Radio Architecture with Reduced Transmitter Power Consumption for H_2 Sensor Networks

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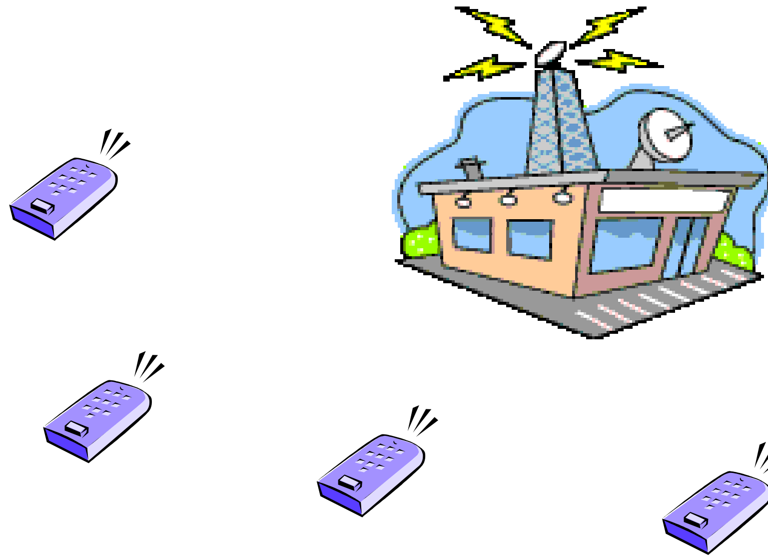
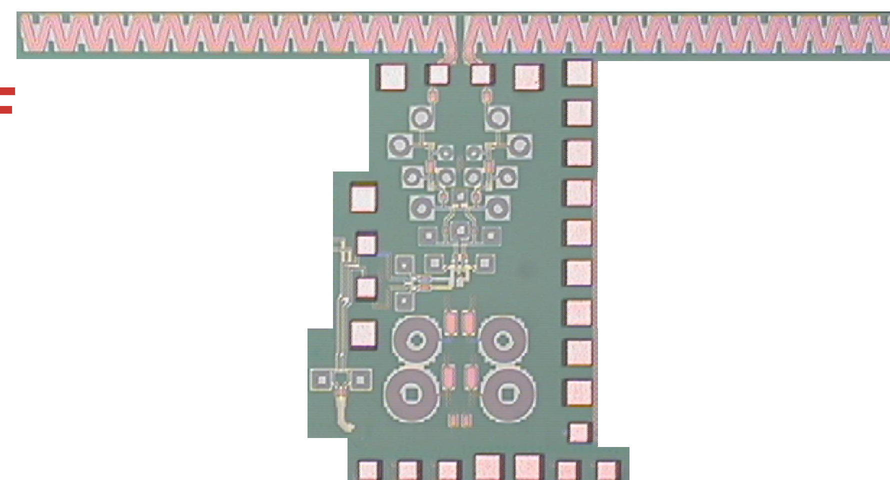
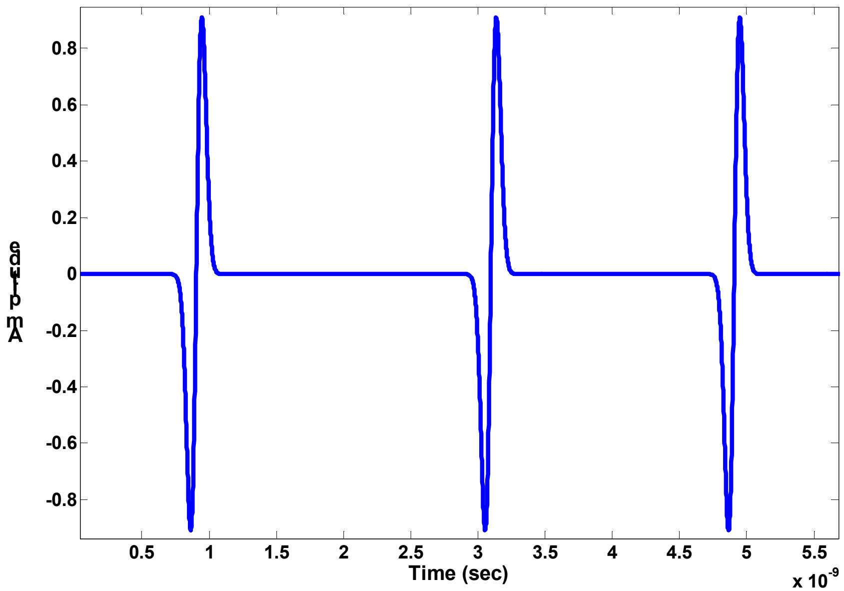
Planned Completion = December 2005

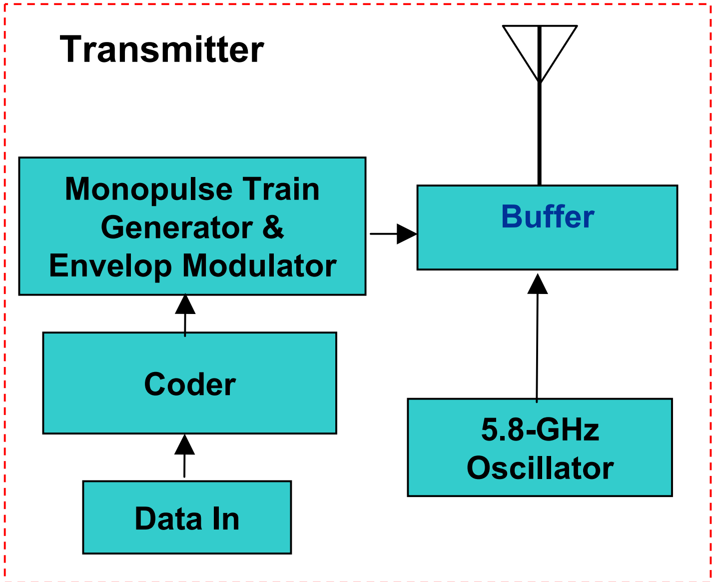
Research Goals and Objectives

To reduce power consumption, cost, and size of H_2 sensor nodes communicating to a base station up to 100m away, this project seeks to develop transmitter architecture with radically reduced power consumption, and seeks to investigate approaches to implement a tiny single chip RF transmitter (~5 mm x 1.0 mm) with on-chip antennas utilizing the architecture and low cost integrated circuits technology.









- **UWB communication using pulse position modulation with reduced TX power. Most of the time, it is not transmitting. For 10 kbps and 2 GHz pulse band width, transmitter is on around 5 μS/sec. With pulse averaging of 10,000, transmitter is on 50 mS/sec.**
- **RX power high (more than 1 W), but should be acceptable for a base station.**
- **Does not need a synthesizer and a mixer, which consume large portions of total power.**
- **UWB communication is tolerant to multiple path effects.**

Center Frequency (f_c)	5.8	GHz
Throughput (Data rate) (R_b)	10	kbps
Range (**R**)	100	m
Transmitted Power (P_{tx})	-12	dBm
Pulse Integration or Retransmission of the Same Bit	10,000	
Peak Transmitted Power	1	dBm
Tx and Rx Antenna Gain (G_t & G_r)	-7 & 10	dBi
Path Loss (**L**)	87.7	dB
Received Power (P_{rx}) (P_{tx}-L+G_t+G_r)	-96.7	dBm
Rx Noise Figure (**NF**)	8	dB
Minimum E_b/N_0 (**S**)	6	dB
Total Avg. Noise Power/bit ($P_n = kTR_b + NF$)	-125.8	dBm
Implementation Loss (**I**)	3	dB
Link Margin ($LM = P_{rx} – P_n – I - S$)	20	dB

- **20 dB link margin should be adequate for TX power of 63 μW.**
- **TX power consumption should be ~ 3 mW. Possible to consider the use of energy scavenging.**

Center Frequency (f_c)	**5.8**	**GHz**
Bandwidth (**BW**)	**2**	**GHz**
Throughput (Data rate) (R_b)	**10**	**kbps**
Range (**R**)	**100**	**m**
Transmitted Power (P_{tx})	**-12**	**dBm**
Pulse Integration or Retransmission of the Same Bit	**10,000**	
Peak Transmitted Power	**1**	**dBm**
Tx and Rx Antenna Gain (G_t & G_r)	**-7 & 10**	**dBi**
Path Loss (**L**)	**87.7**	**dB**
Received Power (P_{rx}) ($P_{tx}-L+G_t+G_r$)	**-96.7**	**dBm**
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- **Assuming a duty cycle of 0.1%, for 2 year operation, need a 44 mA-hr battery. Size 5 battery has ~40 mA-hr.**

Relevance to Current State-of-the-Art

- The maximum communication distance using a pair of on-chip antennas has been suggested to be ~10 m. This is measured at 24-GHz in order to keep the antenna length to ~3 mm. Using an on-chip antenna/high gain antenna pair as well as operating at lower frequency, the maximum communication distance will be increased to 100 m.
- A large part of power consumption of a transmitter is due to that for a synthesizer, mixer and power amplifier. This project seeks to reduce the power consumption to less than 3 mW for transmitters with an on-chip antenna which can communicate up to 100 m. This represents more than 20X reduction in power consumption.

Relevance to NASA

- Will be able to reduce the cost of transmitter to ~50 cents and radically increase the duration between battery replacements for H_2 and other sensors.

Budget, Schedule and Deliverables

- **Budget: $35,000 for FY04**

Phasing Plan

Q1	Q2	Q3	Q4
$6,500	$11,000	$11,000	$6,500

Project award date 9/30/04

Project started 1/1/05

Designed and fabricated on-chip monopole and dipole antennas for operation at 6 and 10 GHz. (6/30/05)

Q1	Q2	Q3	Q4	Q5

Completed evaluation of antennas (9/15/05)

Deliverables:

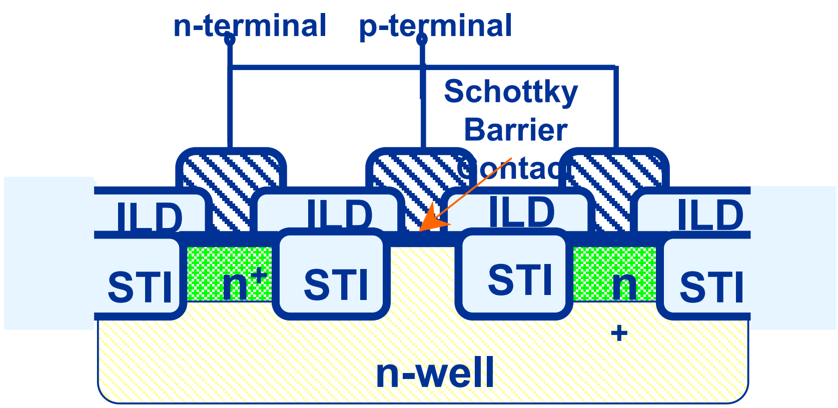
- **On-chip antennas suitable for 100-m applications**
- **Transmitter architecture with reduced power**

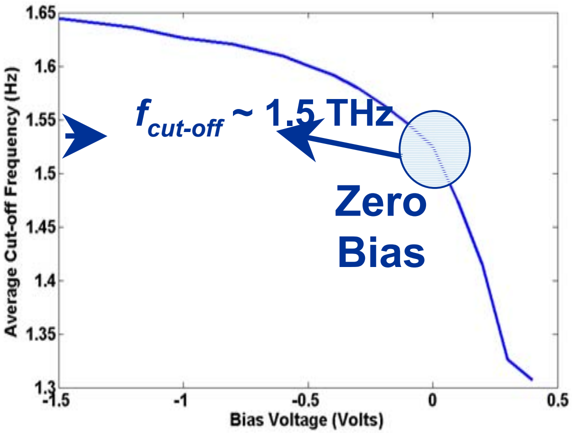
Anticipated Technology End Use

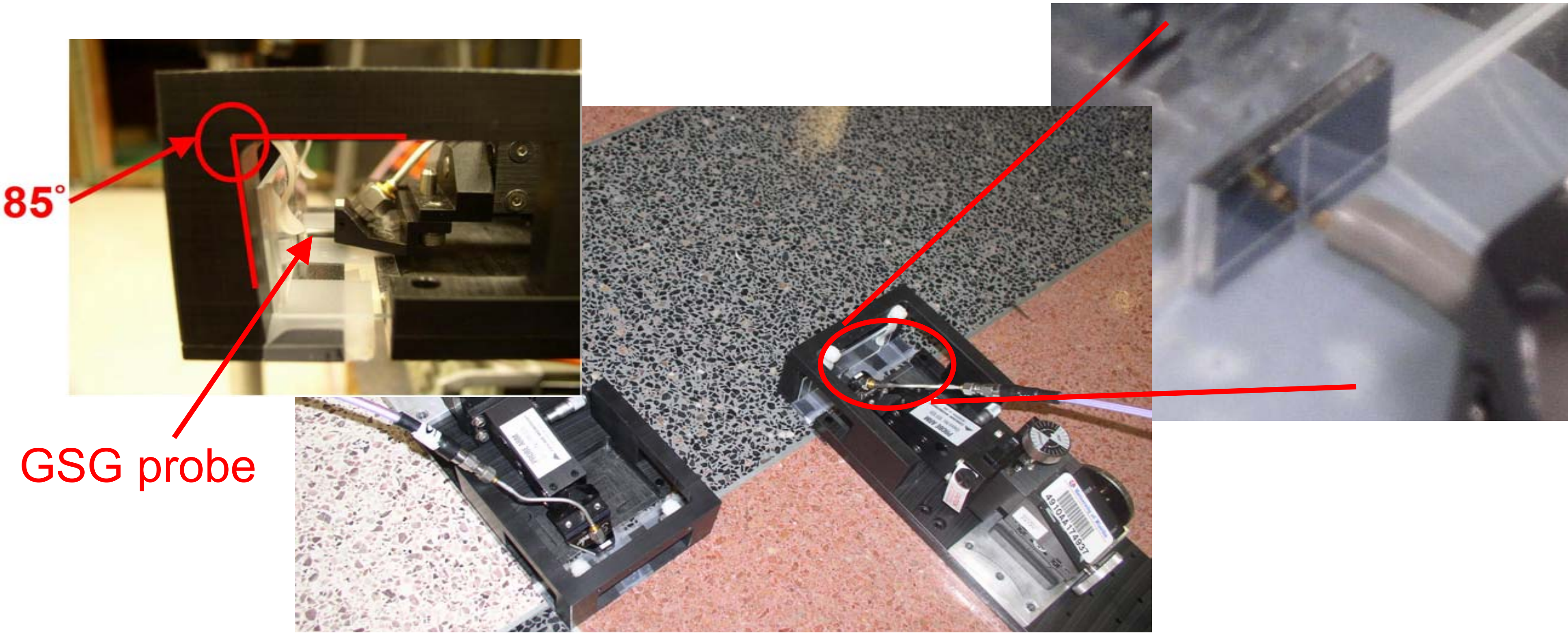
- A communication link for H_2 sensors.
- Communication links for a wide variety of sensors talking to a base station (For example: tire condition monitor).
- Inventory and other asset tracking.

Accomplishments and Results

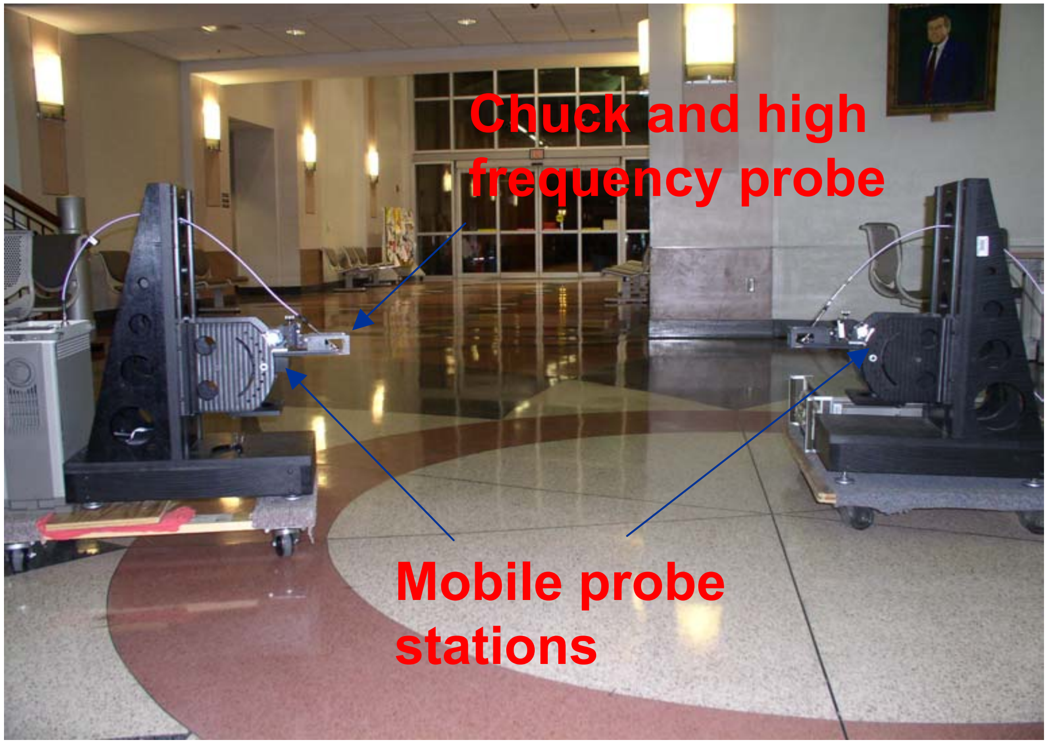
- This project has evolved from a transceiver project in which a receiver and a transmitter without a synthesizer were investigated. This project enabled us to finish up the work on Schottky diodes fabricated in foundry CMOS.
- 1.5-THz is the highest cut-off frequency for any silicon devices in mainstream foundry processes.
- Leakage at -1 V is 1-10 nA (excellent) for 16 x 0.32 x 0.32 mm^2 diode with 8 fF capacitance.
- This work has shown the possibility of using low cost mainstream silicon technology for sub-millimeter wave and THz applications.

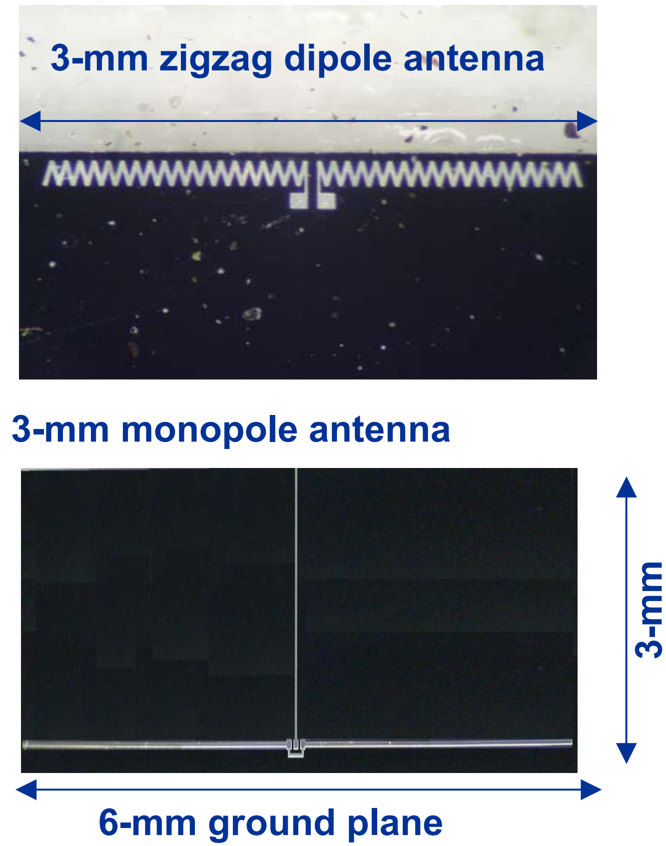


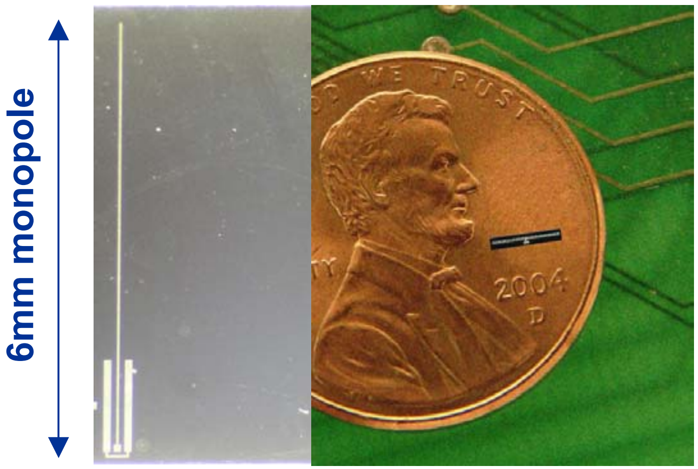




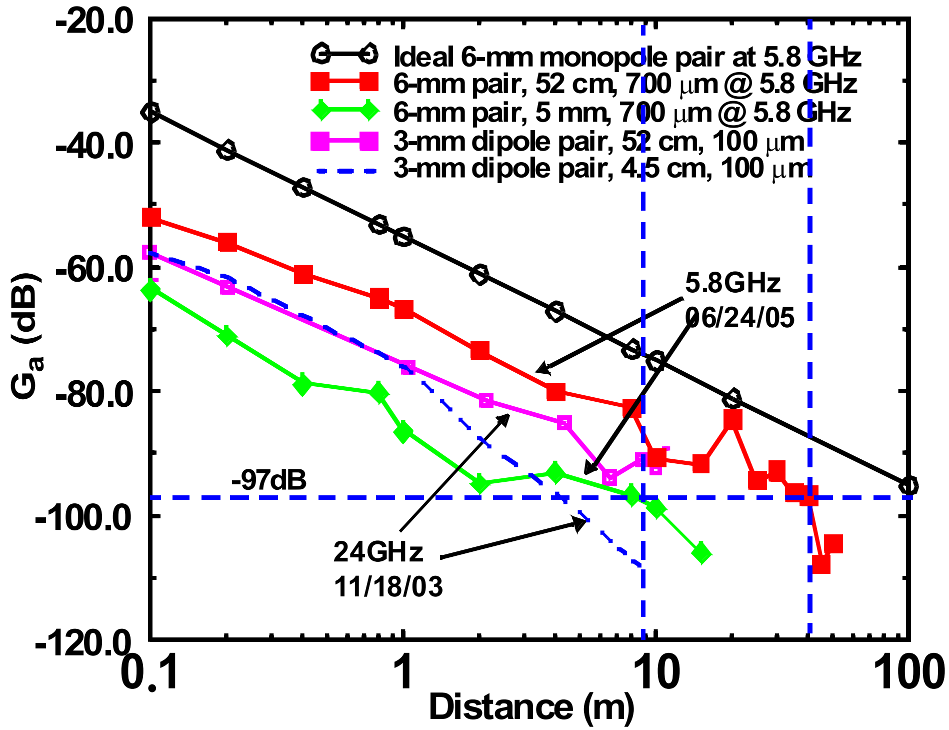
- On-chip monopole antennas have been designed and fabricated.
- A measurement set-up for on-chip monopole antennas has been constructed using Delrin (ε_r= ~3.7).
  - Up-right measurement of on-chip monopoles on a glass slide.
  - 85º chuck alleviates the probe landing problem.
  - Measurements 5 mm from the ground.


Chuck and high frequency probe
Mobile probe stations


3-mm zigzag dipole antenna
3-mm monopole antenna
3-mm
6-mm ground plane

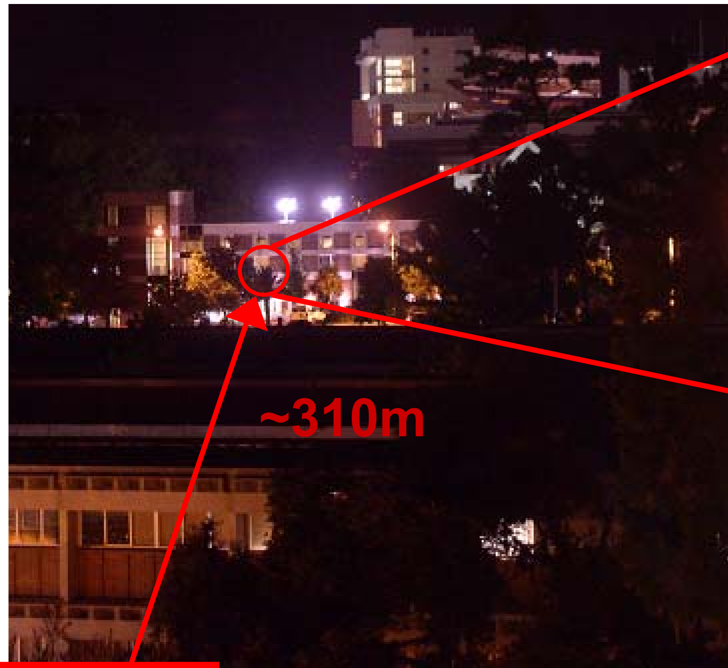


$$G_a = \frac{|S_{21}|^2}{(1-|S_{11}|^2)(1-|S_{22}|^2)} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

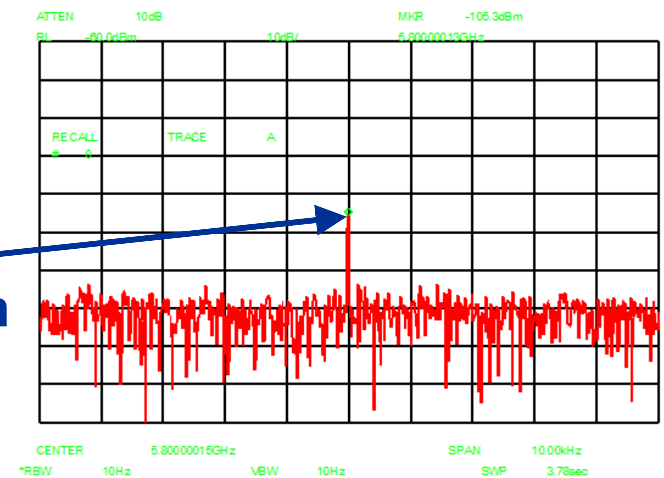


- By using monopoles at 5.8 GHz, increased antenna pair gain. Sufficient gain at 0.5 mm from the ground for 10-m communication. 30% more area than a 3-mm zigzag dipole antenna.
- At 52 cm from the ground, the communication range has been improved from ~10 m to ~ 40 m.
- Should be able to increase by thinning the substrate from 700 to 100 μm.

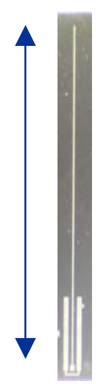
A 0-dBm 5.8-GHz sine wave is transmitted from a glass room in the top of a building using a 6-mm on-chip monopole antenna.



11-dBi receiving patch antenna



-105.3 dBm



6mm monopole

The received power of 5.8-GHz signal is -105 dBm at 310 m away from the transmitter. Sufficient to build a radio with.

Future Plans

- Finalize the transmitter architecture based on the antenna measurement results.

Next year:

- Implement and demonstrate a transmitter in 130-nm CMOS process.
- Receiver design and TX to RX link demonstration.

Publications

[1] K. K. O, K. Kim, B. Floyd, J. Mehta, H. Yoon, C.-M. Hung, D. Bravo, T. Dickson, X. Guo, R. Li, N. Trichy, J. Caserta, W. Bomstad, J. Branch, D.-J. Yang, J. Bohorquez, J. Chen, E.-Y. Seok, L. Gao, A. Sugavanam, J.-J. Lin, S. Yu, C. Cao, M.-H. Hwang, Y.-P. Ding, S.-H. Hwang, H. Wu, N. Zhang, and J. E. Brewer, "The Feasibility of On-Chip Interconnection using Antennas," **(Invited)** Accepted to ICCAD-2005.

[2] J.-J. Lin, H.-T. Wu, and K. K. O, "Compact On-Chip Monopole Antennas on 20-W-cm Silicon Substrates for Operation in the 5.8-GHz ISM Band," Accepted to 2005 IEDM.

[3] S. Sankaran, and K. K. O, "Schottky Barrier Diodes for Millimeter Wave and Detection in a Foundry CMOS Process," IEEE Electron Device Letters, vol. 26, no. 7, pp. 492-494, July 2005.

[4] S. Sankaran, and K. K. O, "A Schottky Diode with Cut-off Frequency of 400 GHz Fabricated in 0.18-μm CMOS," Electronics Letters vol. 41, no. 8, pp. 506-508, Apr. 2005.