Noncontact Detection of Vital Signs and Vibrations Using Micro-Radar

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Outline

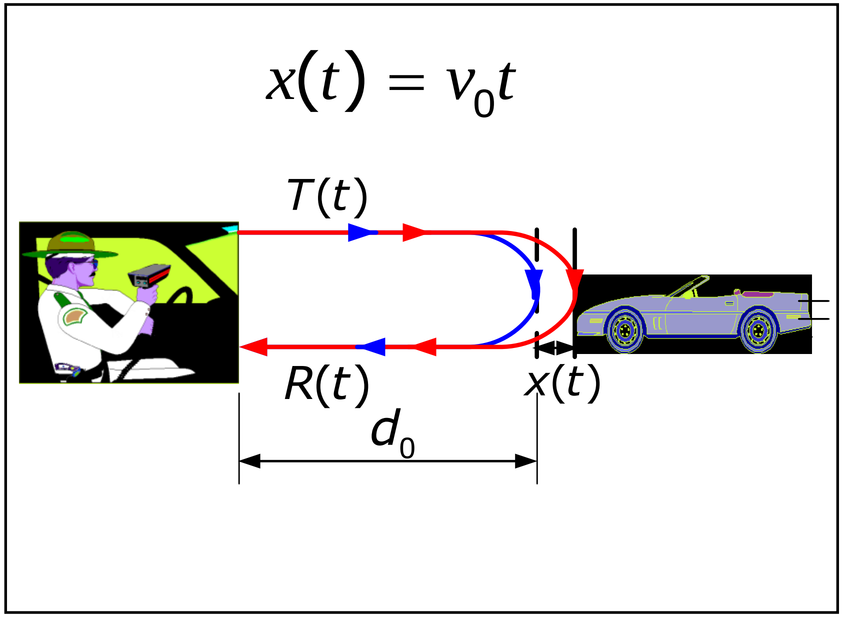
- **Noncontact Detection of Vital Signs (Respiration and Heartbeat)**
  - Detection Method
  - History
  - Examples
- **Noncontact Measurement of Vibrations**
  - Nonlinear Doppler Phase Demodulation
  - Experimental Verification
- **Integration of Micro-Radar Sensor Chips**
  - PCB Modules
  - CMOS Chips
  - SiP with Antennas
- **Applications**

What is it?

This video explains:
http://news.ufl.edu/2008/12/03/baby-vital-signs/

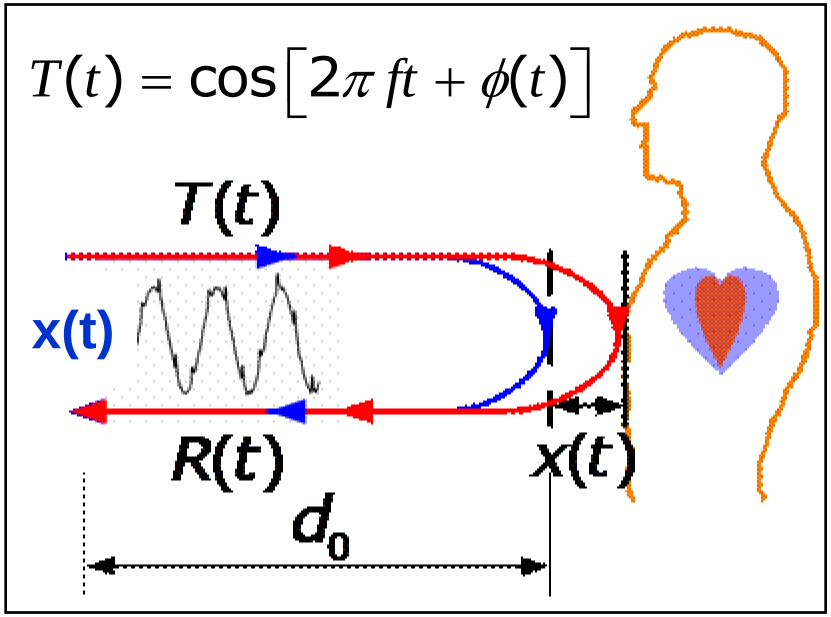
Video

How does it work? Doppler Effect!



$$x(t) = v_0 t$$

Constant Velocity
→ Frequency Shift



$$T(t) = \cos\left[2\pi ft + \phi(t)\right]$$

Periodic Chest Wall Movement
→ Phase Shift

$$R(t) \approx \cos\left[2\pi ft - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi\left(t - \frac{2d_0}{c}\right)\right]$$

$\frac{4\pi d_0}{\lambda} =$ Antenna-to-target round-trip delay

$\frac{4\pi x(t)}{\lambda} =$ Phase modulation due to chest-wall movement

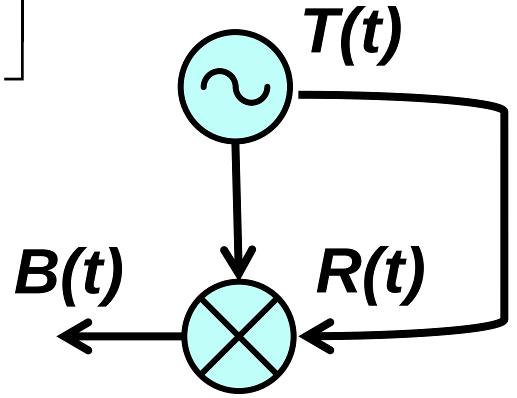
A Simple Detection Method

- Mix received signal with part of transmitted signal as reference in mixer (similar to direct down-conversion):

$$T(t) = \cos\left[2\pi ft + \phi(t)\right]$$

$$R(t) \approx \cos\left[2\pi ft - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi(t - \frac{2d_0}{c})\right]$$

T(t) x *R(t)* → Baseband Signal *B(t):*



$$B(t) \approx \cos\left[\frac{4\pi d_0}{\lambda} + \frac{4\pi x(t)}{\lambda} + \theta_0 + \Delta\phi\right]$$

$\theta_0 =$Phase delay in receiver circuit

$$\Delta\phi = \phi(t) - \phi(t - \frac{2d_0}{c})$$

Small Angle Approximation (Linear)

$$B(t)=\cos\left[\underbrace{\frac{4\pi x(t)}{\lambda}}_{\text{Small } x(t)\ll\lambda}+\underbrace{\frac{4\pi d_0}{\lambda}+\theta_0}_{90^\circ,\ 270^\circ,\ \ldots}+\underbrace{\Delta\phi}_{\text{negligible}}\right]$$

When …

$$\Rightarrow\ B(t)=\sin\left[\frac{4\pi x(t)}{\lambda}\right]\cong\frac{4\pi x(t)}{\lambda}$$

- **It is similar to measuring phase noise using FM discriminator technique.**

How about $\Delta\phi$?

$$T(t) = \cos\left[2\pi ft + \phi(t)\right]$$

$$R(t) \approx \cos\left[2\pi ft - \frac{4\pi d_0}{\lambda} - \frac{4\pi x(t)}{\lambda} + \phi\left(t - \frac{2d_0}{c}\right)\right]$$

$$B(t) \approx \cos\left[\frac{4\pi d_0}{\lambda} + \frac{4\pi x(t)}{\lambda} + \theta_0 + \Delta\phi\right] \longrightarrow$$

~ 0 @ short-range

- Fortunately, if the distance between radar sensor and target is small enough, close-in phase noise (slow variation) of R(t) and T(t) are correlated.

→ Range Correlation Effect

A. D. Droitcour, O. Boric-Lubecke, V. Lubecke, J. Lin, G. Kovacs, “Range Correlation and I/Q performance benefits in single chip silicon Doppler radars for non-contact cardiopulmonary signs sensing,” *IEEE Trans. Microwave Theory Tech.*, Vol. 52, No. 3, pp. 838-848, March 2004

Earliest Research Report

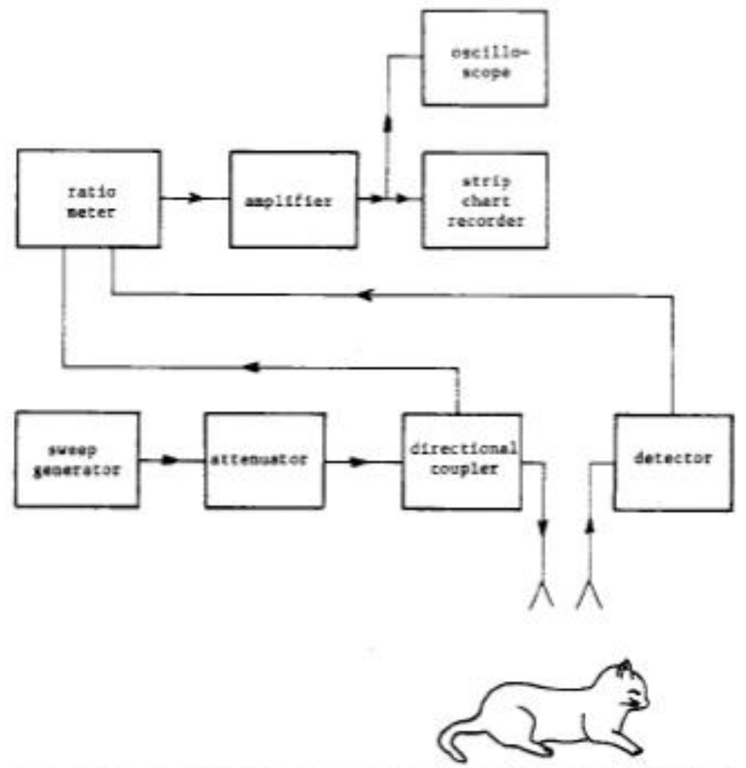


Fig. 1. Experimental setup of noncontact microwave respiration measurement.

Rabbit

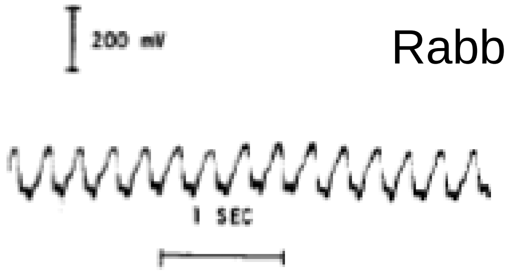


Fig. 2. Microwave measurement of respiratory movement of intact (unanesthetized) rabbit.

Human

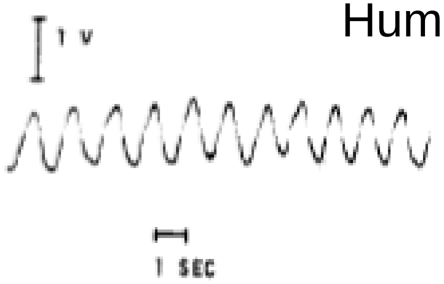
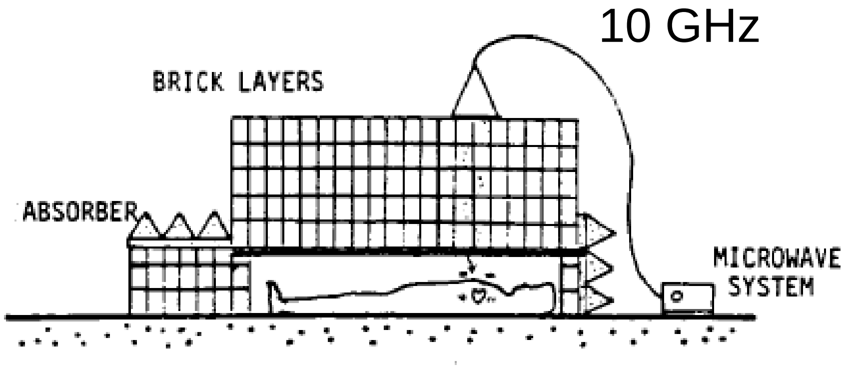
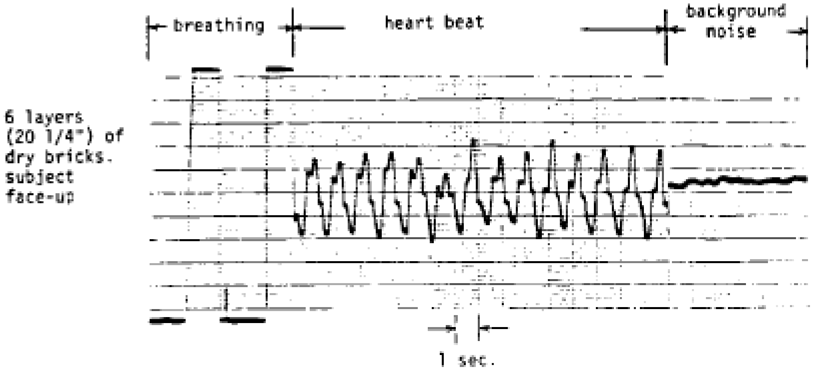


Fig. 3. Microwave respiratory measurement for seated human subject breathing at 47 times per minute.

- J. C. Lin, "Noninvasive Microwave Measurement of Respiration," Proceedings of the IEEE, vol. 63, no. 10, p. 1530, Oct. 1975.

Early Research Effort

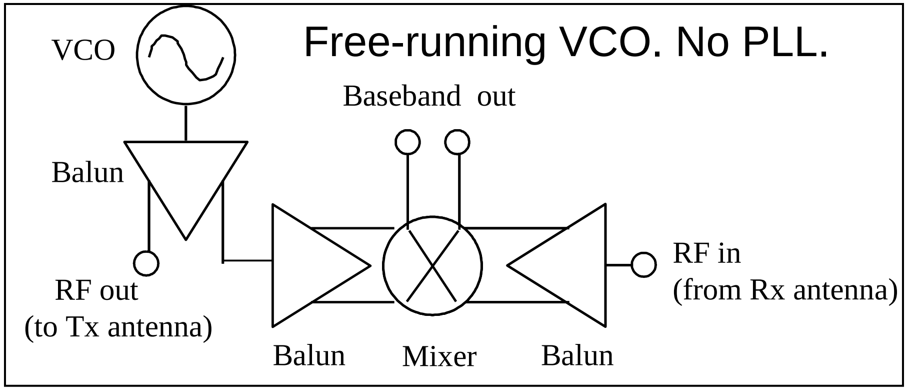




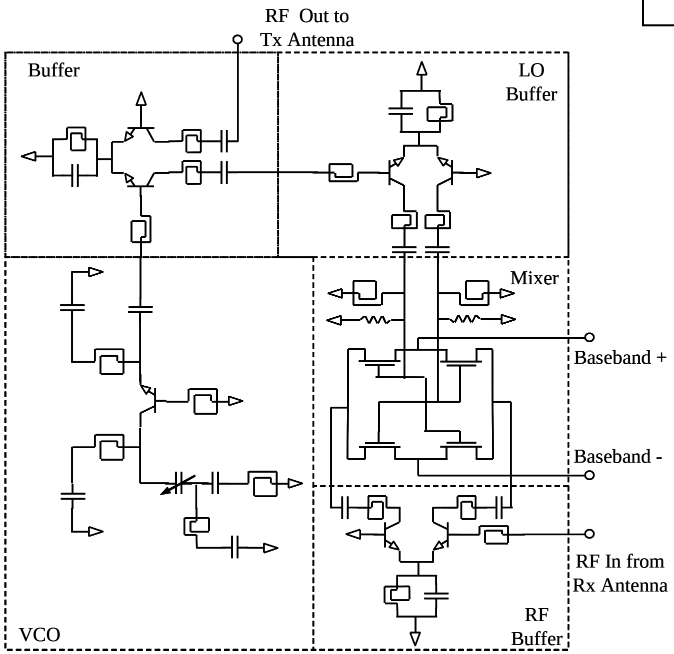
- K.-M. Chen and H.-R. Chuang, “Measurement of Heart and Breathing Signals of Human Subjects Through Barriers with Microwave Life-Detection Systems,” IEEE EMBC 1988.
  - 10GHz: 1.5 ft of dry bricks
  - 2GHz: 3 ft of dry bricks
- H.-R. Chuang, Y.-F. Chen, and K.-M. Chen, “Automatic Clutter-Canceler for Microwave Life-Detection System,” IEEE Trans. Instrumentation and Measurement, Vol. 40, No. 4, August 1991.

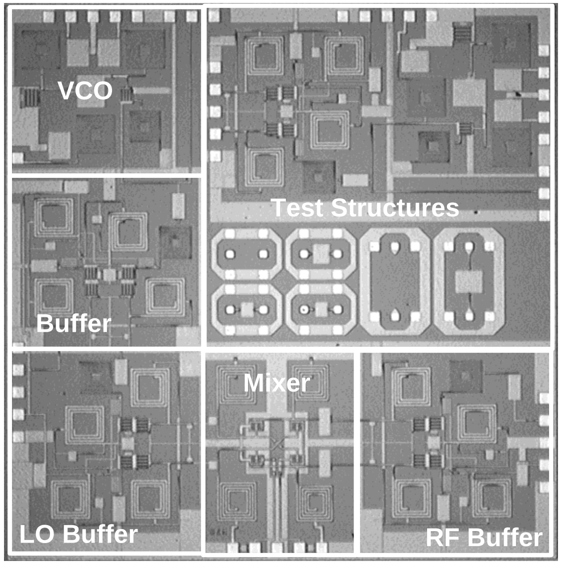
First Non-Contact Vital Sign Sensor Chip

- 0.25 µm BiCMOS
- 3.75mm x 3.75mm
- 1.6 GHz transmitted
- Output power = 6.5dBm



Free-running VCO. No PLL.

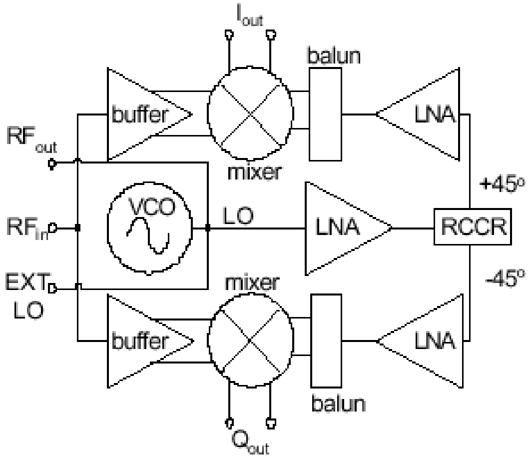


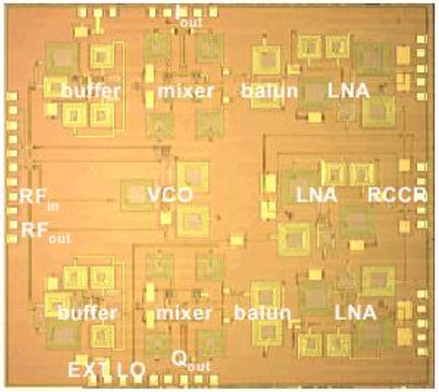


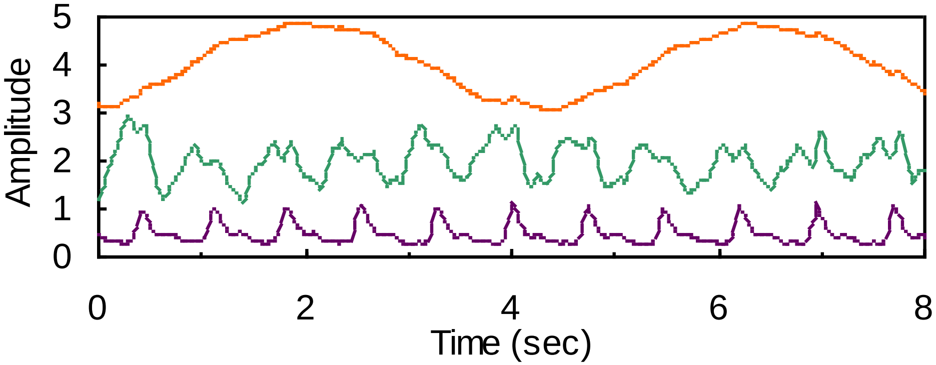
A. D. Droitcour, O. Boric-Lubecke, V. Lubecke, J. Lin, “0.25µm CMOS and BiCMOS Single Chip Direct Conversion Doppler Radars for Remote Sensing of Vital Signs,” *IEEE International Solid State Circuits Conference Digest of Technical Papers*, pp. 348-349, 2002.

2nd Non-Contact Vital Sign Sensor Chip

- 0.25 µm CMOS
- 2.4 GHz transmission frequency
- Direct-conversion – no IF and no image-reject filter
- Free running VCO – no PLL, no crystal.
- Quadrature receiver – to avoid null-point problem.







A. Droitcour, O. Boric-Lubecke, V. Lubecke, J. Lin, G. Kovacs, “Range Correlation Effect on ISM Band I/Q CMOS Radar for Non-Contact Vital Signs Sensing,” *IEEE MTT-S International Microwave Symposium Digest*, Vol. 3, pp. 1945-1948, 2003.

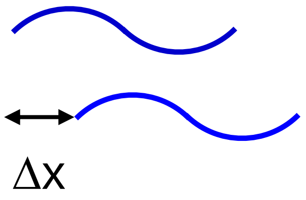
2003 – present

Research @ University of Florida

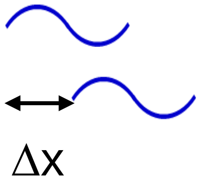
CW Radar Carrier Frequency

- Short wavelength is more sensitive to small displacement
  - improve signal level while keeping transmitted power low.
  → Increase the carrier frequency.

$$B(t) = \cos\left(\frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda} + \phi\right) \cong \frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda}$$



Same Δx

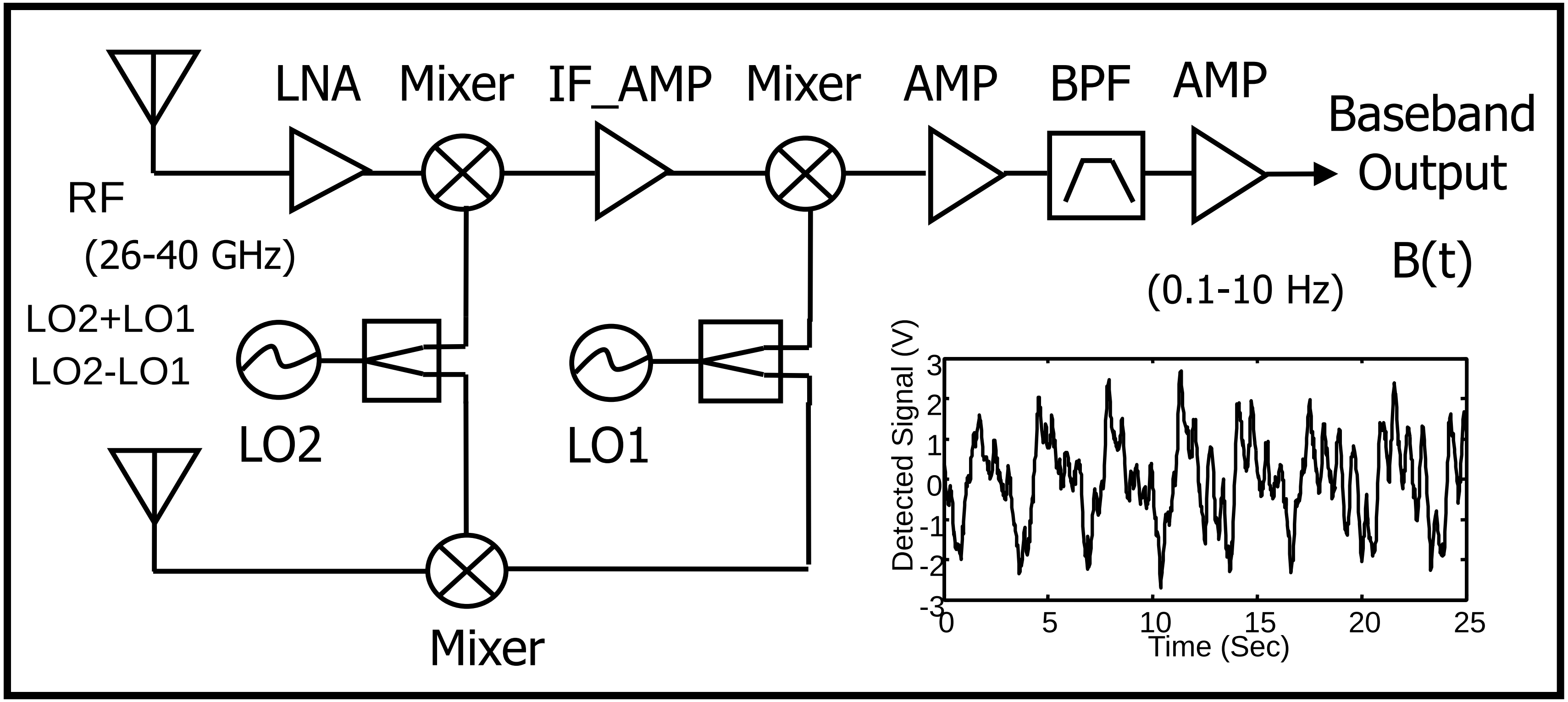


Long wavelength λ
→ Small Δϕ

Short wavelength λ
→ Large Δϕ

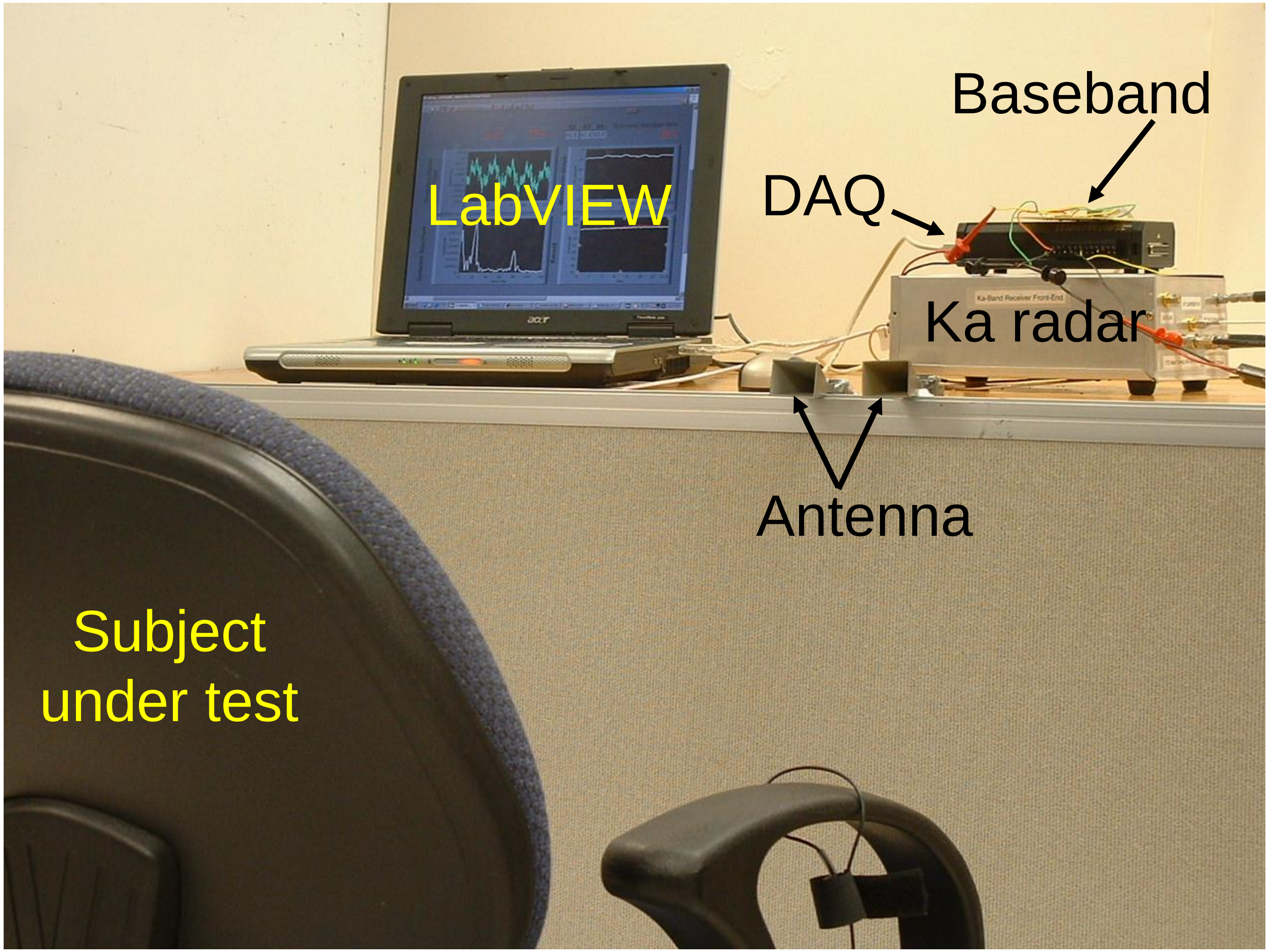
Y. Xiao, J. Lin, O. Boric-Lubecke, V. Lubecke, “A Ka-Band Low Power Doppler Radar System for Remote Detection of Cardiopulmonary Motion,” *Proceedings of the 27th IEEE Engineering in Medicine and Biology Society Annual International Conference*, pp. 7151-7154, 2005.

Double-Sideband Transmission/Detection Example @ Ka-Band



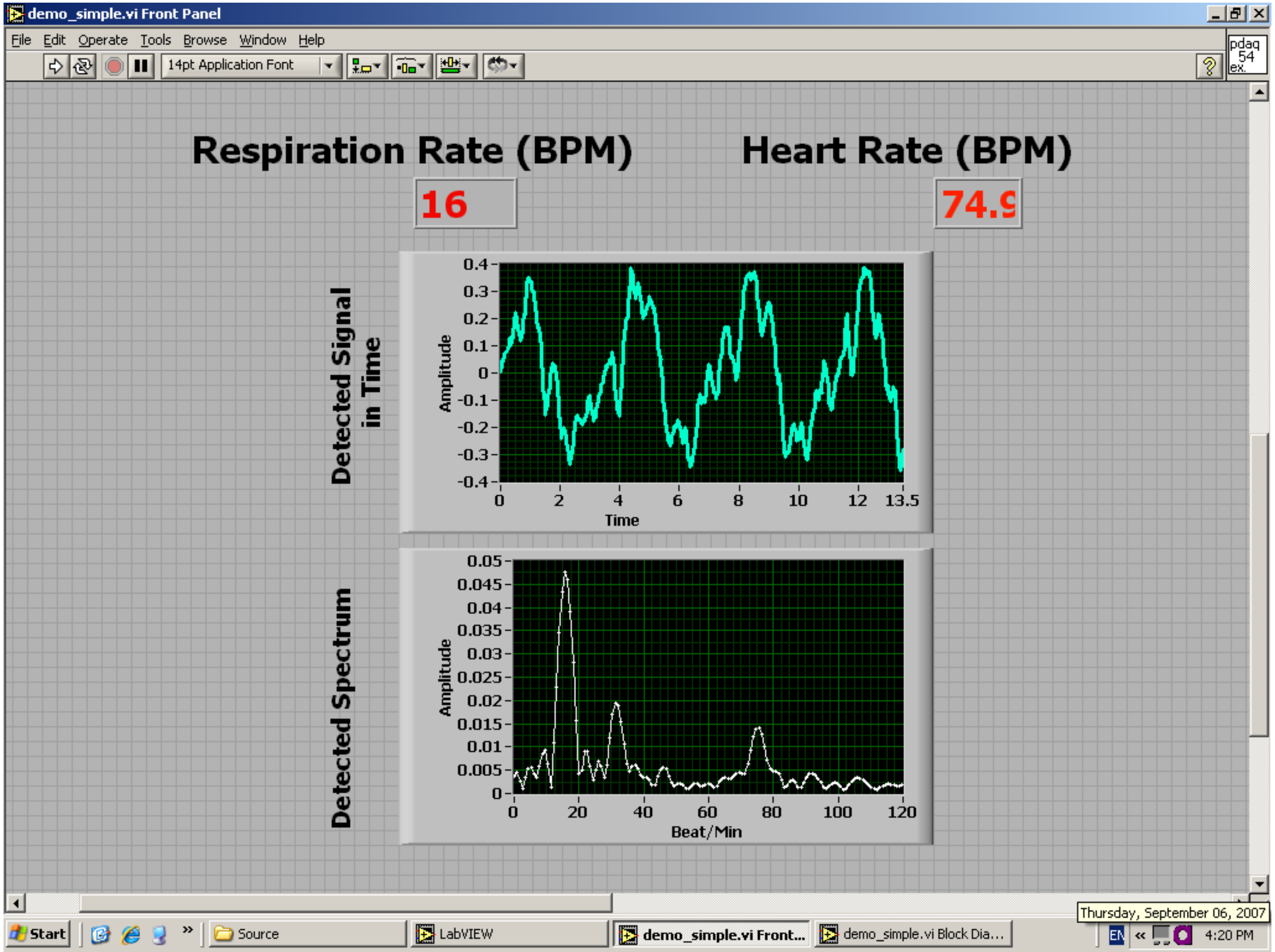
Double-sideband transmission and detection
→ no image rejection needed → simple architecture
→ Feasible for monolithic integration on one chip

Ka-band Bench-Top System



User Interface

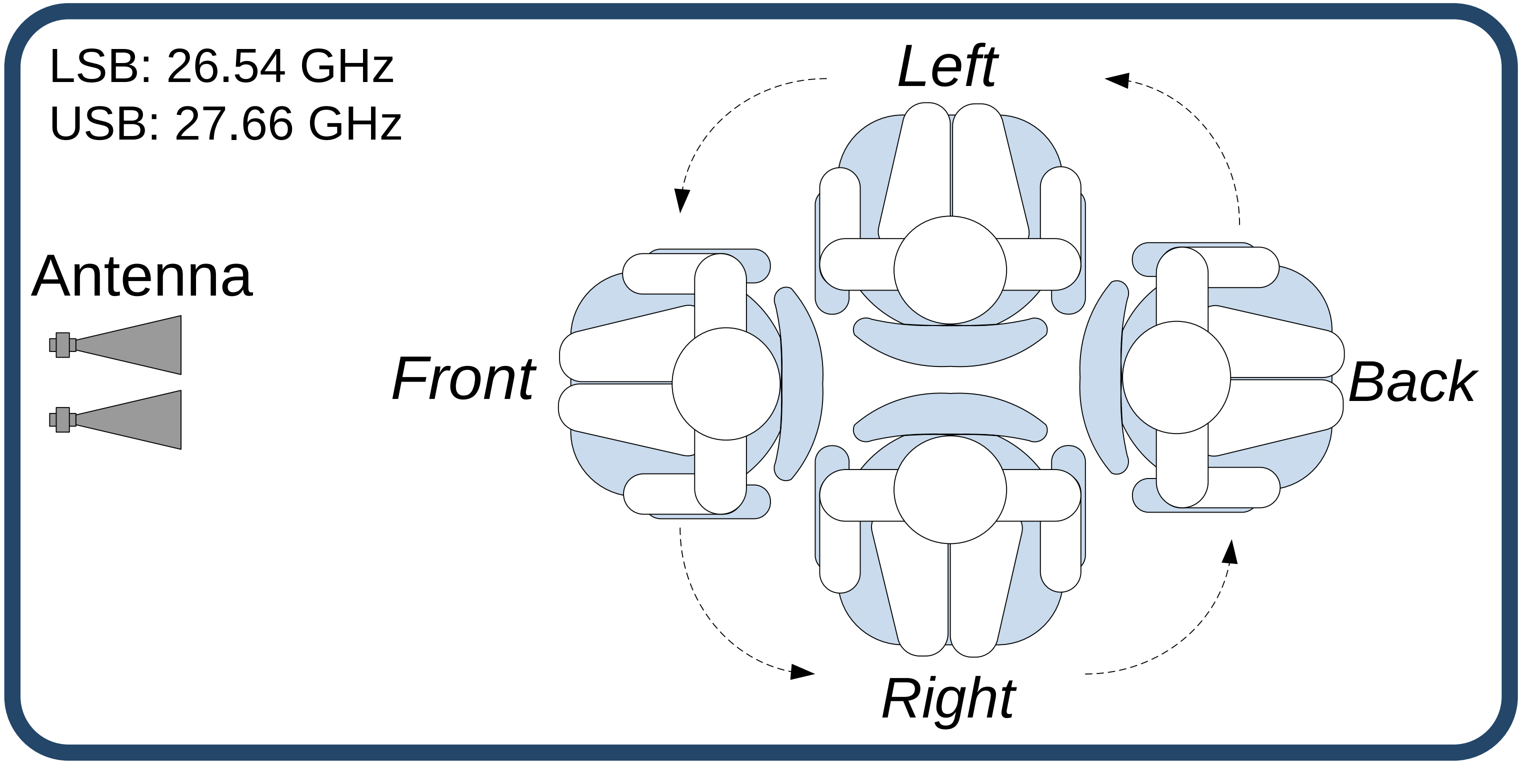
Labview – data acquisition and signal processing



Respiration Rate (BPM) 16

Heart Rate (BPM) 74.9

Measurement from Four Sides



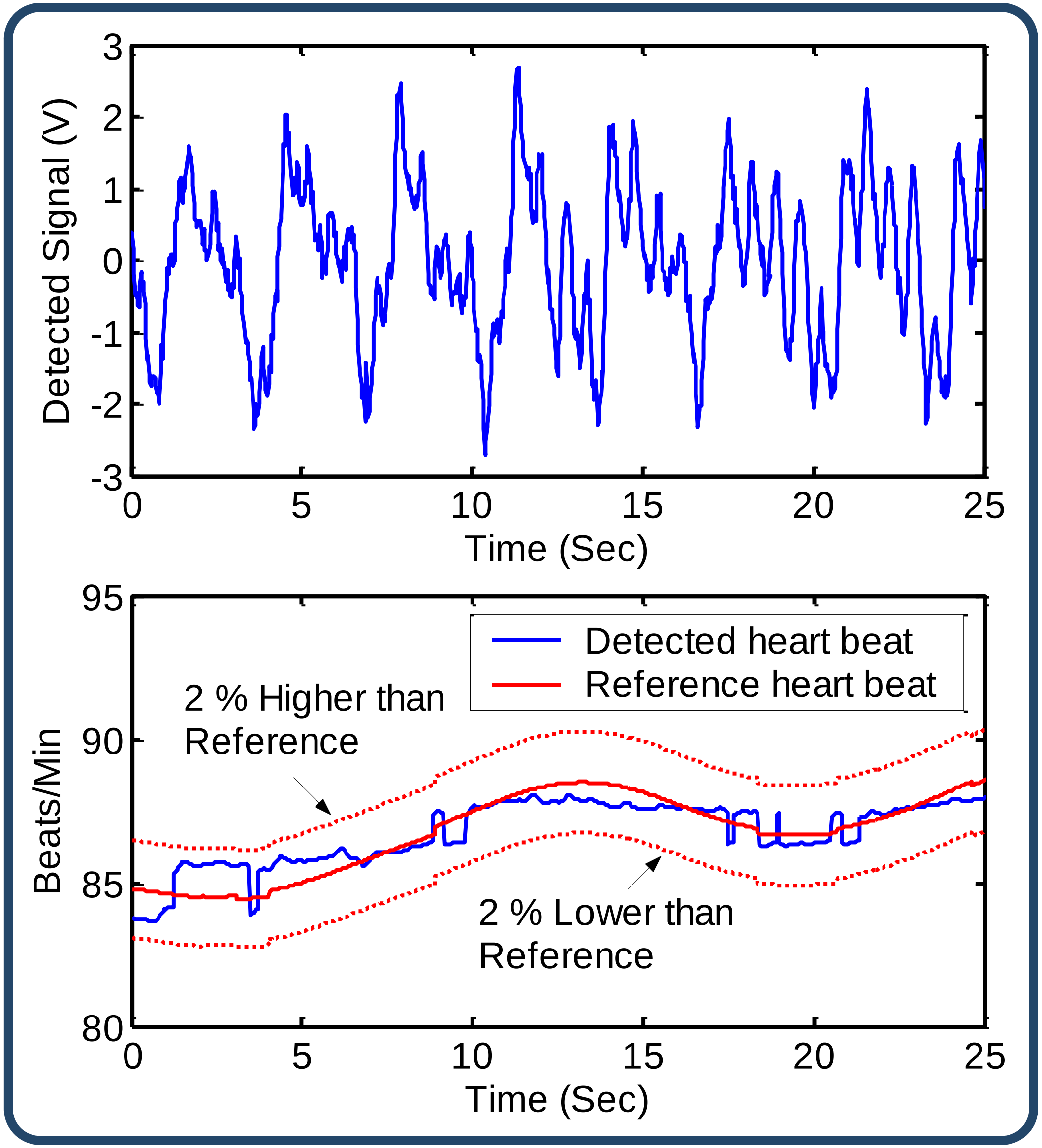
- Two power levels: 14.2 μW, 350 μW
- Five distances: 0.5m, 1m, 1.5m, 2m, 2.5m

Y. Xiao, C. Li, J. Lin, “Accuracy of A Low-Power Ka-Band Non-Contact Heartbeat Detector Measured from Four Sides of A Human Body,” *IEEE MTT-S International Microwave Symposium Digest*, pp. 1576-1579, June 2006.

Typical Test Result

Time-Domain Signal

Calculated Heart Rate



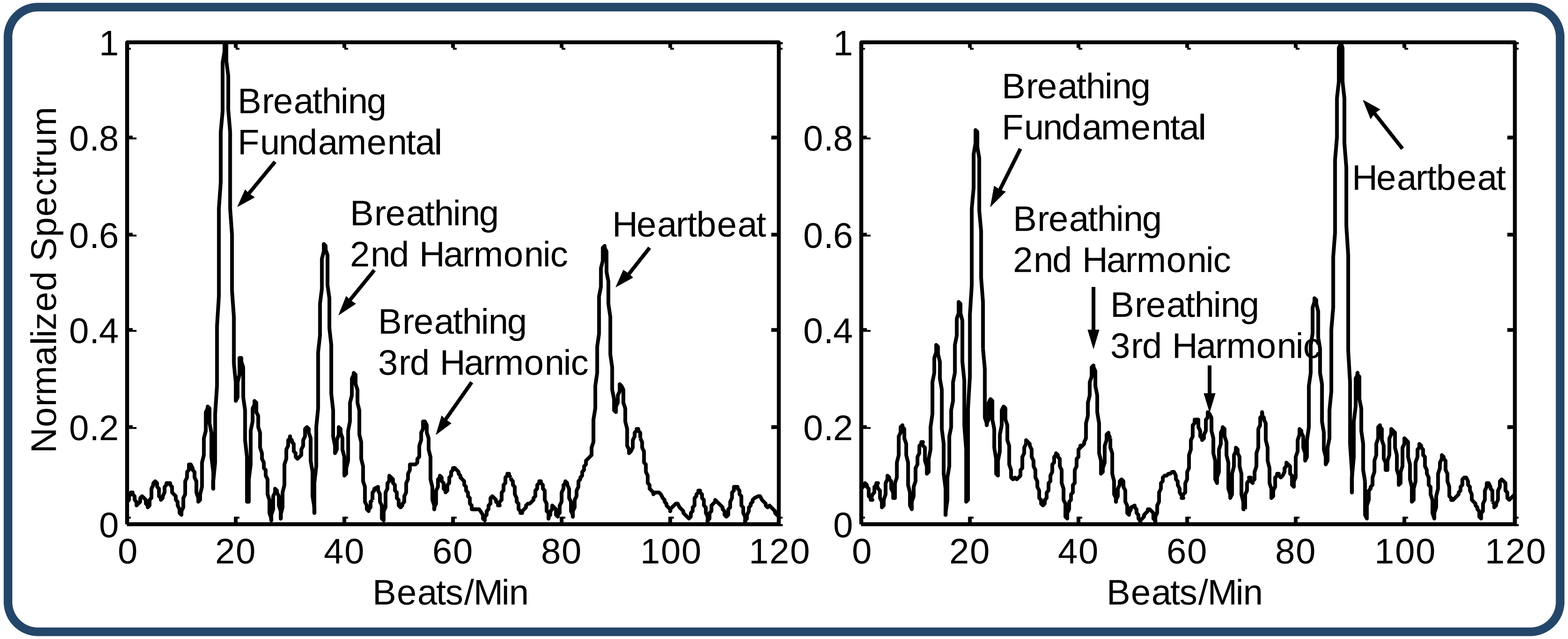
Test Results

SUMMARY OF HEART RATE DETECTION ACCURACY

Distance (m)	***Front***	***Left***	***Right***	***Back***
Double sideband transmitting power: 14.2 μW				
0.5	99.1%	96.3%	100%	97.6%
1	89.8%	89.8%	93.2%	100%
1.5	98.9%	89%	93.8%	94.3%
2	85.2%	80.5%	97.4%	93.6%
2.5	83.3%	85.7%	85.1%	85.5%
Double sideband transmitting power: 350 μW				
0.5	100%	100%	100%	100%
1	94.8%	94.7%	93.2%	100%
1.5	98.1%	97.6%	100%	100%
2	100%	100%	100%	100%
2.5	95.1%	100%	95.2%	97.2%

Interesting Observations

- Very good accuracy achieved with very low transmission power.
- Accuracy better than 80% from any side, at any distance, and under either power level.
- Measurement from the back: the best performance! WHY?



Front

Back

Nonlinear Doppler Phase Demodulation
and
Measurement of Vibrations

Nonlinear Doppler Phase Demodulation

Small angle approximation:

$$B(t) = \cos\left(\frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda} + \phi\right)$$

$$\cong \frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda}$$

when $\phi = 90°$ and

$x_h(t), x_r(t) << \lambda$

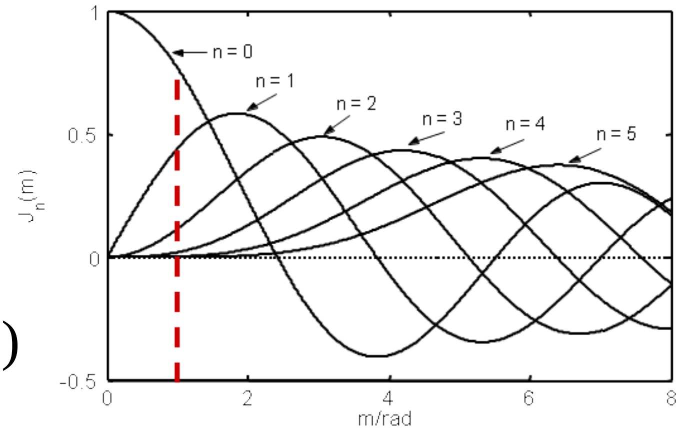
However, at high frequency (short wavelength), the displacement might not be small enough and the small angle approximation might not be valid.

$$\xcancel{x_r(t) << \lambda}$$

Nonlinear Doppler Phase Demodulation

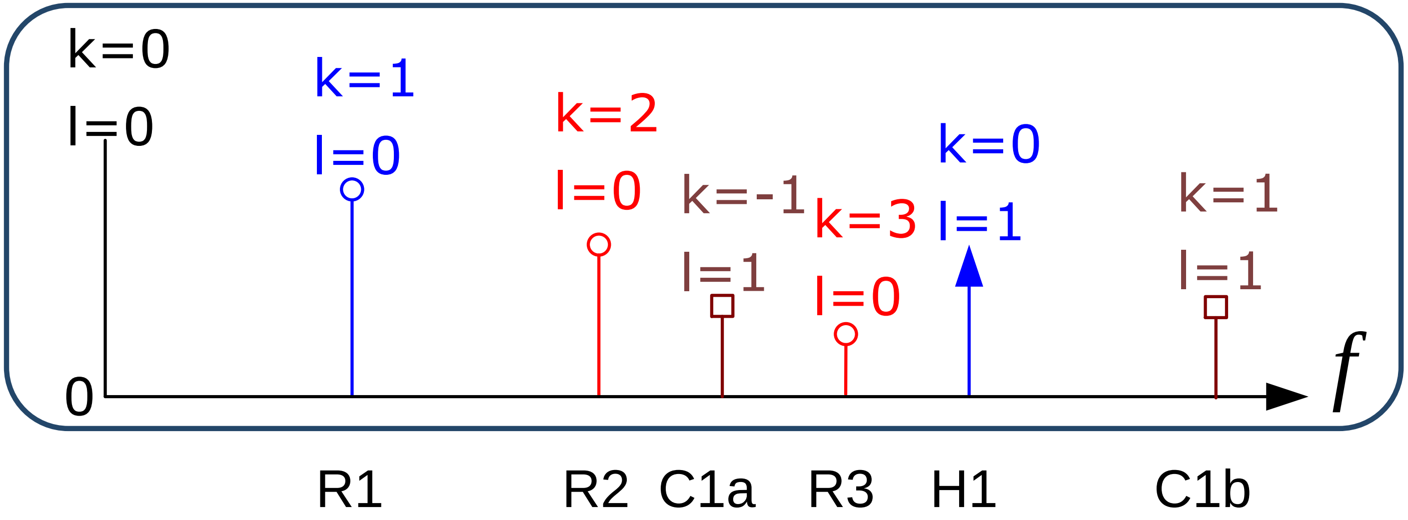
Periodic body movements due to heartbeat and respiration

$$x_h(t) = m_h \cdot \sin\omega_h t,\ x_r(t) = m_r \cdot \sin\omega_r t$$



$$B(t) = \cos\left(\frac{4\pi x_h(t)}{\lambda} + \frac{4\pi x_r(t)}{\lambda} + \phi\right)$$

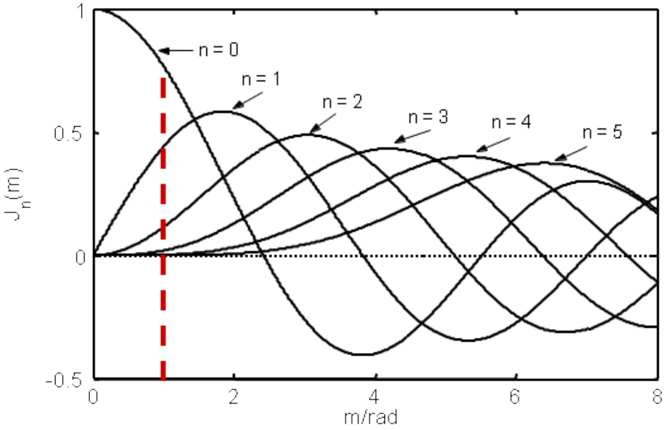
$$= \sum_{k=-\infty}^{\infty}\sum_{l=-\infty}^{\infty} J_l\left(\frac{4\pi m_h}{\lambda}\right) J_k\left(\frac{4\pi m_r}{\lambda}\right)\cos(k\omega_r t + l\omega_h t + \phi)$$



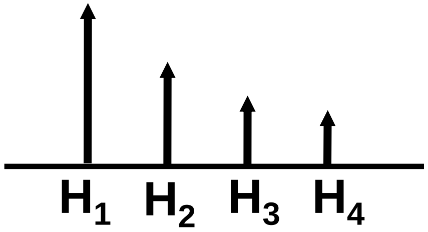
C. Li, Y. Xiao, J. Lin, "Experiment and Spectral Analysis of a Low-Power Ka-Band Heartbeat Detector Measuring from Four Sides of a Human Body," *IEEE Transactions on Microwave Theory and Techniques*, IMS2006 Special Issue, Vol. 54, No. 12, pp. 4464-4471, December 2006.

Accurate Measurement of Periodic Motion

- For a single tone vibration, ma in baseband spectrum are det
  - Residual phase
  - Wavelength
  - Displacement of vibration



$$H_1 : H_2 : H_3 : H_4 = \left| J_1\left(\frac{4\pi m}{\lambda}\right)\cos\phi \right| : \left| J_2\left(\frac{4\pi m}{\lambda}\right)\sin\phi \right| :$$



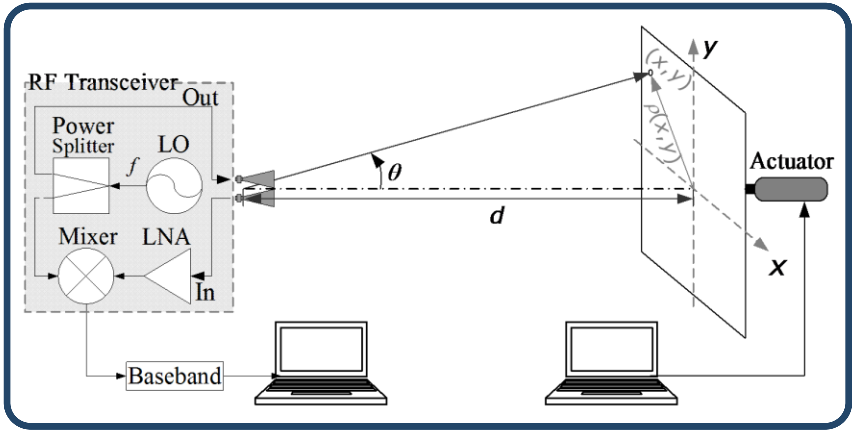
$$\left| J_3\left(\frac{4\pi m}{\lambda}\right)\cos\phi \right| : \left| J_4\left(\frac{4\pi m}{\lambda}\right)\sin\phi \right| .$$

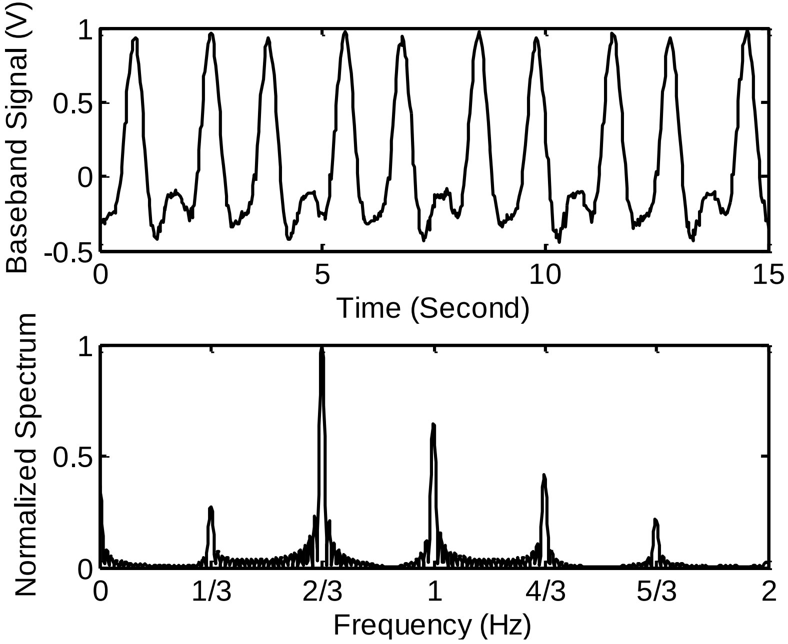
The displacement of vibration can be accurately determined from the ratio of harmonics!

C. Li, J. Lin, "Non-Contact Measurement of Periodic Movements by a 22-40GHz Radar Sensor Using Nonlinear Phase Modulation," *IEEE MTT-S International Microwave Symposium Digest*, pp. 579-582, June 2007

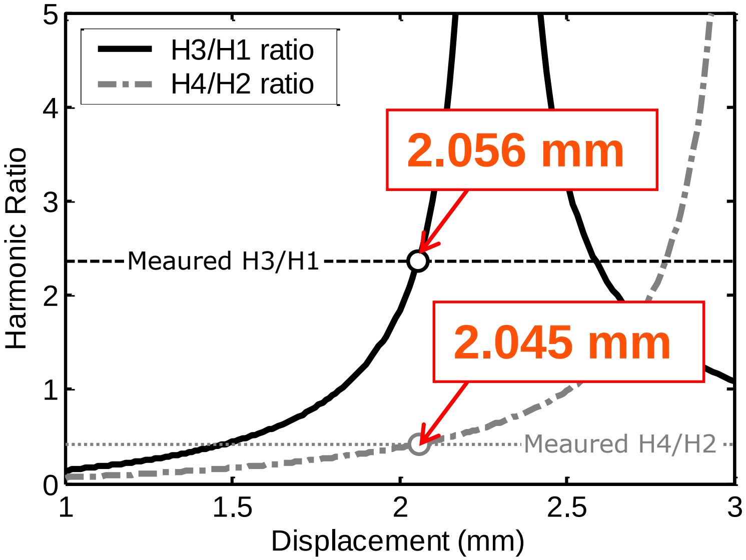
Measurement Example

- Movement period T = 3 sec amplitude = 2 mm
- f_{RF}: 40 GHz,
- Transmission power: 50 µW
- Distance: 1.65m





(a) Baseband signal, spectrum



2.056 mm

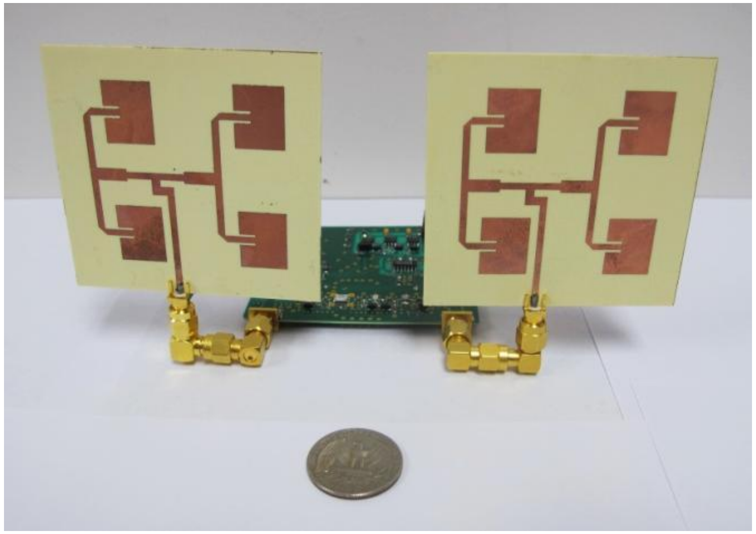
2.045 mm

(b) Displacement extraction, self-verification

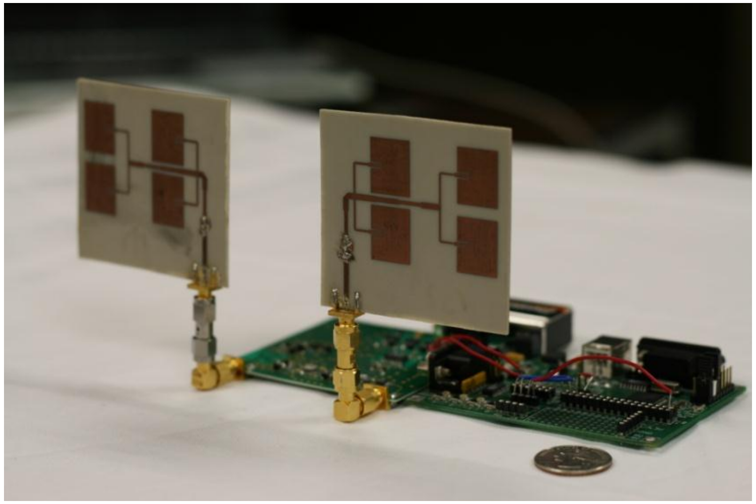
Development of Integrated Radar Sensors at University of Florida

- PCB modules
- IC chips: RFIC
- System-in-Package: Antennas integrated

PCB Modules

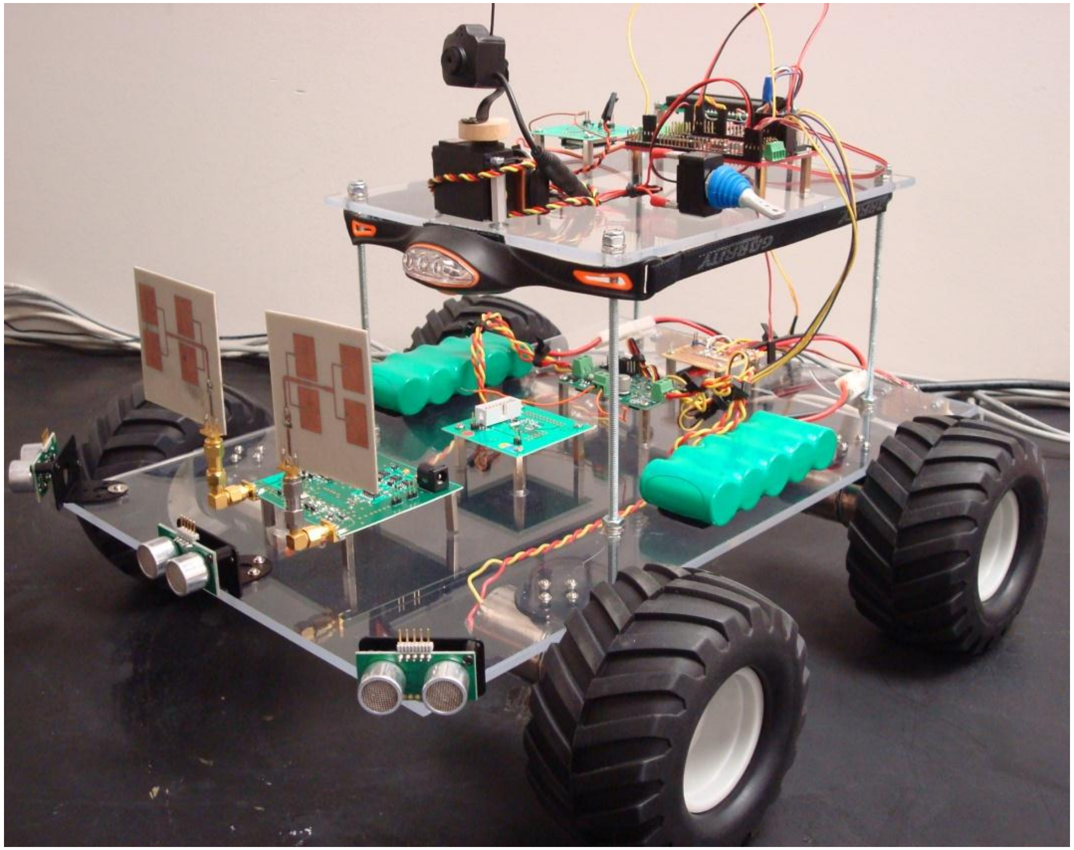


External ADC and Signal Processing: Output connected to data acquisition module (DAQ) and notebook computer. Both radar module and DAQ can be powered by USB cable, external power supply/charger, or battery.



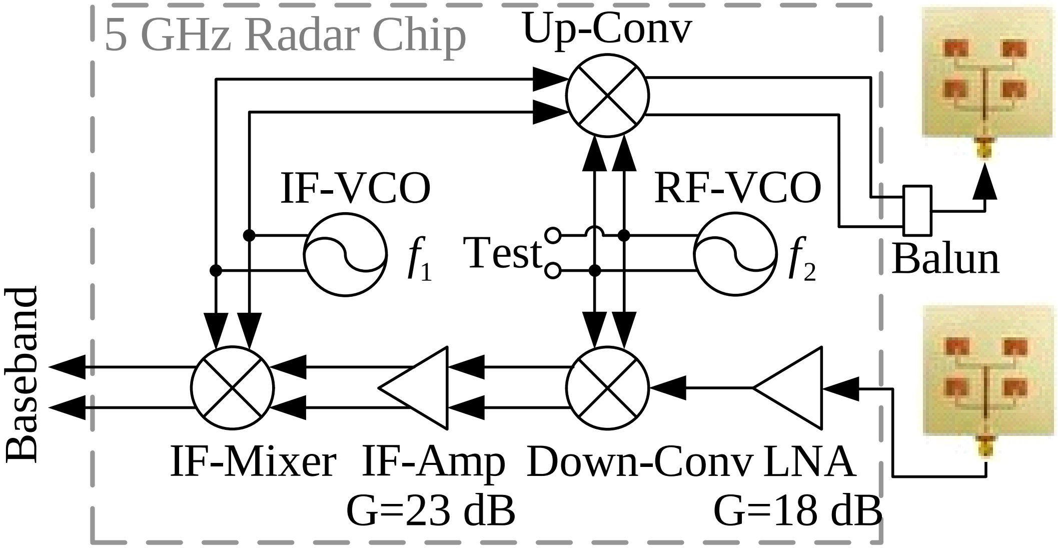
On-board ADC and Signal Processing: Onboard ARM processor and ADC. No external DAQ and notebook computer needed. Powered by a battery.

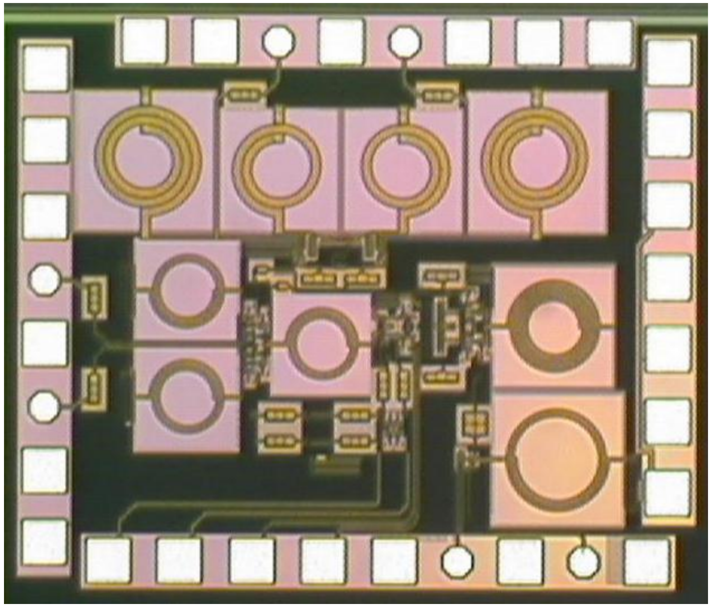
Search and Rescue Robot



Wireless data link sends detected data to a remote station.

Double-Sideband Radar Sensor Chip





f_1 = 60~520 MHz; f_2 = 4.6~5.7 GHz

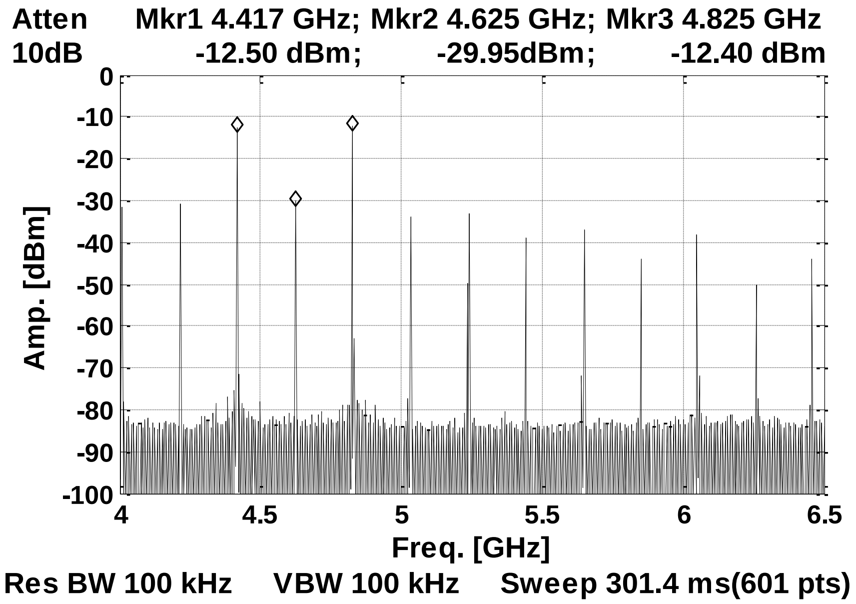
UMC 0.18 µm CMOS

1.3×1.6 mm^2

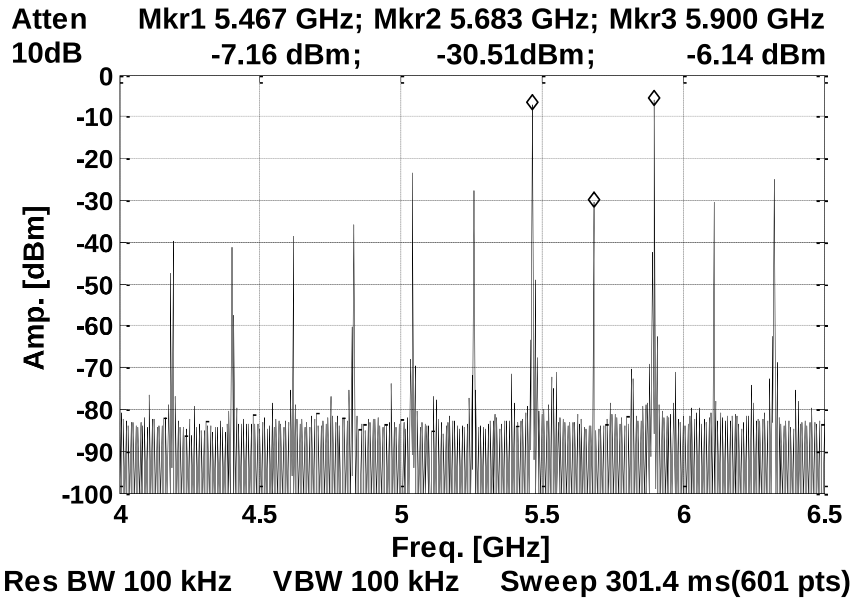
C. Li, Y. Xiao, J. Lin, "A 5-GHz Double-Sideband Radar Sensor Chip in 0.18-µm CMOS for Non-contact Vital Sign Detection," accepted, *IEEE Microwave and Wireless Components Letters*, 2008

Test Result – Output Spectrum

RF VCO tuned to the lowest



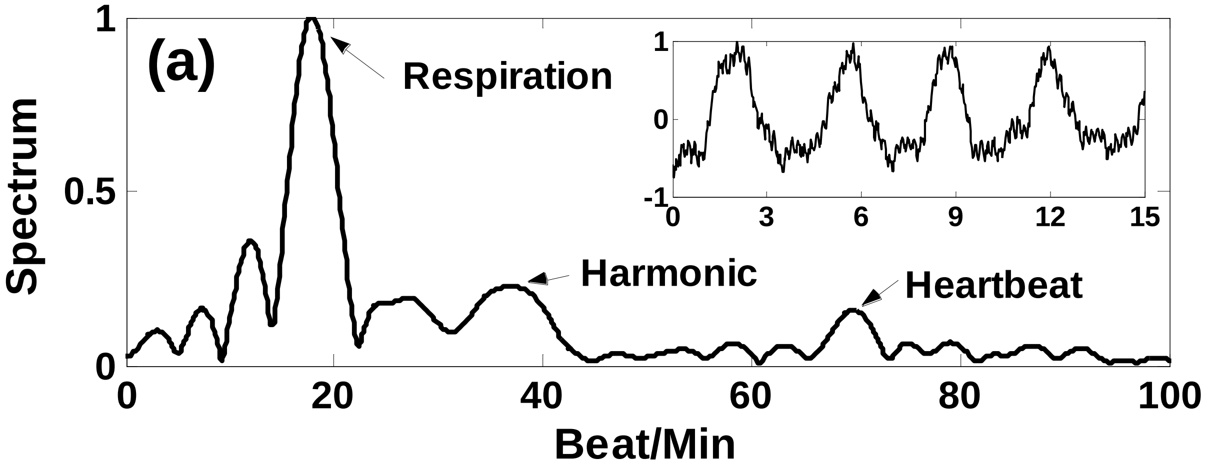
RF VCO tuned to the highest



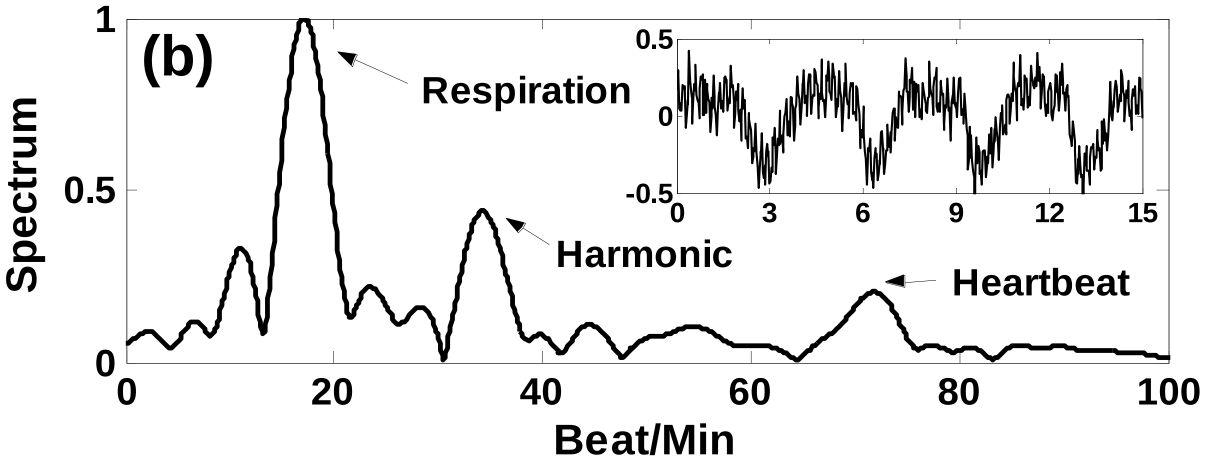
Spurs will be out of band and filtered out after down-conversion

Test Result – Vital Sign Detection

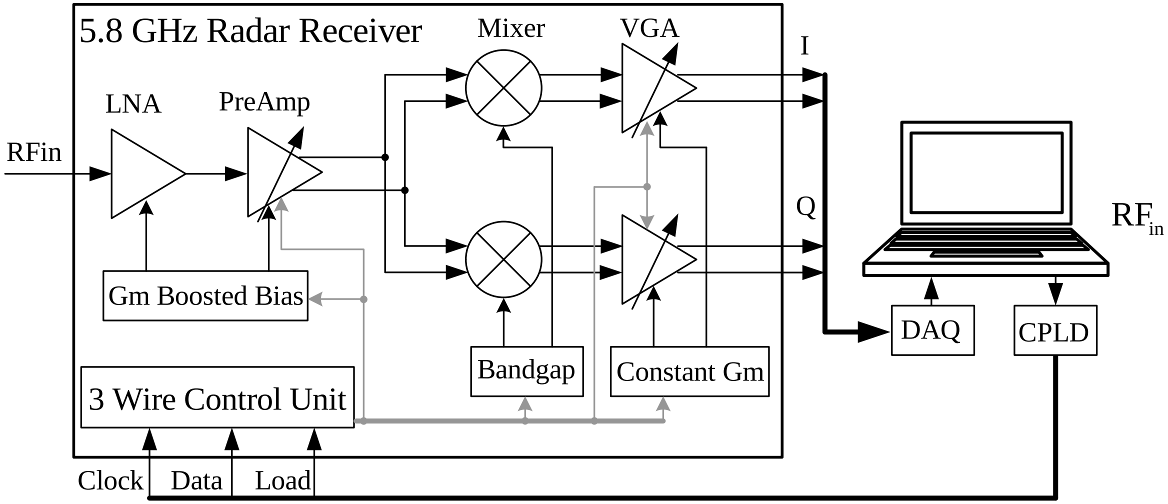
0.5 m

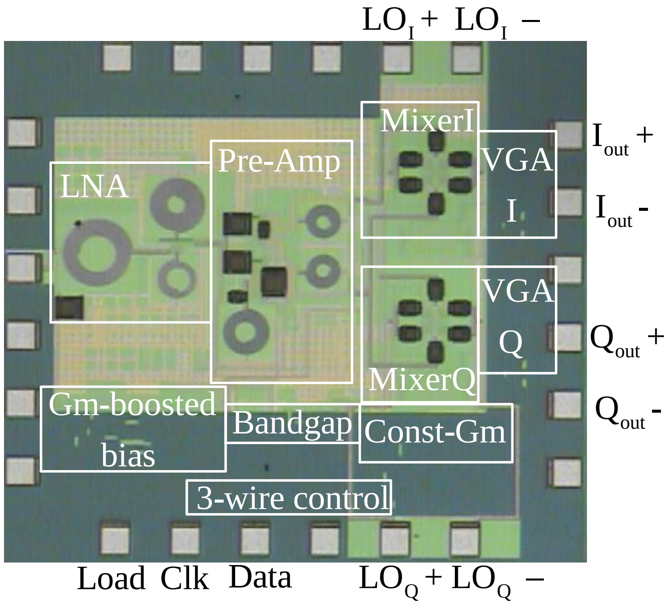


2 m



Radar Receiver with Gain Control



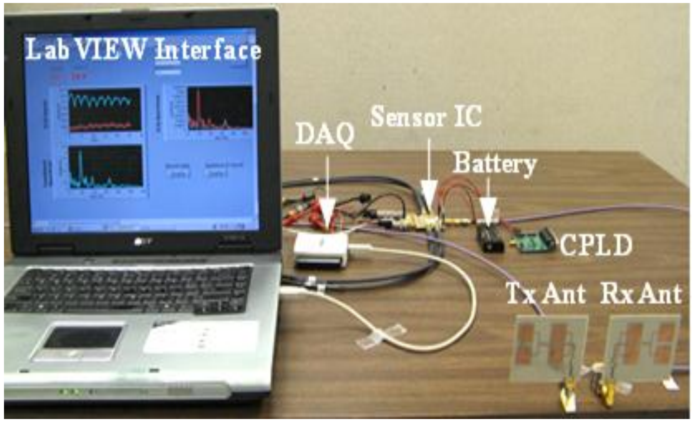


UMC 0.13 µm CMOS

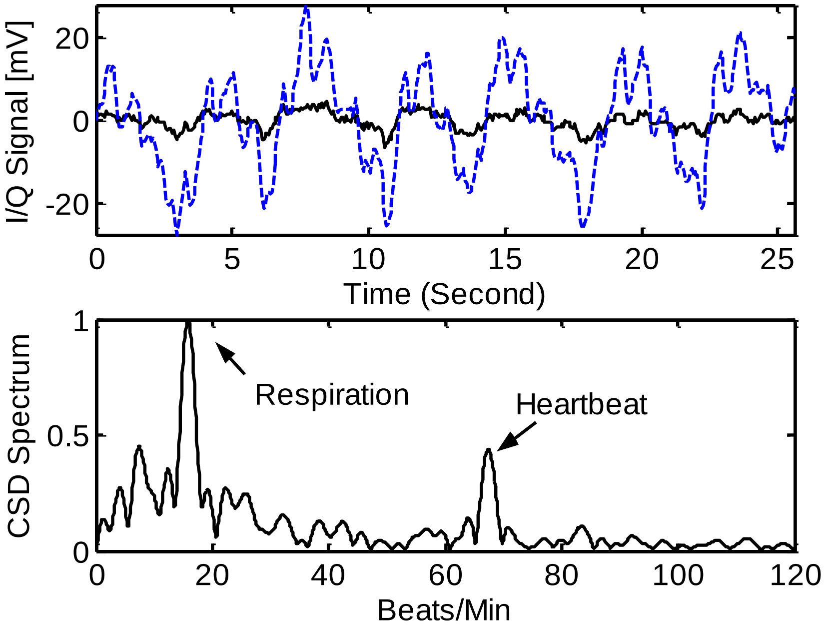
1.2×1.2 mm^2

C. Li, X. Yu, D. Li, L. Ran, J. Lin, "Software Configurable 5.8 GHz Radar Sensor Receiver Chip in 0.13 µm CMOS for Non-contact Vital Sign Detection," *IEEE RFIC Symposium Digest of Papers*, June 2009

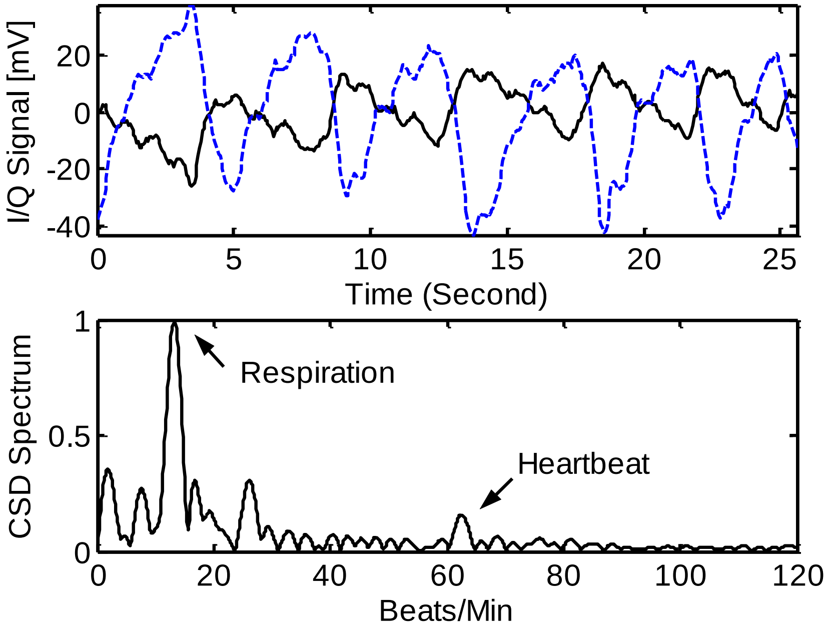
Test Result



Power: 1.5 V battery
3-wire program: Xilinx XC9536 CPLD
Antenna: 2-by-2 patch array, 9 dB gain
DAQ: NI USB-6008, 12 bit, 0-5V input



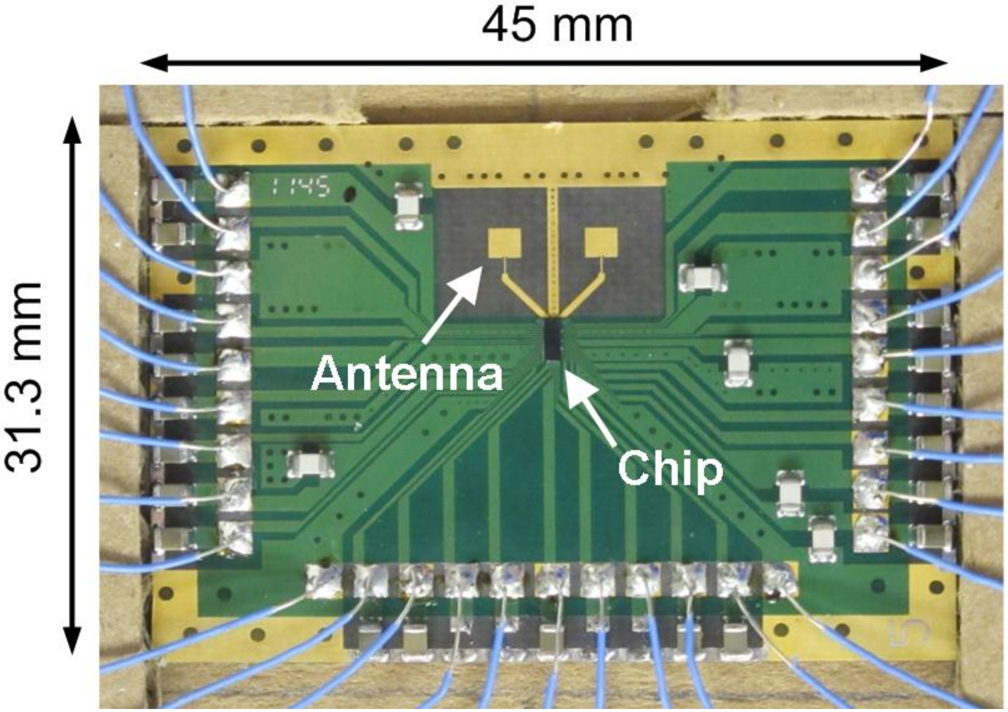
Detect from the back @ 0.5m away



Detect from the front @ 1.5m away

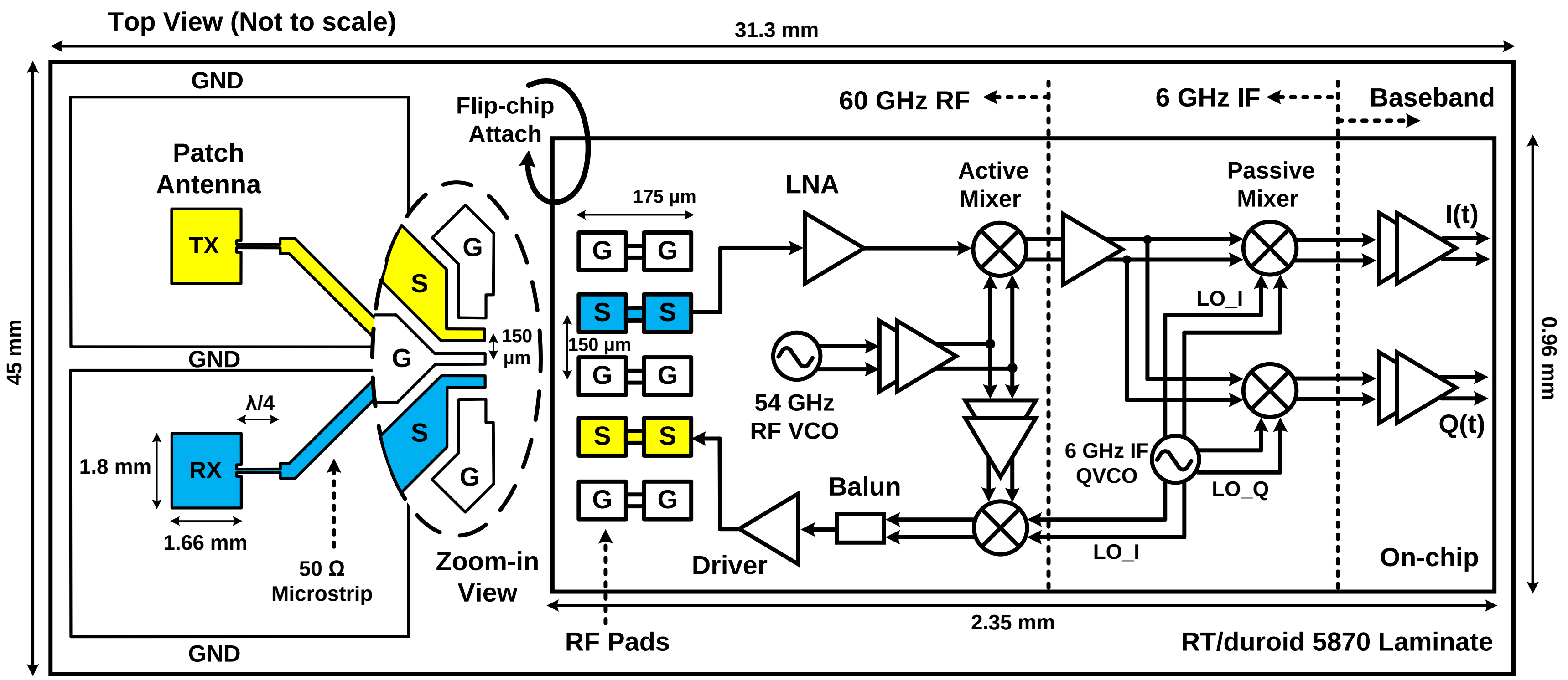
60 GHz Flip-Chip Integrated Micro-Radar

- Flip-chip radar transceiver (UMC 90nm CMOS), two PCB patch antennas, and DC biasing through blue wires.
- Weight less than 10 gram (0.3 ounce). Size 31.2 mm x 45 mm.



T.-Y. J. Kao, A. Y.-K. Chen, T.-M. Shen, Y. Yan, J. Lin, "A Flip-Chip-Packaged and Fully Integrated 60 GHz CMOS Micro-Radar Sensor for Heartbeat and Mechanical Vibration Detections," *IEEE RFIC Symposium Digest of Papers*, June 2012.

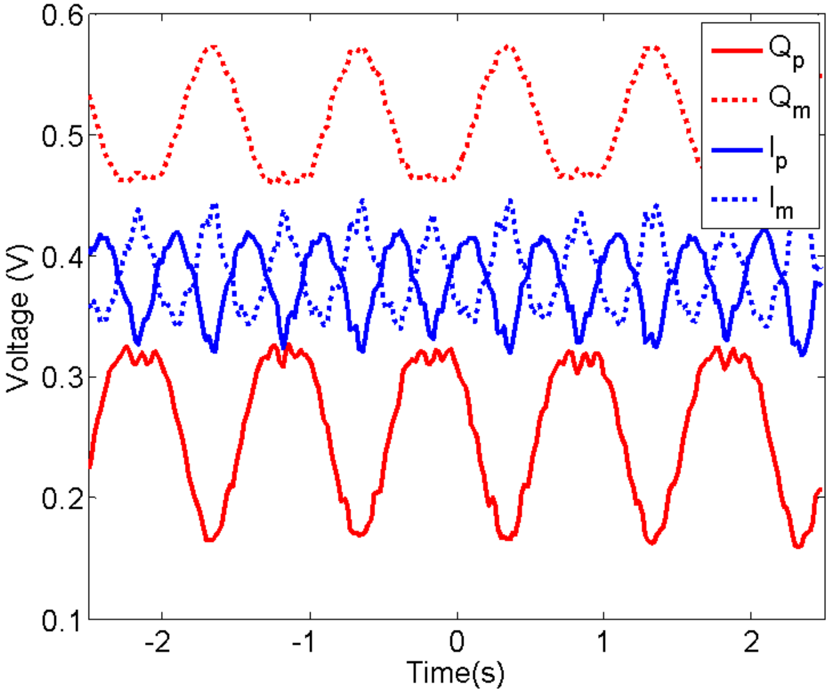
Block Diagram of 60 GHz Micro-Radar



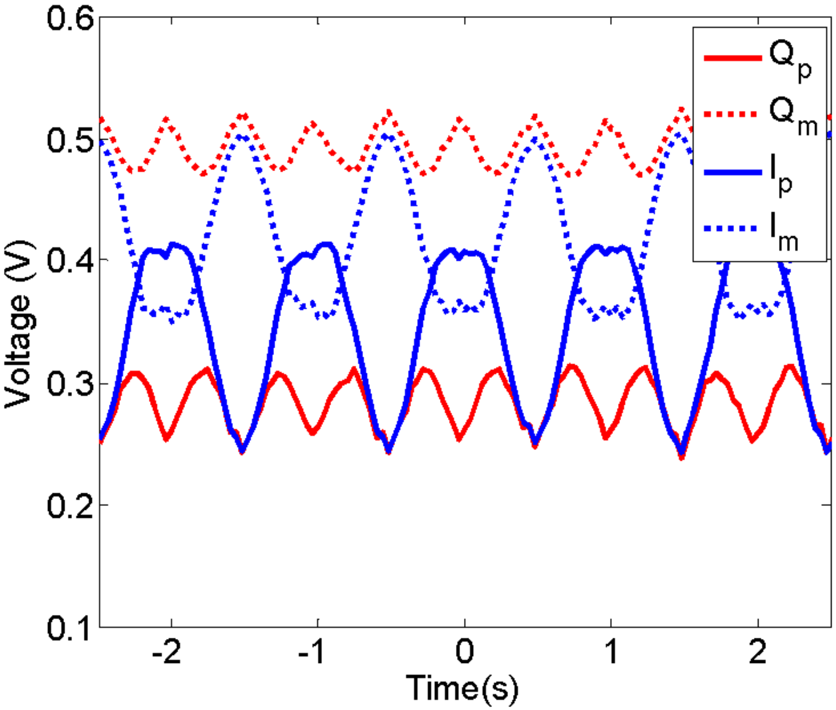
- ❖ Indirect down-conversion with passive mixers – low flicker noise
- ❖ I/Q generation at IF
- ❖ Same VCOs for up- and down-conversion - range correlation effect

Experiment – I/Q Channel Test

Actuator vibrating at distance (D) = 0.3 m away
displacement (A) = 1 mm, f = 1 Hz



Q near optimal point,
I near null point



I near optimal point,
Q near null point

Complex Signal Demodulation

Combining I and Q channels

$$B(t) \approx \cos\left(\frac{4\pi x(t)}{\lambda} + \phi_t\right).$$

→ **Optimal and null detection points**

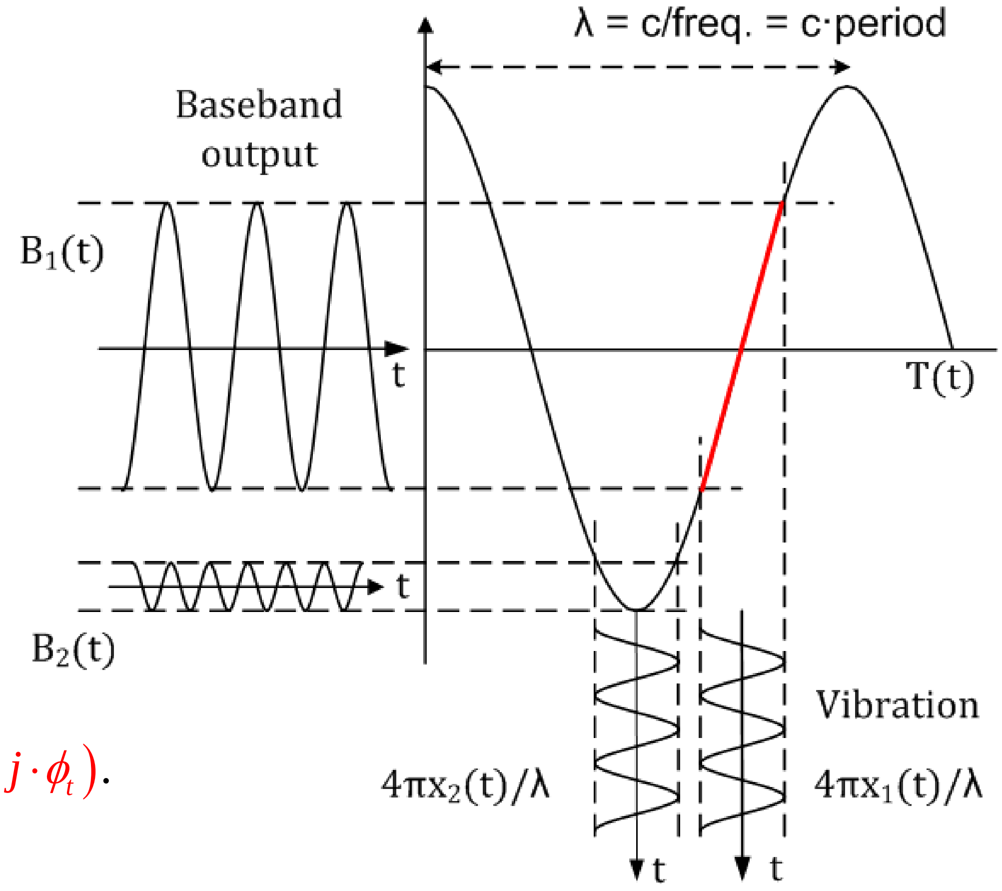
Complex signal demodulation (CSD):

$$S(t) = I(t) + j \cdot Q(t)$$

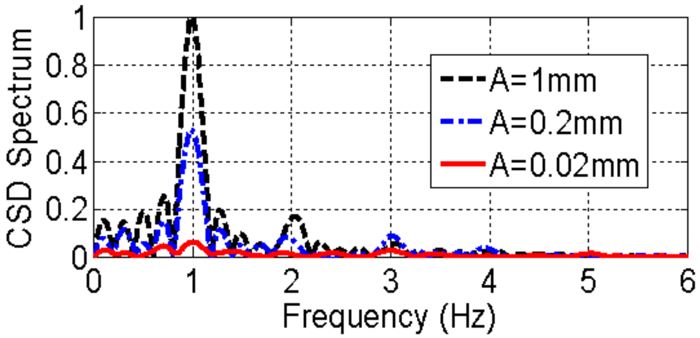
$$= \cos\left(\frac{4\pi x(t)}{\lambda} + \phi_t\right) + j \cdot \sin\left(\frac{4\pi x(t)}{\lambda} + \phi_t\right)$$

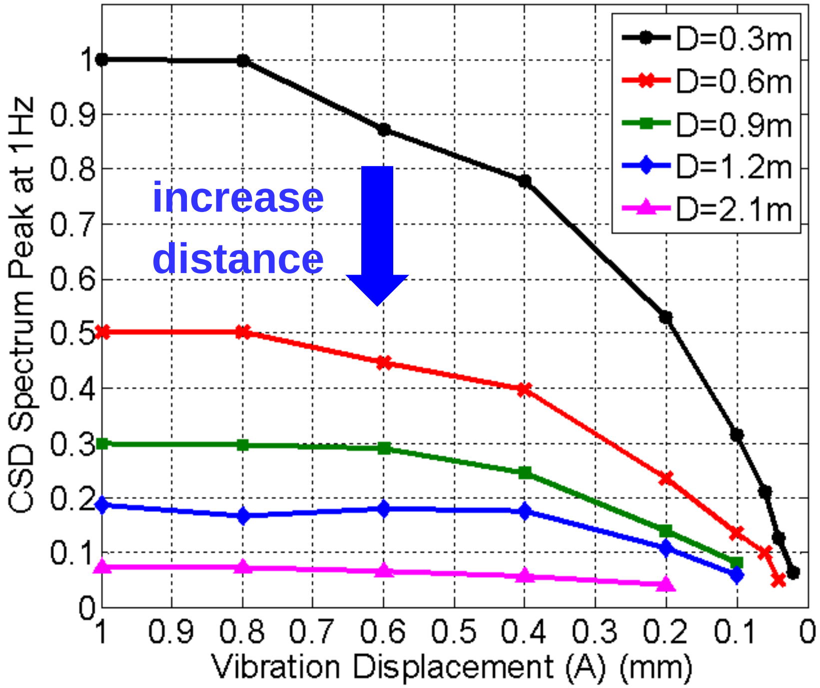
$$= \exp\left\{ j\left[\frac{4\pi x(t)}{\lambda} + \phi_t\right]\right\} = \exp\left[j\frac{4\pi x(t)}{\lambda}\right] \cdot \exp\left(j \cdot \phi_t\right).$$

→ **Quadrature(I/Q) radar receiver needed**



Experiment – Small Mechanical Vibration Detection





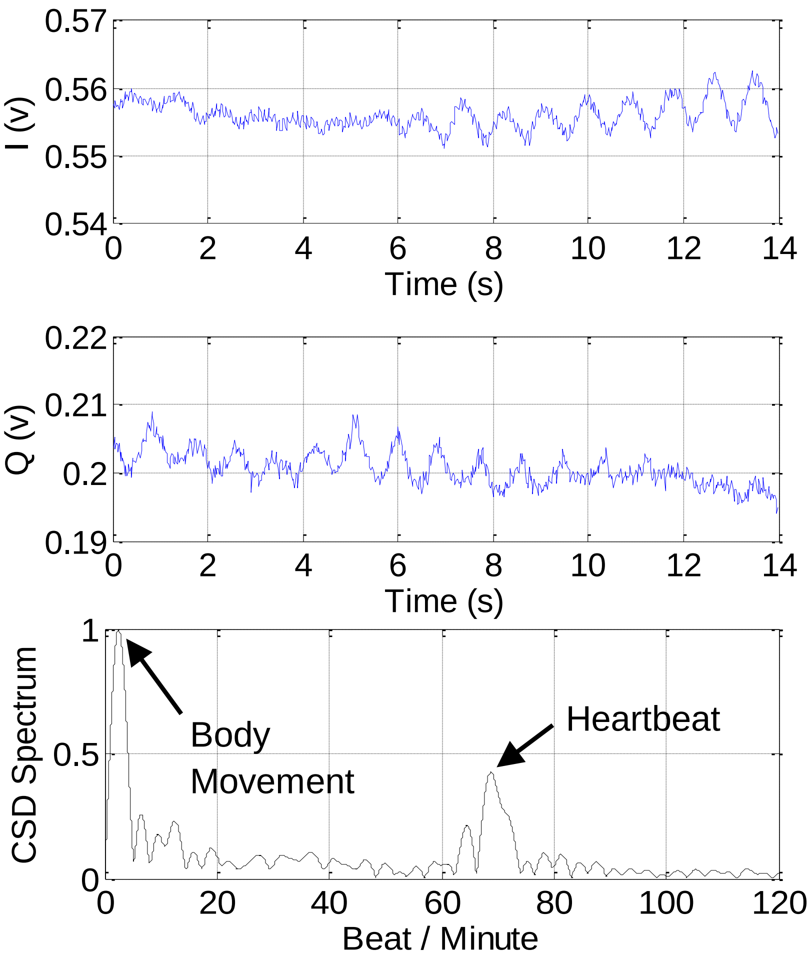
Vibration (f = 1 Hz, D = 0.3m):

→ minimum “detectable” displacement A = **20 μm**

All data points are normalized to the largest CSD spectrum peak (A = 1 mm, D = 0.3 m)

→ A = 0.2 mm can be detected at D =2.1 m away

Experiment – Heartbeat Detection



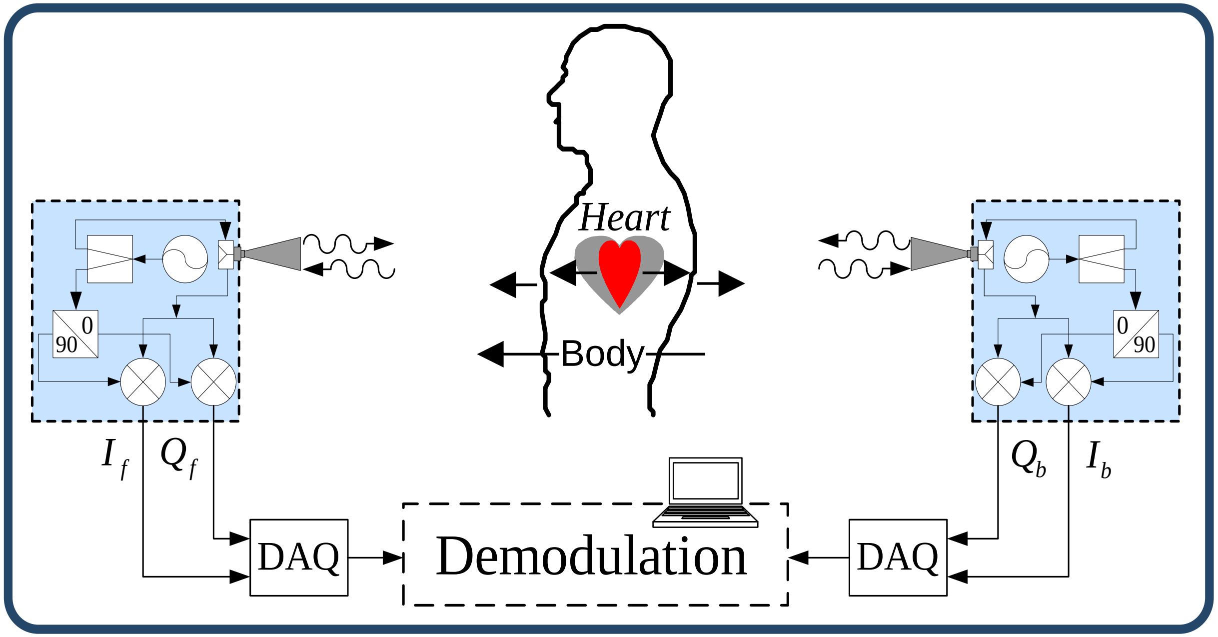
(Holding breath)

- Subject sitting on a chair 0.3 m in front the radar.
- At t = 0 ~ 7 sec, Q was around the optimal point, and I was near the null point.
- After t = 9 sec, I channel started to take over the detection due to slight body movement (null point every $\lambda/4$).
- Baseband noise voltage is around 1mV$_{rms,}$ corresponding to a baseband SNR around 5 (14 dB)

Problem of Random Body Movement During Vital Sign Measurement

A Solution…

Random Body Movement Cancellation – Concept

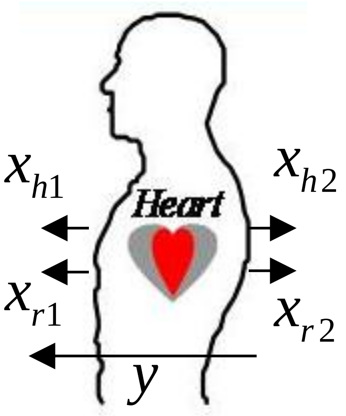


- **Cardiorespiratory movements on both sides of the body move in the same direction w.r.t to their detecting radars**
- **Random body drift movements are in the opposite directions w.r.t. to their detecting radars**

Random Body Movement Cancellation – Theory

Front: $S_f(t)=\exp\left\{j\left[\frac{4\pi x_{h1}(t)}{\lambda}+\frac{4\pi x_{r1}(t)}{\lambda}\boxed{+}\frac{4\pi y(t)}{\lambda}+\phi_1\right]\right\}$

Back: $S_b(t)=\exp\left\{j\left[\frac{4\pi x_{h2}(t)}{\lambda}+\frac{4\pi x_{r2}(t)}{\lambda}\boxed{-}\frac{4\pi y(t)}{\lambda}+\phi_2\right]\right\}$



x_{h1}, x_{h2}, x_{r1}, x_{r2}: physiological movements

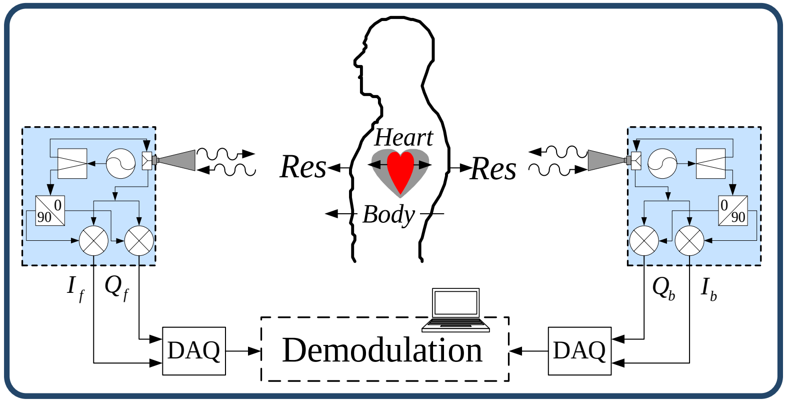
y(t): random body movement

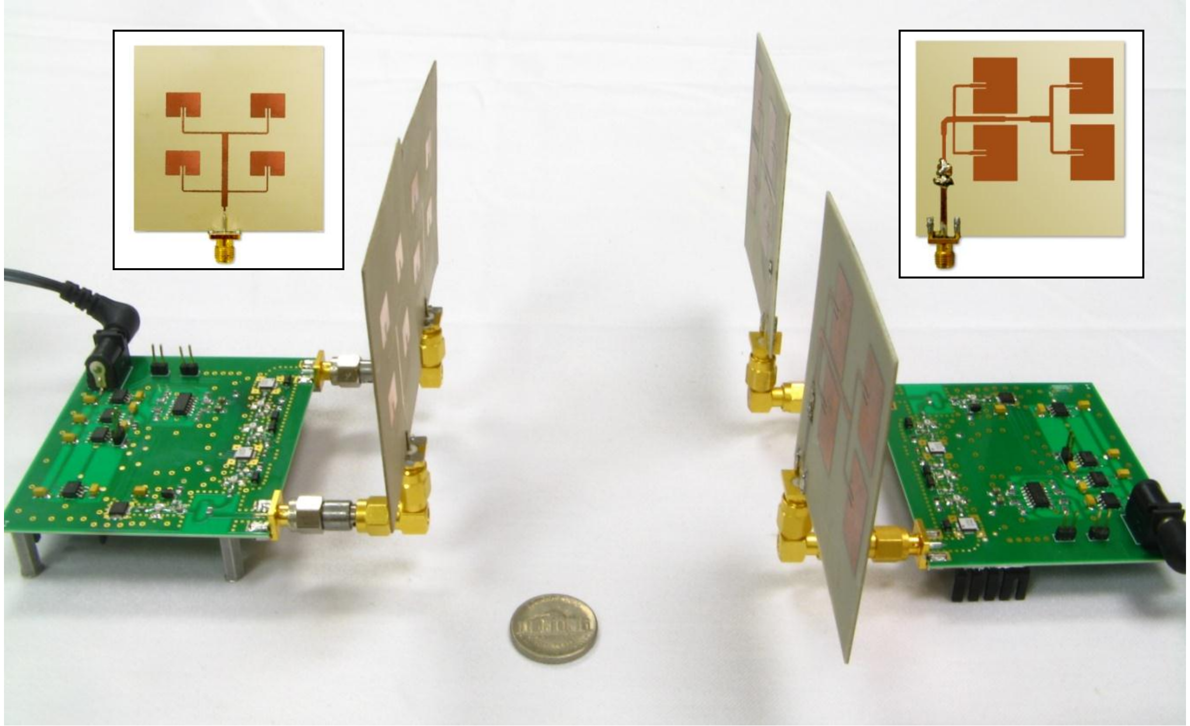
Combine signals from both sides:

$$S_{fb}(t)=S_f(t)\cdot S_b(t)=\exp\left\{j\left[\frac{4\pi\left[x_{h1}(t)+x_{h2}(t)\right]}{\lambda}+\frac{4\pi\left[x_{r1}(t)+x_{r2}(t)\right]}{\lambda}+\phi_1+\phi_2\right]\right\}$$

y(t) (random body movement) disappeared!

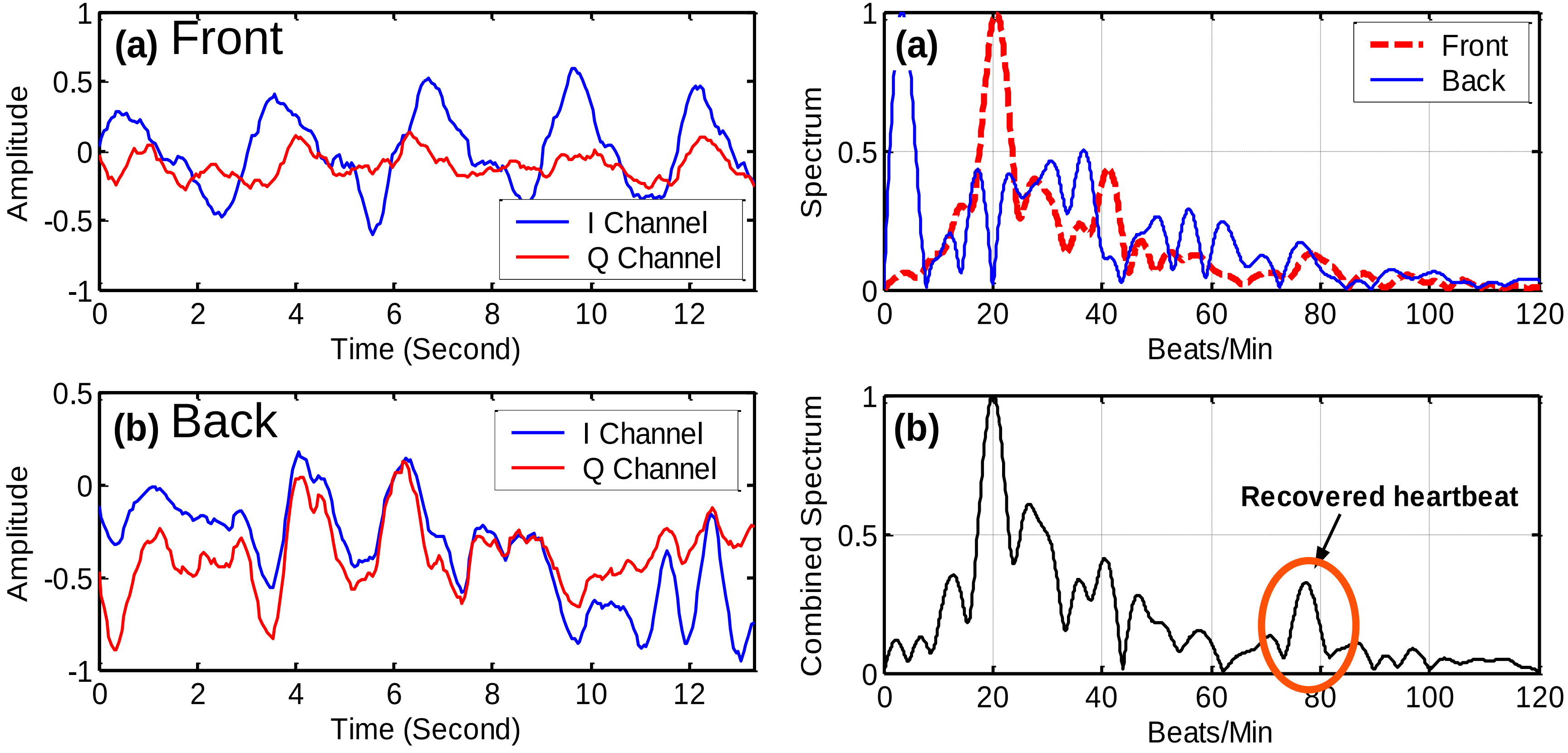
Random Body Movement Cancellation – Experiment





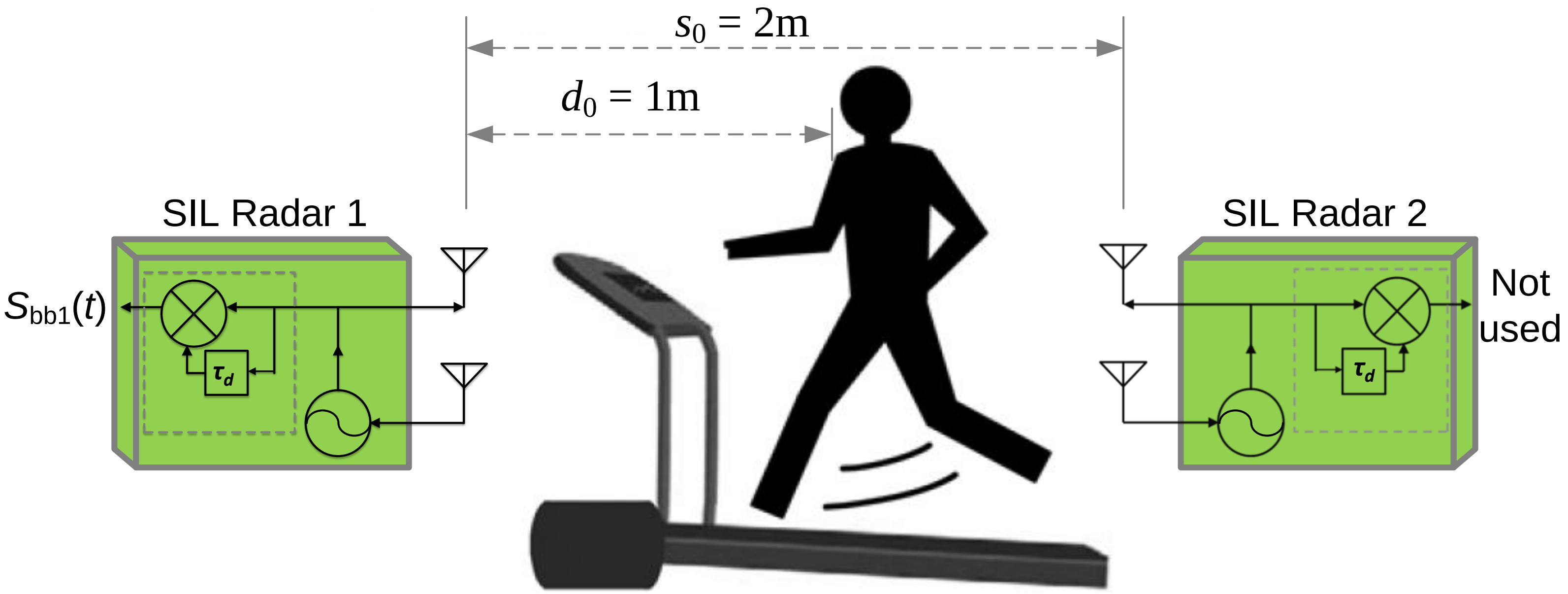
Isolation between two radars: antenna polarizations & slight frequency offset between TX and RX

Random Body Movement Cancellation – Result



C. Li, J. Lin, “Random Body Movement Cancellation in Doppler Radar Vital Sign Detection,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 56, issue 12, pp. 3143-3152, December 2008.

First Demonstration of Noncontact Vital Sign Measurement on Treadmill

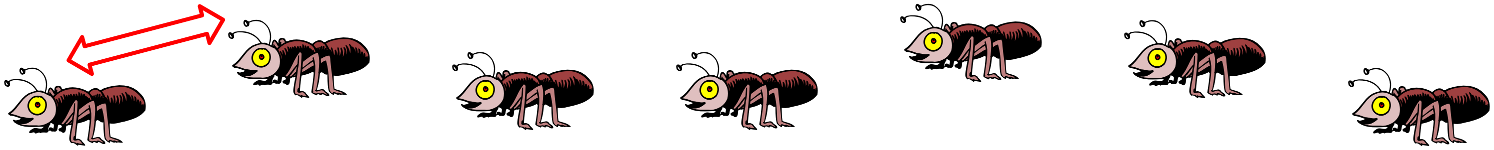


SIL: Self-Injection Locking

F.-K. Wang, T.-S. Horng, K.-C. Peng, J.-K. Jau, J.-Y. Li, and C.-C. Chen, "Single-Antenna Doppler Radars Using Self and Mutual Injection Locking for Vital Sign Detection With Random Body Movement Cancellation," ***Microwave Theory and Techniques, IEEE Transactions on,*** **vol. 59, pp. 3577-3587, 2011.**

Applications

- Search-and-rescue
- Human healthcare; Animal care
- Radar in cell phone - lie (or emotion) detection radar
- Sports, video games, …
- When the complete radar system can be made very small…
  - small radar sensor chip + small antenna + small robot + wireless ad hoc network + wireless energy or energy harvesting
  - Searching survivors under rubbles will be much more effective with a swarm of small robots, e.g., robotic ants.



Summary

- Doppler micro-radar sensors have been demonstrated – PCB modules, RFIC, System-in-Package (SiP).
- Small micro-radars can be added to many electronic devices – computers, phones, tablets
- The technology can be used to detect any motion of an object reflecting radio waves
- With proper signal processing, useful and interesting information can be extracted for various applications (biomedicine, biometrics, …).
- New hardware architectures and sign processing algorithms are being developed by many groups in the world.

Thank you for your attention!