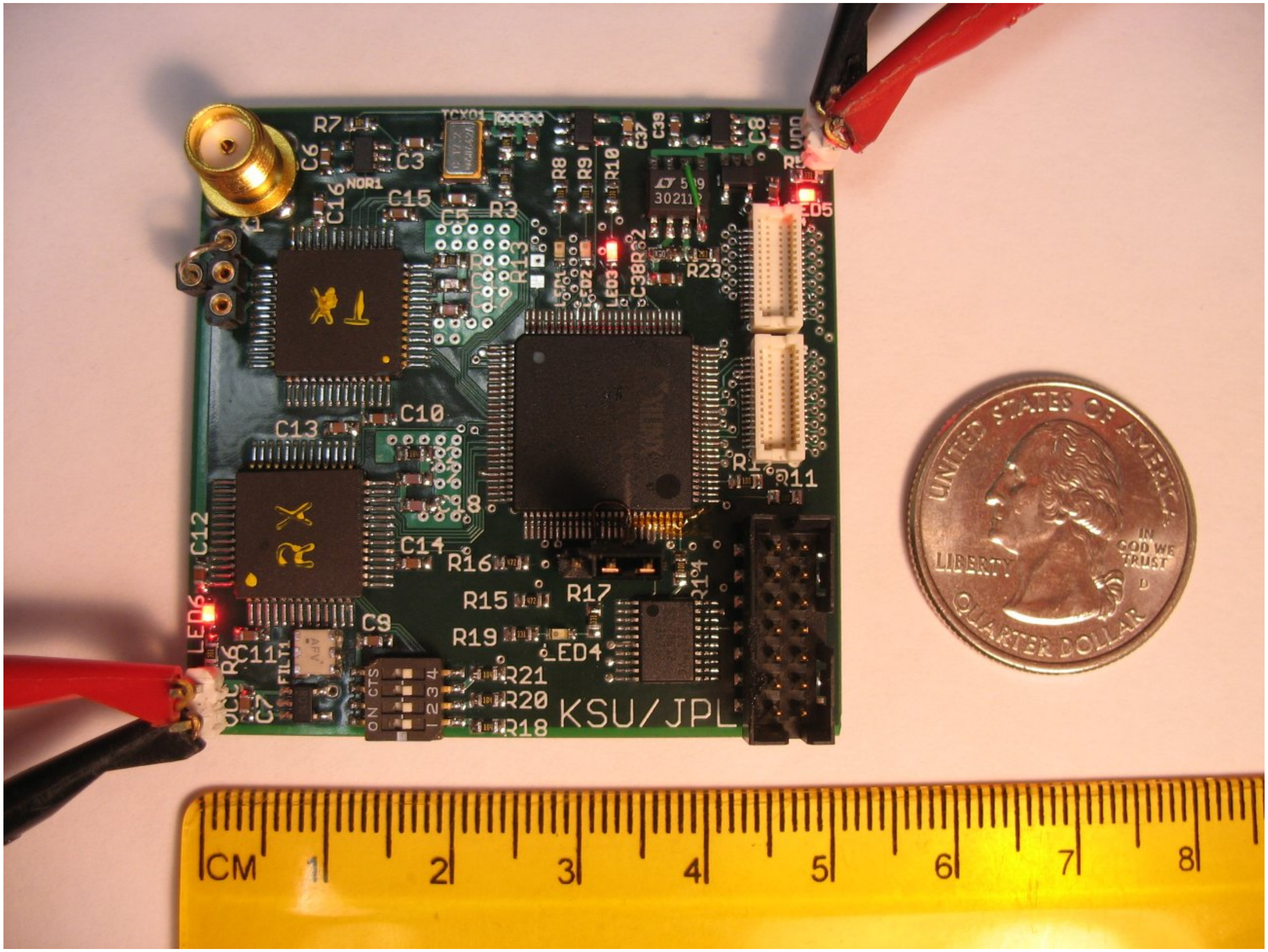


4-Layer PCB Layout
Approximate size = 5 x 5 cm



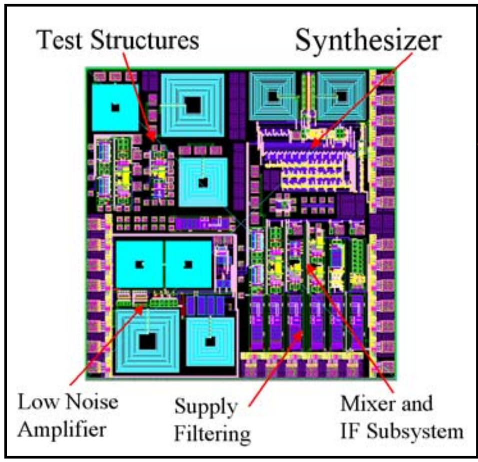
- PC board developed to allow hardware test of digital modem signal processing
- Will also allow early system-level hardware testing to investigate PCB noise issues
- Employs Fab1 Receiver and Fab2 Transmitter RFICs
- JPL will use Spartan 3E FPGA for digital circuit testing

System-Level Test Vehicle

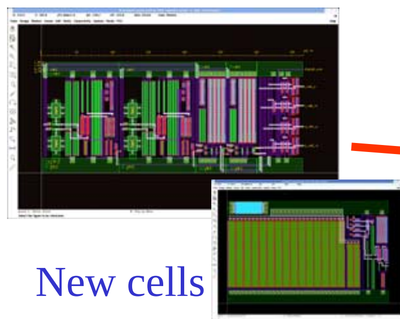


RF Integrated Circuit Development

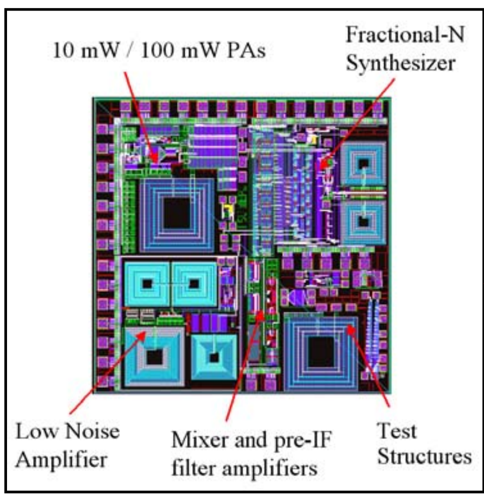
Fab-4 Full Transceiver Chip (Fall 2006)



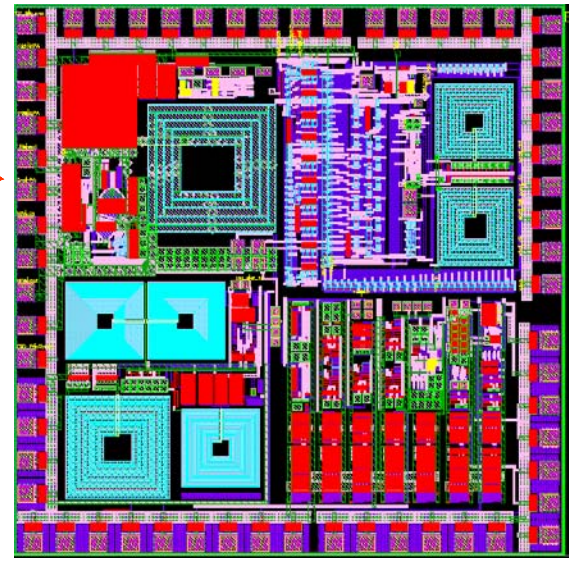
Fab1 die (Mar 05)



New cells



Fab2 die (Sept 05)

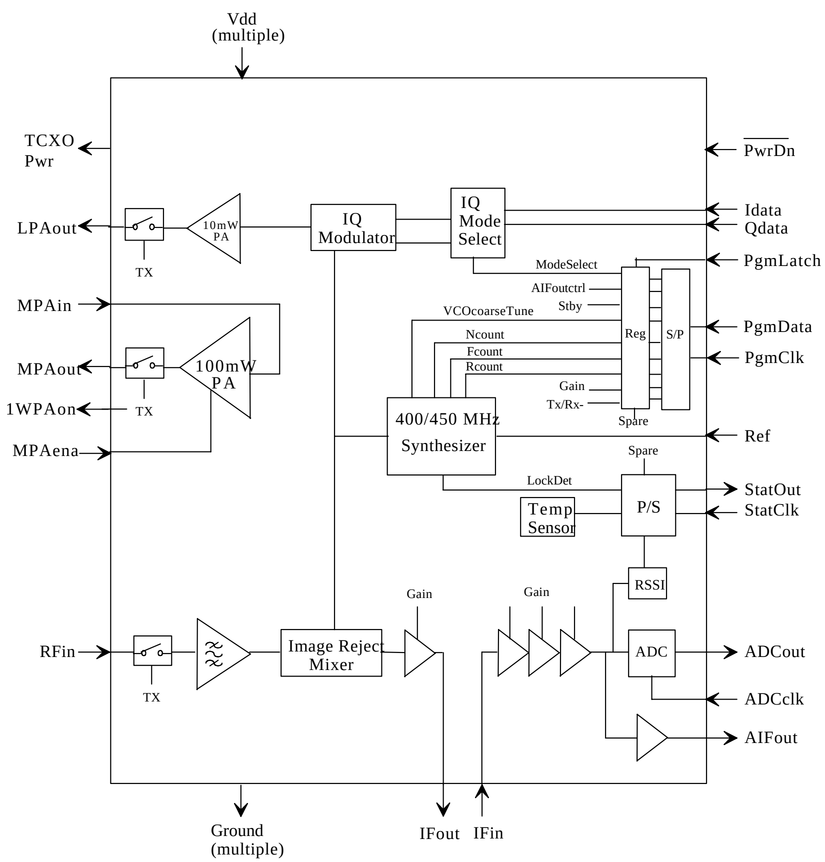


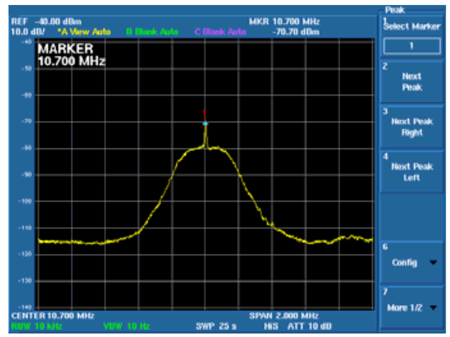
Fab4 die (Sept 06)

- Die size increased to 3.2 x 3.2 mm, 60 pins
- Corrected problems found during fab-1 and fab-2 testing, adding differential signaling, extra pwr/gnd pins, etc.
- Added analog IQ modulator inputs, analog IF output, temperature sensor, lock detector, standby current mode, and full digital control (programming and status registers).

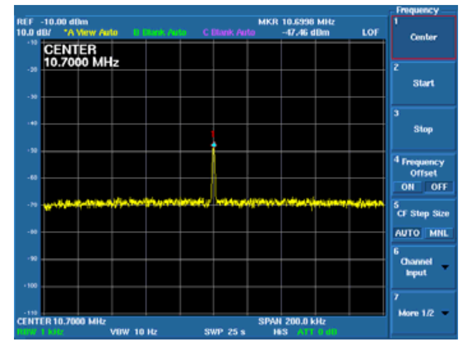
Fab4 Initial Performance Assessments

Fab4 Test Results (2007)

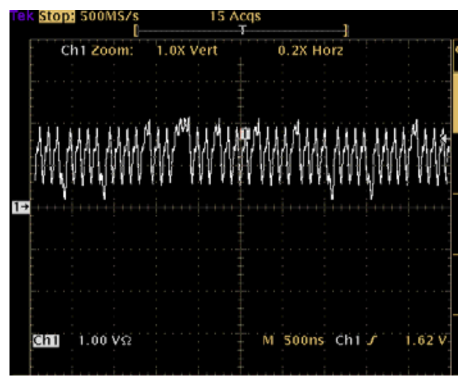




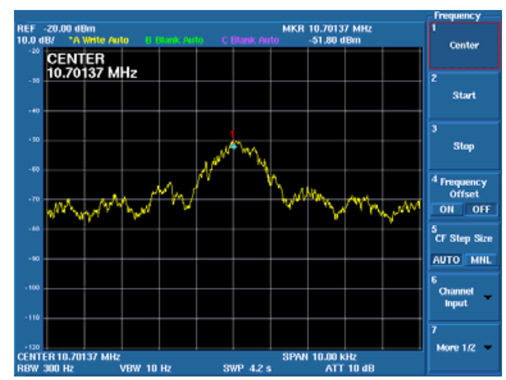
-120 dBm RF signal converted to 10.7 MHz IF at 10 kHz RBW, demonstrating full sensitivity.



-120 dBm RF signal converted to 10.7 MHz IF at 1 kHz RBW, validating 3 dB noise figure and no in-band spurs (this plot does not include switch losses)



1-bit ADC output datastream with 19.2 MHz sample rate. Single-ended output shwon.



Spectrum analyzer view of 1-bit ADC output bitstream validating end-to-end receiver operation.

Fab4 Test Results Summary

Tested Items

- Serial to parallel programming registers
- Power-on resets
- TCXO clock output
- VCO coarse and fine tuning
- BPSK and RC-BPSK modulation (including new line receivers)
- 10 / 100 mW PA outputs
- TR switch on both TX and RX modes
- Receiver, through IF filter
- ADC output
- Analog IF output
- Synthesizer reference divider
- PFD/CP output
- Status register output
- Lock detect (design problem found)
- Nominal current consumption

*__Green__ = working

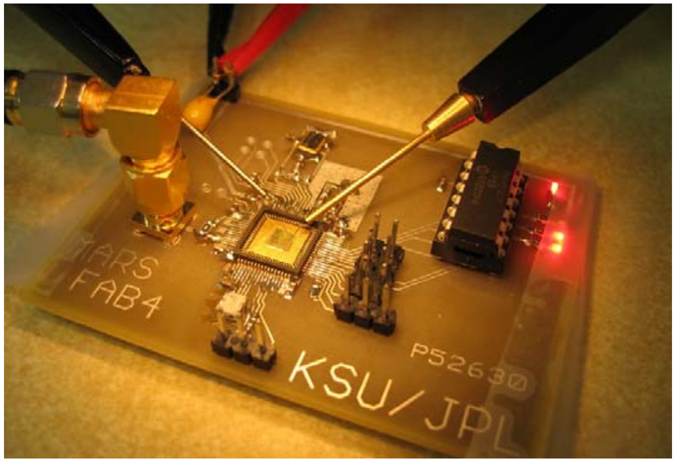
*__Red__ = problem found
(will be fixed in 2007 fab when additional refinements are also made)

Items being debugged

- Some constellation issues in 100 mW mode

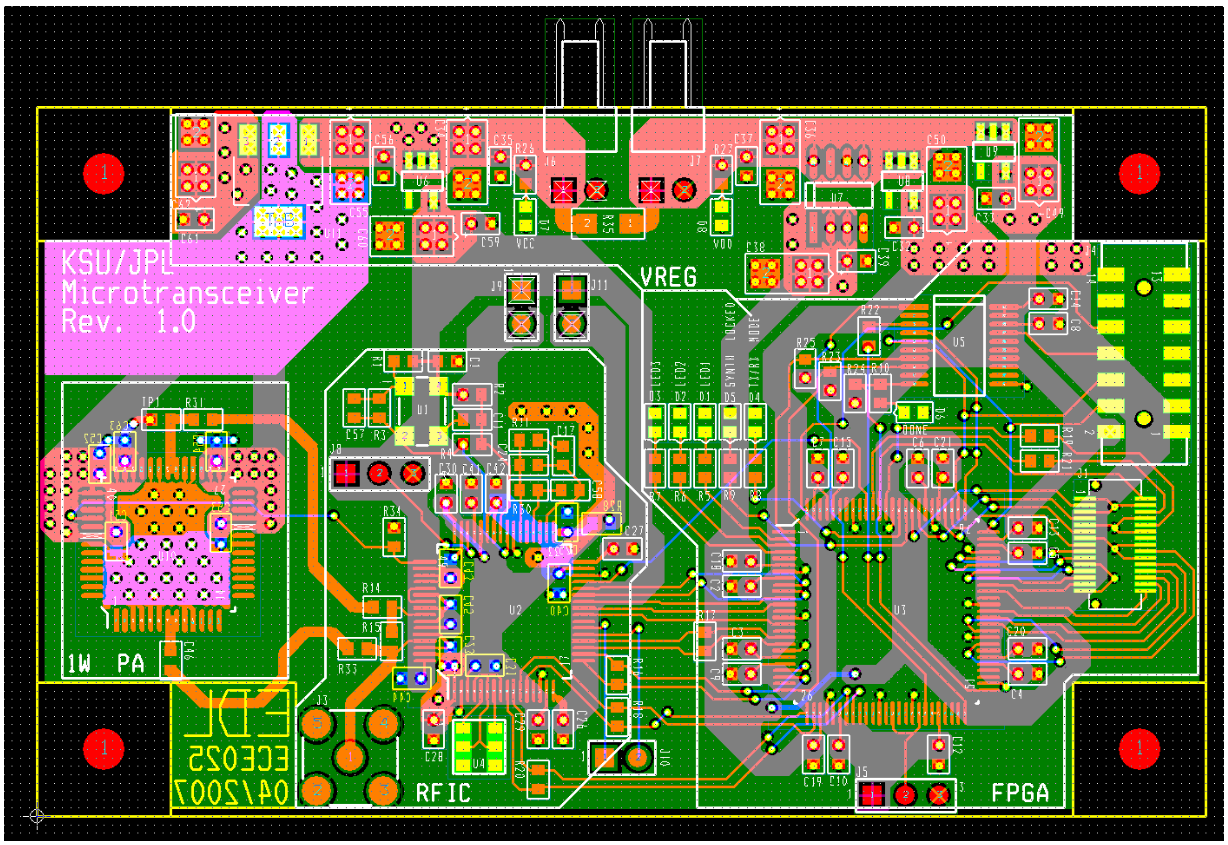
Items not yet tested

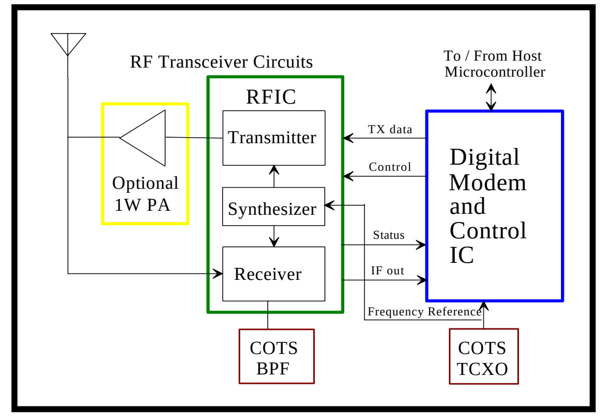
- Analog modulation inputs
- Temperature sensor
- Power down switch circuits
- ESD tolerance on RF input
- Temperature tolerance



Evaluation Board with Full Chip Complement

Developed for evaluation of Micro-transceiver by Mission Planners

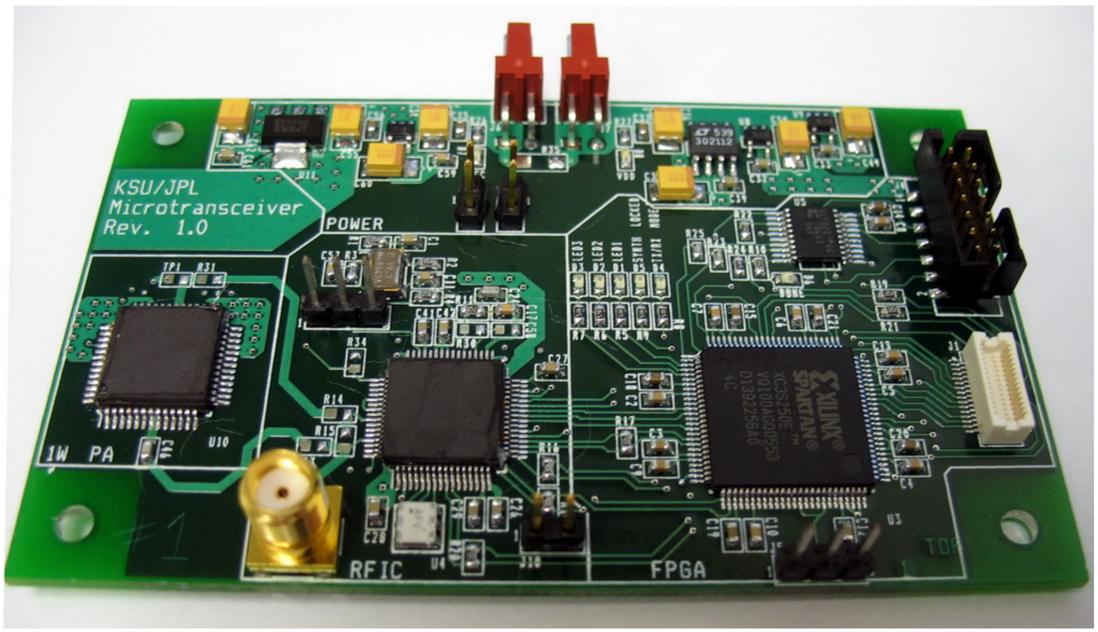




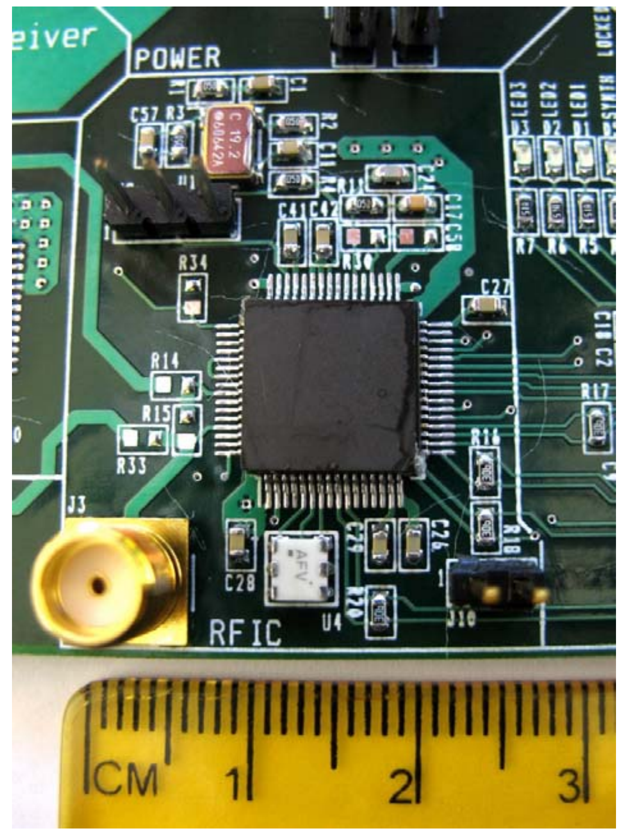
- 4 cm x 6 cm
- 4-layer PCB with internal power and ground for signal integrity
- JTAG programming connector
- LED status lights for testing
- CMOS I/O to host processor on board edge connector
- SMA RF connector to antenna/test-equipment
- On-board regulators for protection of overvoltage

Evaluation Board Photo and Size

Full 1-Watt Eval-Board

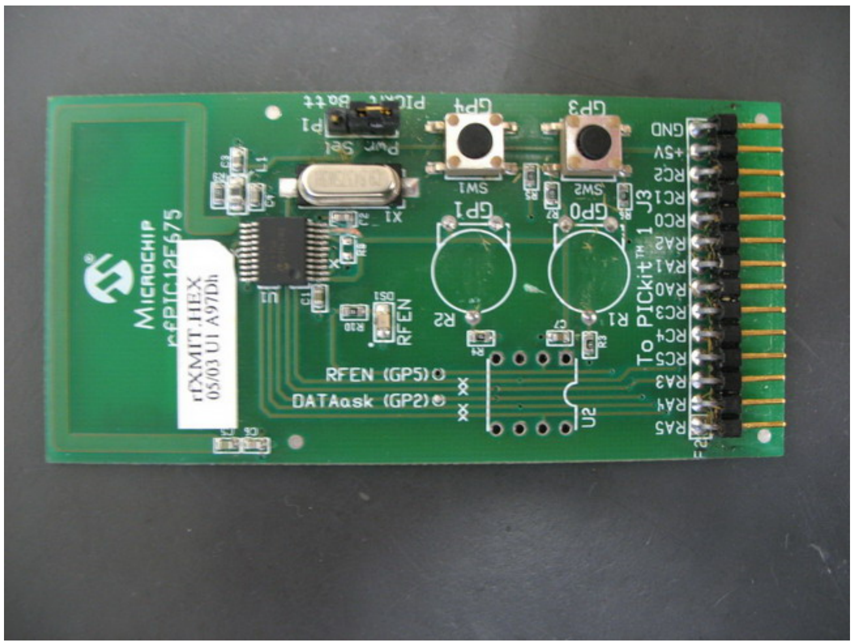


RFIC Portion



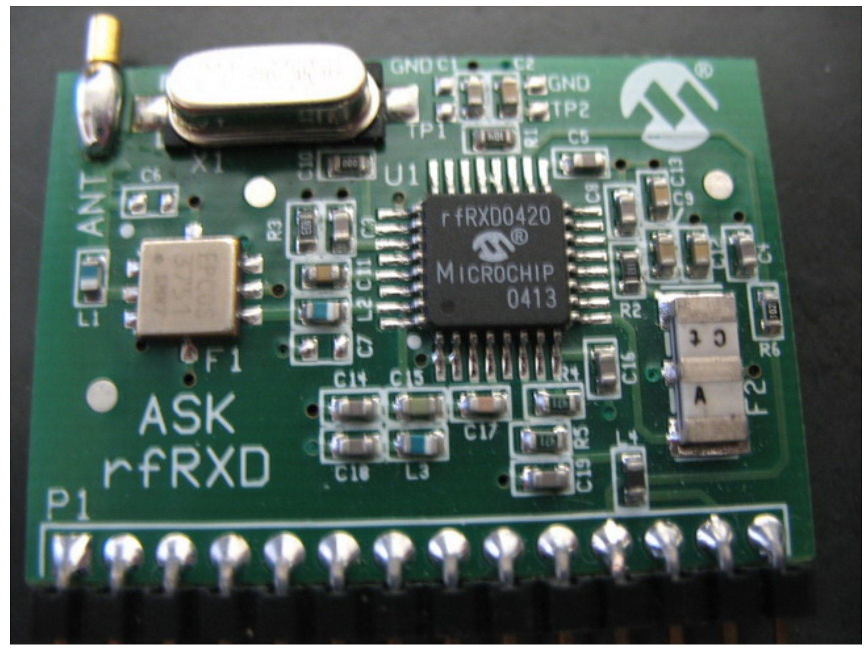
Commercial Offerings at Start of Project

Microchip UHF ASK/FSK Transmitter



- Two-chip solution, and no T/R switch
- <+2 dBm versus +20 to +30 dBm RF output
- >-110 dBm versus -120 dBm sensitivity

Microchip UHF ASK/FSK Receiver



- Not designed for cryogenic temperature
- Not Rad-Hard
- Not Prox-1 Compatible

Commercial Offerings at End of Project

ANALOG DEVICES

High Performance Narrowband ISM Transceiver IC

Preliminary Technical Data **ADF7021**

FEATURES

Low power, low IF transceiver
Frequency bands
  80 MHz to 650 MHz
  862 MHz to 940 MHz
Modulation schemes
  2FSK, 3FSK, 4FSK
Spectral shaping
  Gaussian and raised-cosine filtering
Data rates supported
  0.05 kbps to 25 kbps
2.3 V to 3.6 V power supply
Programmable output power
  −16 dBm to +13 dBm in 63 steps
Automatic PA ramp control
Receiver sensitivity
  −125 dBm at 1 kbps, 2 FSK
On-chip VCO and fractional-N PLL
On-chip 7-bit ADC and temperature sensor
Fully automatic frequency control loop (AFC)
Digital RSSI
Integrated Tx/Rx switch
Leakage current <1 µA in power-down mode

APPLICATIONS

Narrow-band standards
  ETSI EN 300-220, FCC Part 90, FCC Part 15, FCC Part 95, ARIB STD-T67
Low cost, wireless data transfer
Remote control/security systems
Wireless metering
Private mobile radio
Wireless medical telemetry service (WMTS)
Keyless entry
Home automation
Process and building control
Pagers

FUNCTIONAL BLOCK DIAGRAM

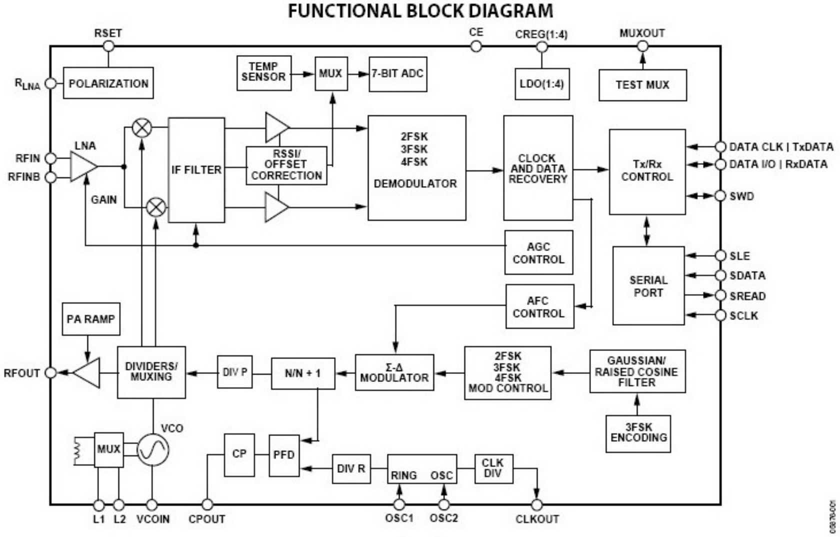


Figure 1.

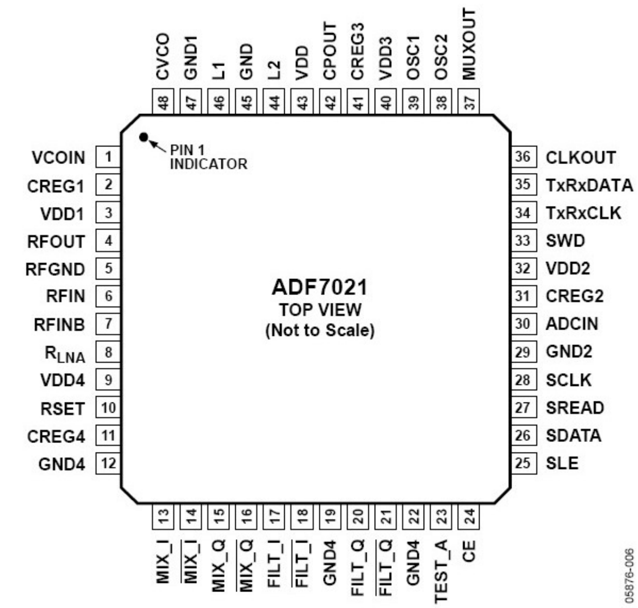
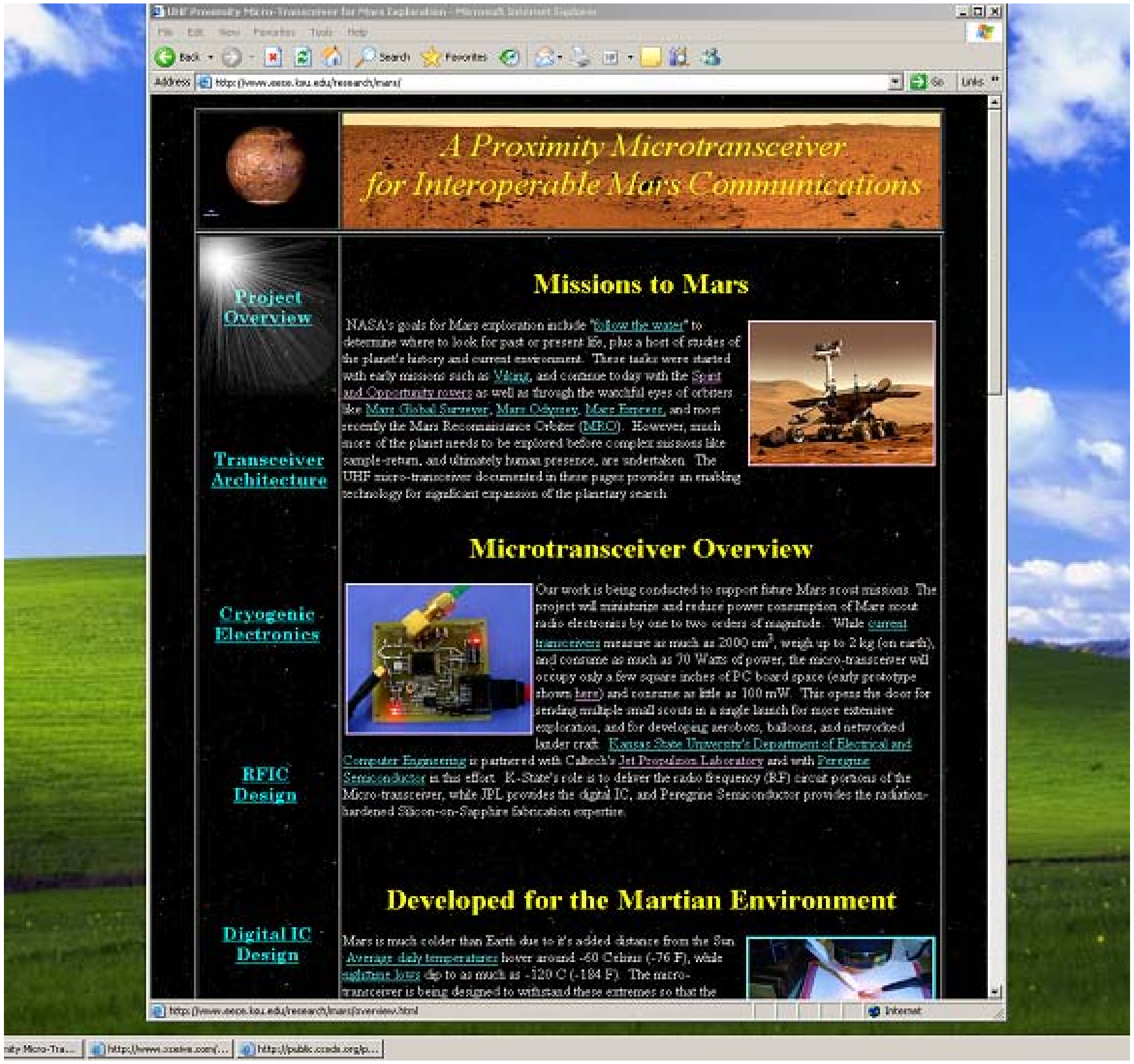


Figure 10. Pin Configuration

- Sensitivity to -123 dBm
- Full on-chip frac-N synthesizer

- No T/R switch
- <+13 dBm versus +20 to +30 dBm RF output
- Not designed for cryogenic temperature
- Not Rad-Hard
- Not Prox-1 Compatible

To Learn More…



Public Site

www.eece.ksu.edu/research/mars

Intended Audience

- General Public / Academics
- Scout Mission Planners
- New Project Personnel

Contents

- Conference published material
- Photos illustrating product form-factor, testing, etc.
- Links to publicly available on-line documents and sites

Publications/Presentations

Published Papers

- W. B. Kuhn, M. Mojarradi, and A. Moussessian, "A resonant switch for LNA protection in watt-level CMOS transceivers," IEEE Transactions on Microwave Theory and Techniques, 2819-25, Sep 2005.
- Yogesh Tugnawat and William Kuhn, "Low Temperature Performance of COTS Electronic Components for Future MARS Missions," 12th NASA VLSI Design Symposium, Coeur d'Alene, Idaho, October 4-5, 2005
- William Kuhn, Norman Lay, Edwin Grigorian, "A Low-Volume, Low-Mass, Low-Power UHF Proximity Micro-Transceiver for Mars Exploration," 12th NASA VLSI Design Symposium, Coeur d'Alene, Idaho, October 4-5, 2005
- William Kuhn, Norman Lay, Edwin Grigorian, Dan Nobbe "A UHF Proximity Micro-Transceiver for Mars Exploration," 2006 IEEE Aerospace Conference.
- Yogesh Tugnawat and William Kuhn, "Low Temperature Performance of COTS Electronic Components for Future MARS Missions," 2006 IEEE Aerospace Conference
- J. Jeon and William Kuhn, "A UHF CMOS Transceiver Front-end with a Resonant TR Switch," 2007 IEEE RAWCON

In Preparation

- William Kuhn, Norman Lay, Edwin Grigorian, Dan Nobbe "A Micro-transceiver for UHF Proximity Links including Mars Surface-to-Orbit Applications," Accepted to special issue on Proceedings of IEEE.

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- Igor Kuperman, JPL
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- Evan Cullens, K-State undergrad
- Keith Kovala, K-State undergrad
- Jack Harder, K-State undergrad