A Low-power Data Transmission Technique using Inductive Coupling and Its Application to Biomedical Sensor Devices

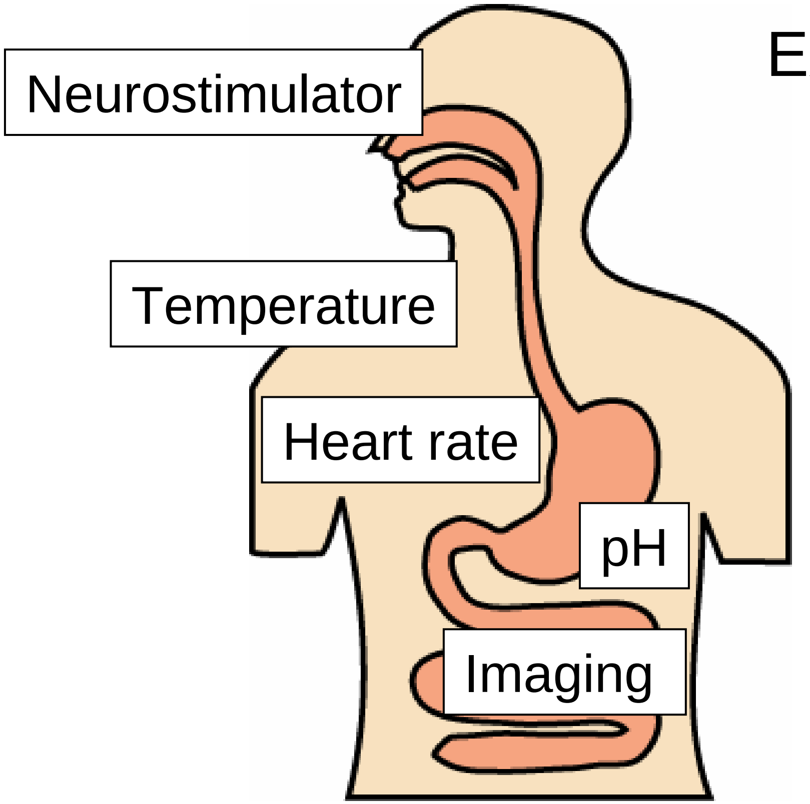
Shinya Itoh and Shoji Kawahito

Research Institute of Electronics

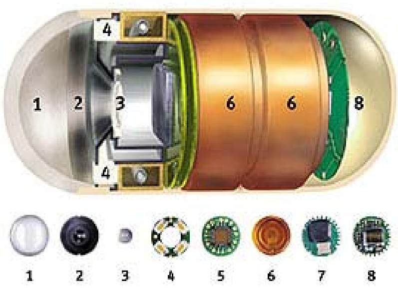
Shizuoka University, Japan

(Email:sito@idl.rie.shizuoka.ac.jp)

Wireless Biomedical Sensors



Example: Capsule Endoscope system



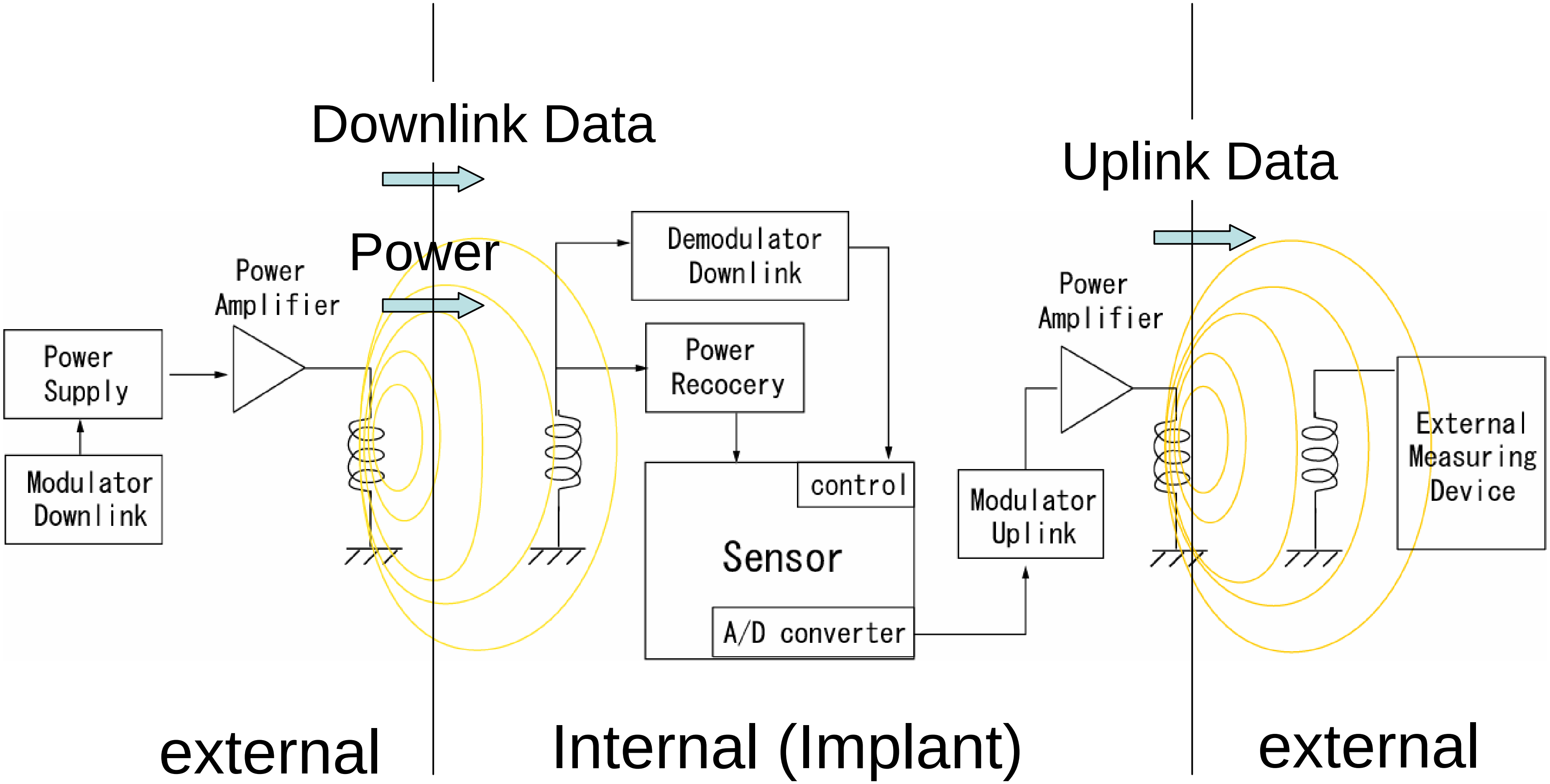
Israel: Given Imaging Ltd

- ✓**Low power consumption**
- ✓**High data rate**
- ✓**Miniature size**
- ✓**Low cost**

Key Block

Short Range Wireless

Data Communication Link using Inductive Coupling



Downlink

Uplink

Inductive Data Link for Implantable Wireless

- ✓ Simple implementation
- ✓ Less body loss at lower frequencies
- ✓ Power transmission into an implantable device.

- ✗ Low data rate for Uplink
  (Maximum 25kbps to 250kbps)
- ✗ Low energy efficiency
  (power-loss in the inductive load driver)

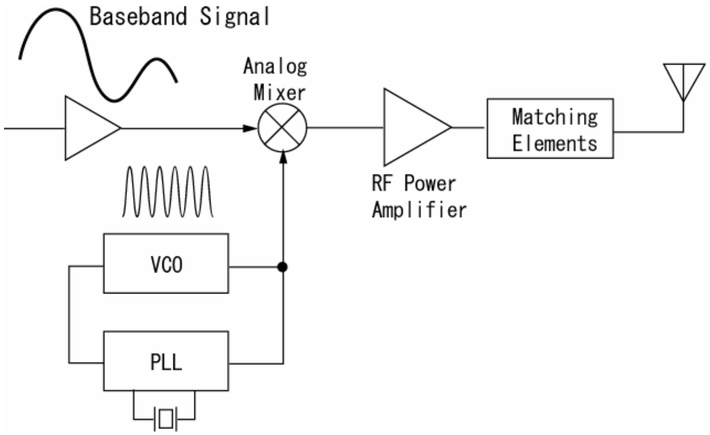
Challenge

A new design method of further low power transmitters which introduces the concept of class-F amplifier

Modulator Design Choices

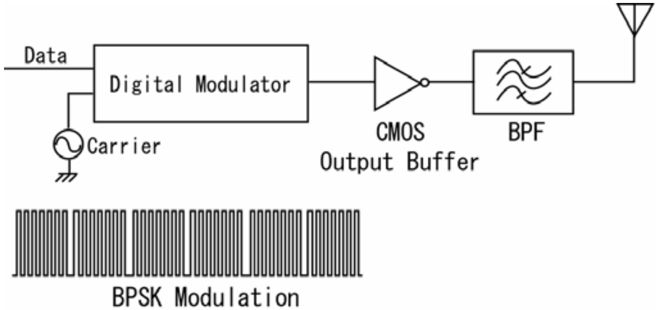
High Frequency Analog
300MHz～5GHz

PLLs, VCOs, Power Amplifiers
Antenna, Matching Elements



High speed analog circuits consume large power and large circuit area

Low Frequency Digital
10MHz ~40MHz

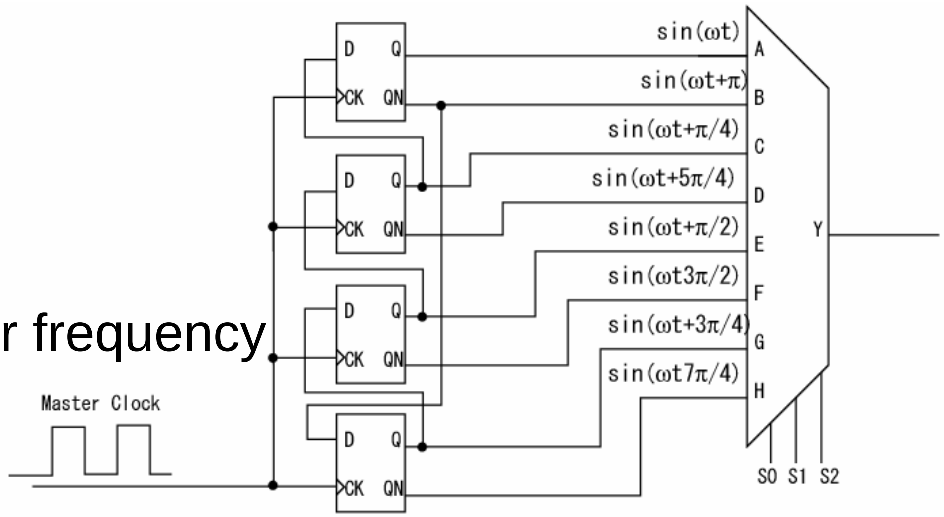


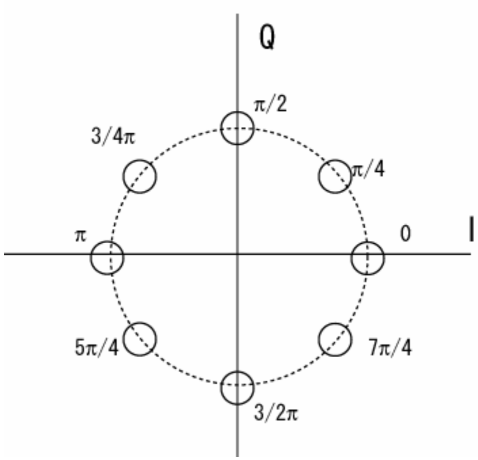
Modulated signal can be directly generated by digital logic gates

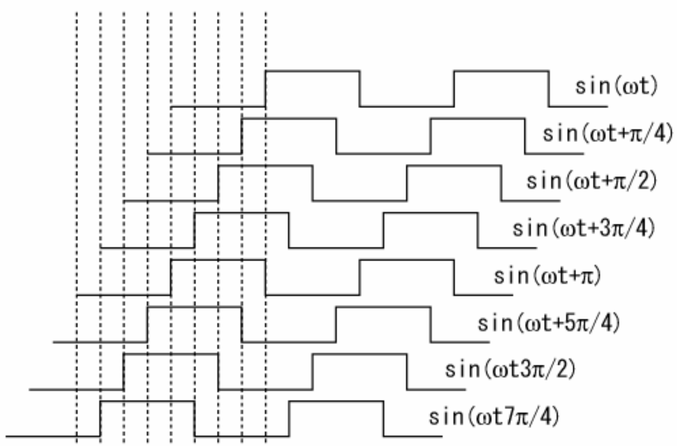
Digital Direct M-PSK Modulation

All the circuits are constructed by digital circuits.

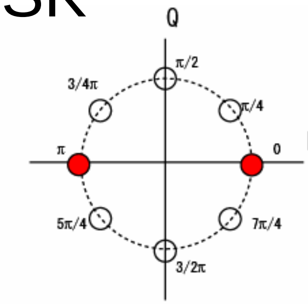
8xcarrier frequency



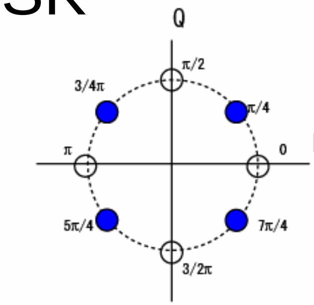




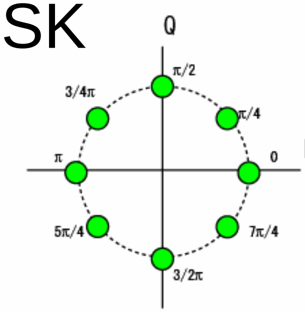
BPSK



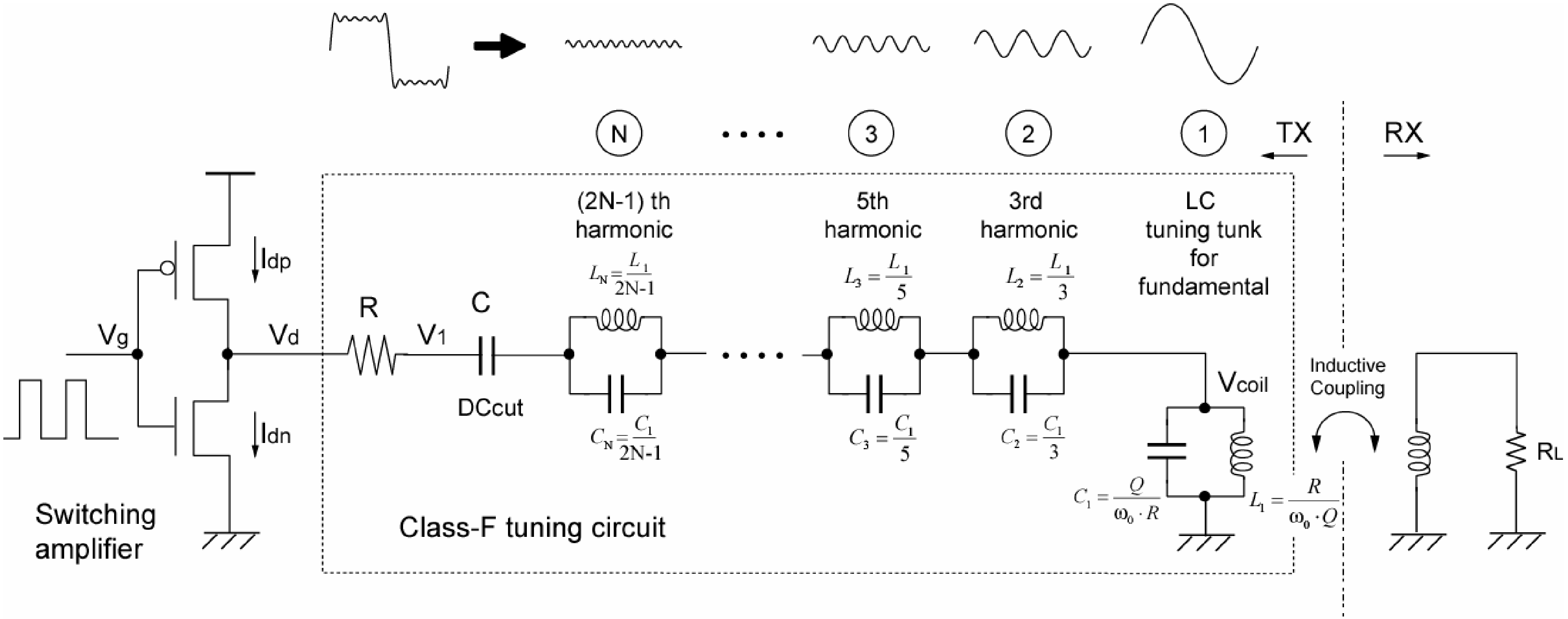
4PSK



8PSK

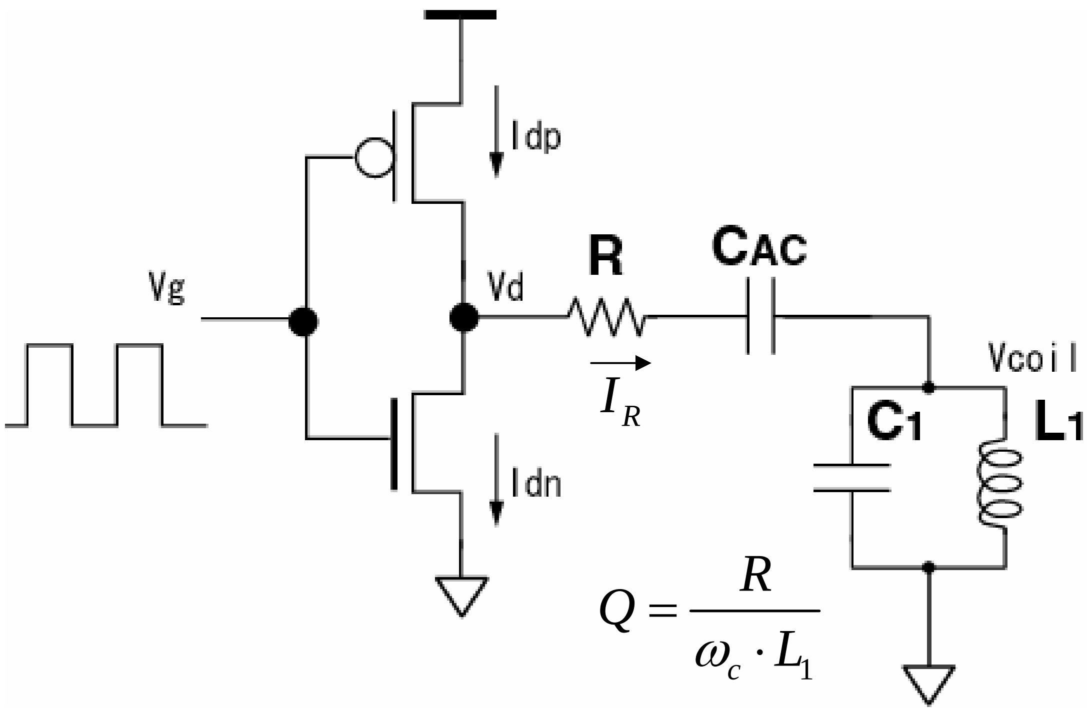


Proposed Primary Coil Driver Design
which introduces the concept of Class-F amplifiers

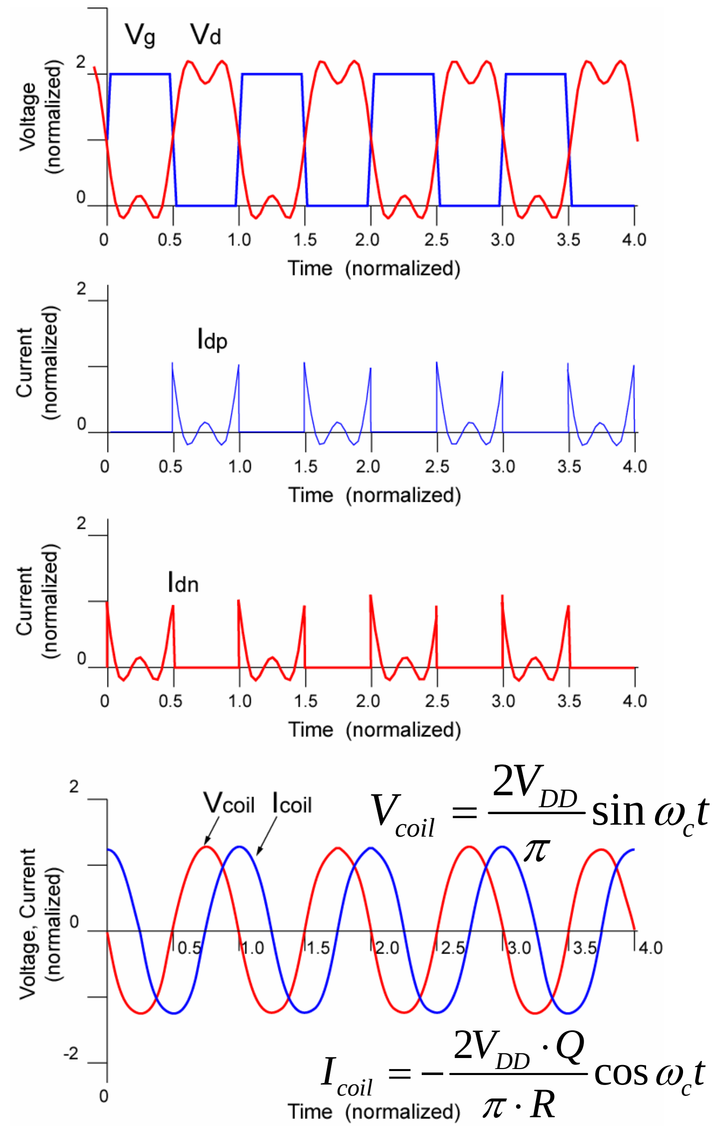


Parallel LC resonators of the first through Nth stages are tuned to the first through Nth odd harmonics of the carrier frequency.

Circuit Operation (Simple case N=1)



$$Q = \frac{R}{\omega_c \cdot L_1}$$



$$V_{coil} = \frac{2V_{DD}}{\pi} \sin \omega_c t$$

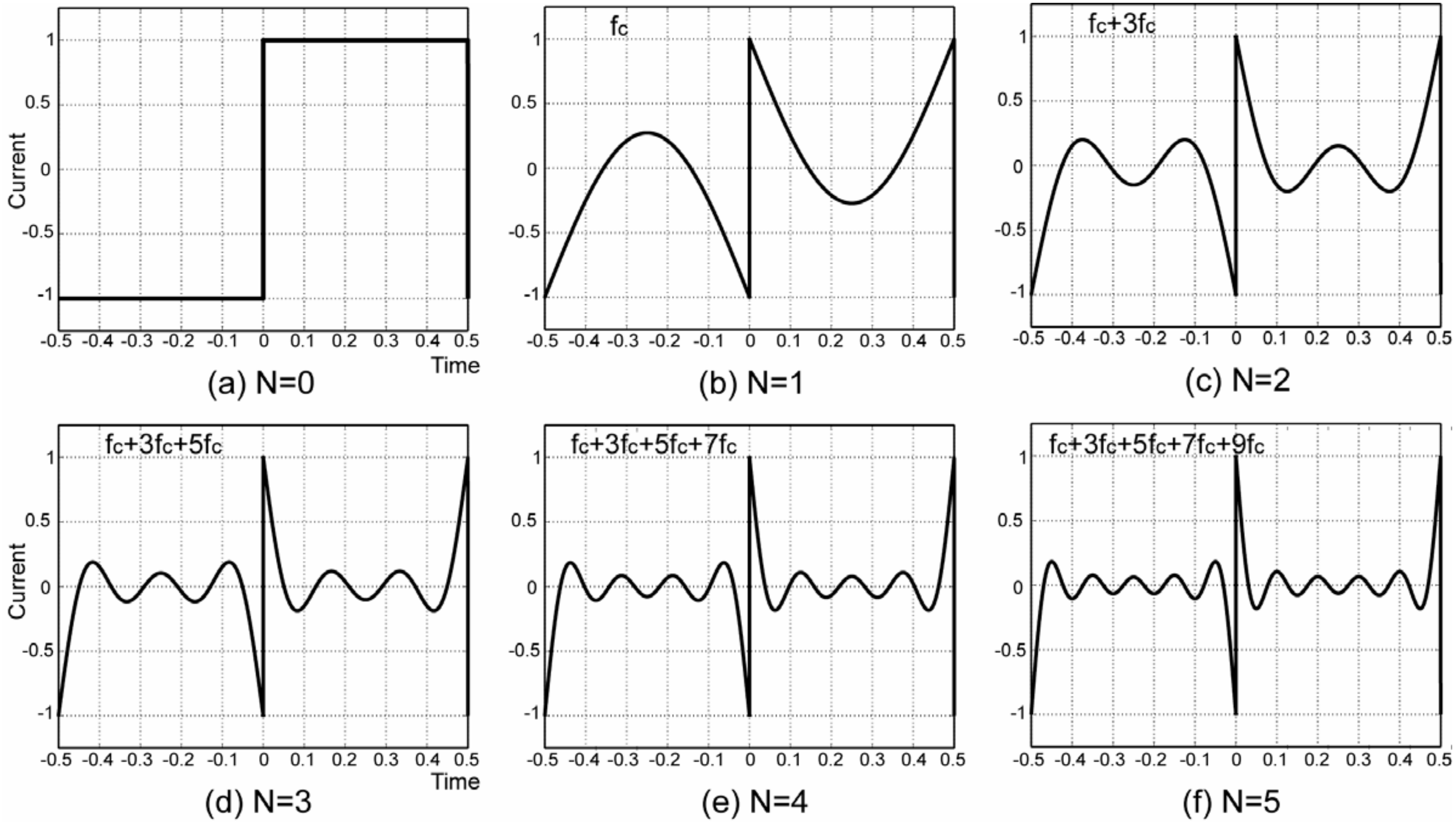
$$I_{coil} = -\frac{2V_{DD} \cdot Q}{\pi \cdot R} \cos \omega_c t$$

A square wave of carrier frequency ωc contains the fundamental frequency and all odd harmonics.

By removing harmonics from the square voltage waveform, this circuit generates an accurate sine waveform voltage and current at the output LC tank.

Steady-state current waveforms I_R flowing through the resistor R

Normalized by $I_{max} = \frac{V_{DD}}{2R}$

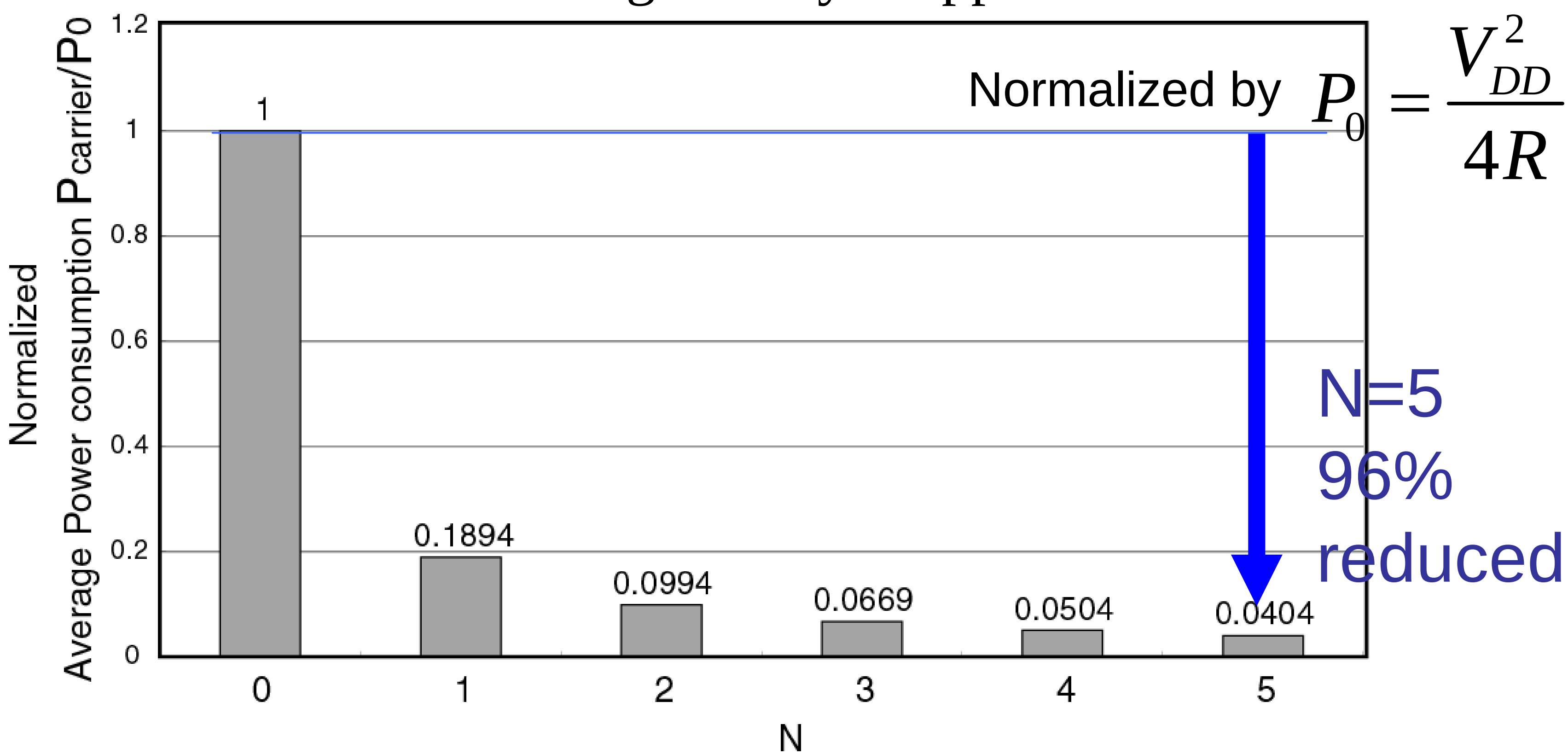


(a) N=0 (b) N=1 (c) N=2
(d) N=3 (e) N=4 (f) N=5

At resonance frequency, series LC resonators create a high impedance to the amplifier at the respective odd harmonic frequencies.

Static Power Consumption with the Nth order harmonic resonators

In the case that carrier signal only is applied



$$P_0 = \frac{V_{DD}^2}{4R}$$

As the number of odd harmonic resonators increases, the coil-driver's power efficiency can be significantly increased.

Estimation of the Driver's Power Consumption

In the case that carrier signal only is applied,
the power consumption of the coil driver $P_{carrier}$ is given by

$$P_{carrier} = \frac{8}{\pi^2} \cdot \frac{V_{DD}^2}{4R} \cdot \sum_{k=N+1}^{\infty} \frac{1}{(2k-1)^2}$$

The dynamic energy consumption E_{symbol} due to symbol transition is

$$E_{symbol} = \frac{8 \cdot C_1 \cdot V_{DD}^2}{\pi^2} \sum_{m=1}^{N} \left[\frac{1}{(2m-1)^3} \right]$$

$$P_{symbol} = E_{symbol} \cdot f_s \cdot \alpha_s$$

f_s : Symbol rate

α_s : Transition probabilities

The total power consumption $P_{total} = P_{carrier} + P_{symbol}$

Estimated Average Power Consumption of the primary coil driver

This simulation assumes a BPSK modulated carrier signal.
The power consumption of the modulator circuit is not included.

$$V_{DD} = 2V, Q = 8, R = 1k\Omega, L_1 = 1\mu H, C_1 = 63pF$$

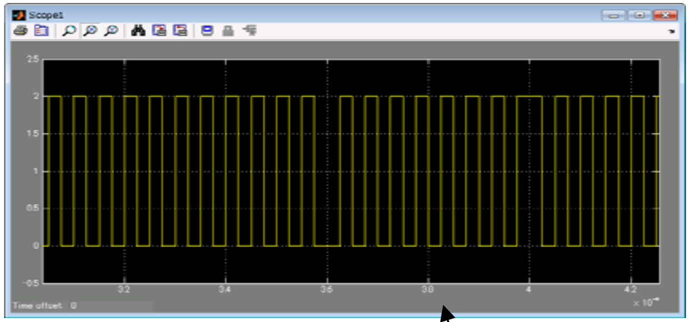
carrier frequency f_c=20M[Hz], f_s=2.5M[sample/s], $\alpha_s = 0.5$

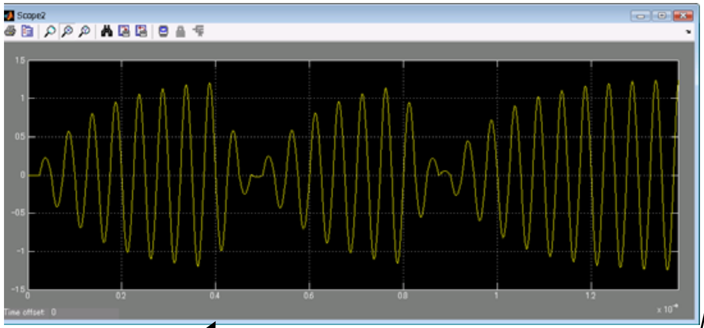
N	Odd Harmonics	$P_{carrier}$ [μW]	P_{symbol} [μW]	P_{total} [μW]	Energy Cost [nJ/bit]
1	1	189	255	444	0.178
2	1,3	99	265	359	0.144
3	1,3,5	67	267	334	0.134
4	1,3,5,7	50	268	318	0.127
5	1,3,5,7,9	40	268	308	0.123

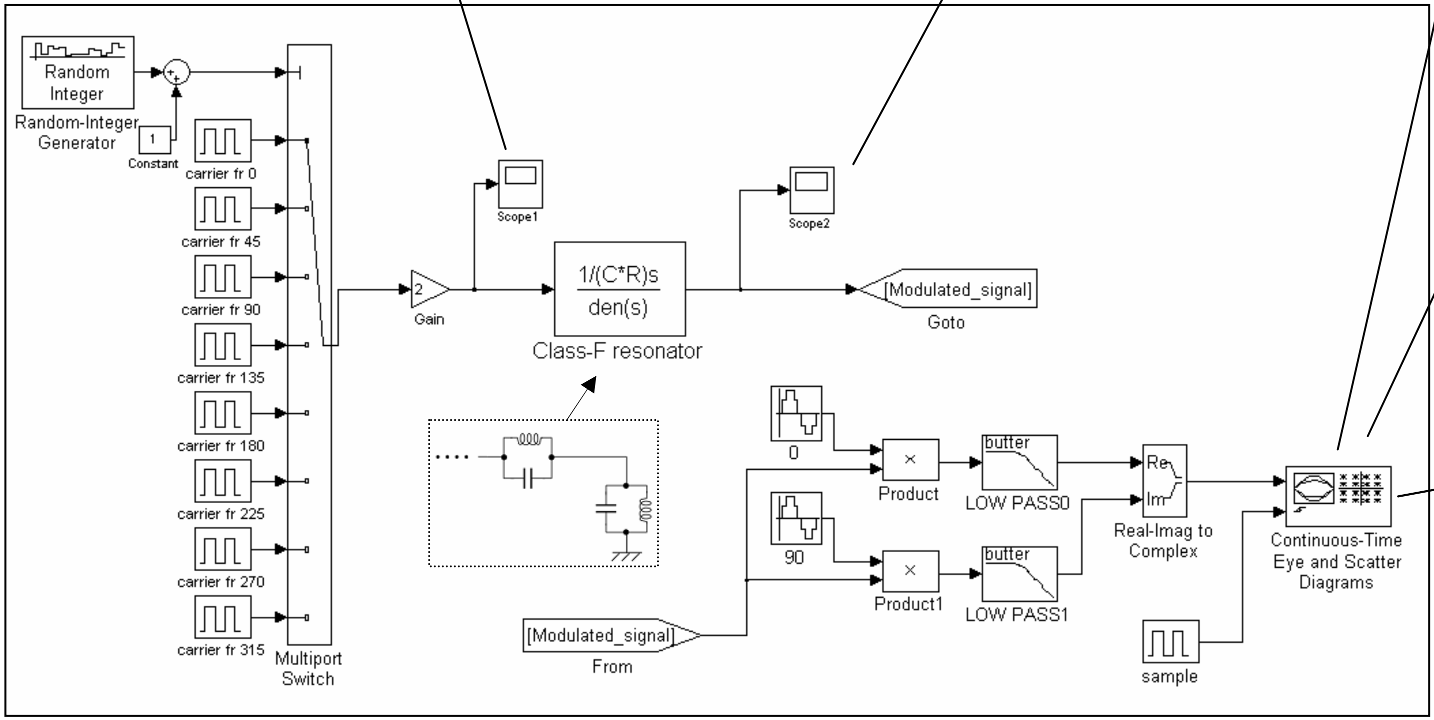
$$I_{coil} = -\frac{2V_{DD} \cdot Q}{\pi \cdot R} \cos \omega_c t = 20.3mA_{p-p}$$

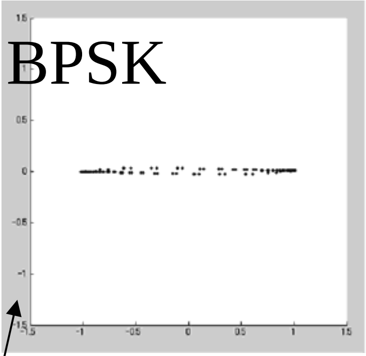
Average Power <500uW

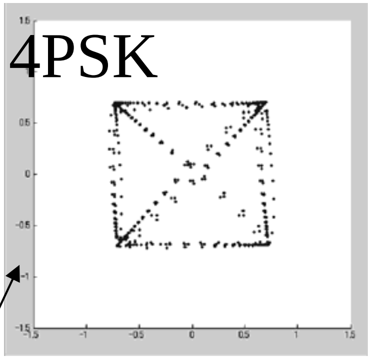
Matlab simulation of M-PSK modulation using a 50%-duty-cycle square wave

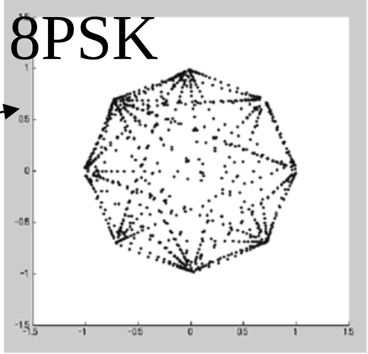








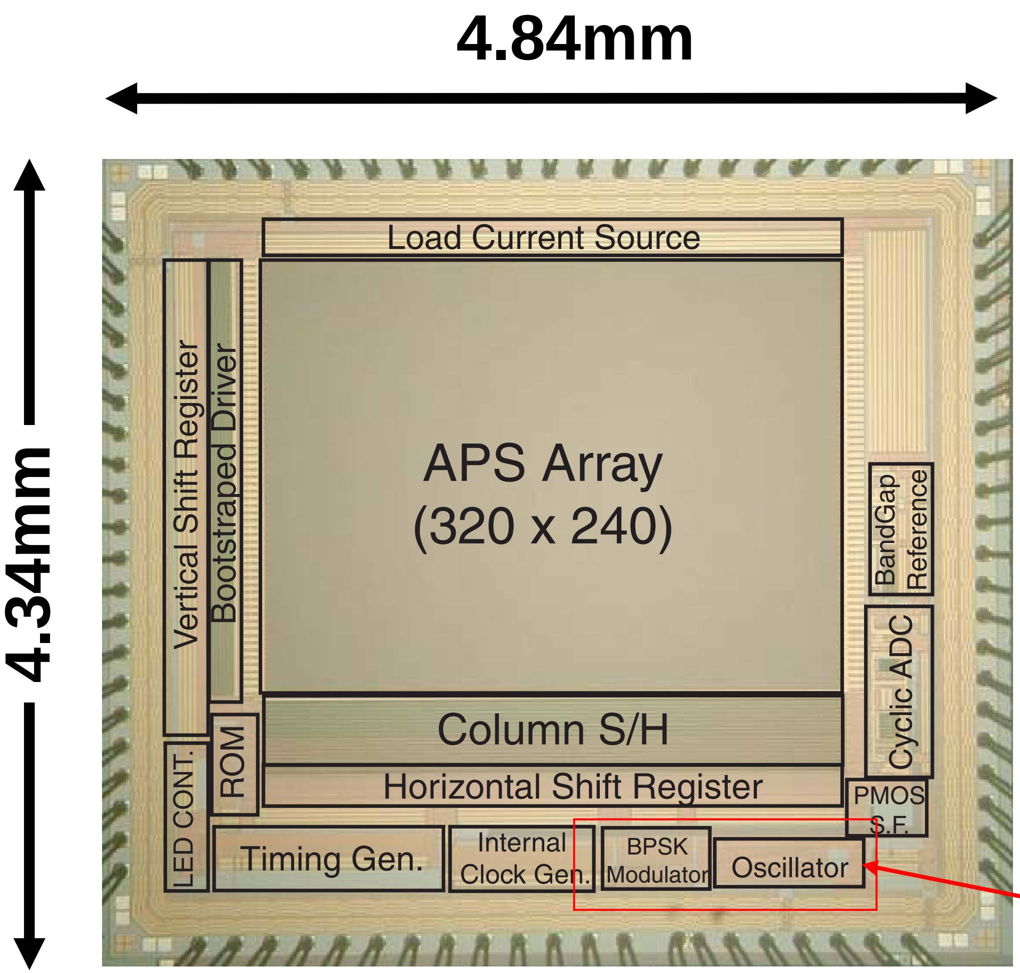




A implementation of a one-chip wireless camera device for a capsule endoscope

A first prototype of the single-chip CMOS wireless camera

1P4M 0.25μm CMOS CIS process



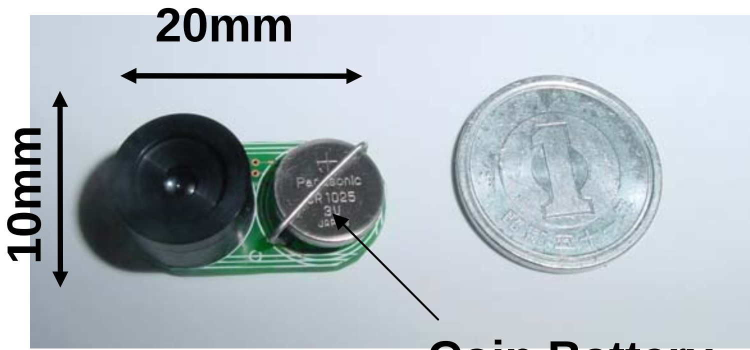
- Supply Voltage 2V
- 320x240 Pixel (QVGA)
- Clock Generator
- 10b Cyclic A/D
- Band Gap Reference
- BPSK Modulator
- Coil Driver for Inductive Link

All required camera functions and wireless components are integrated into a single silicon chip.

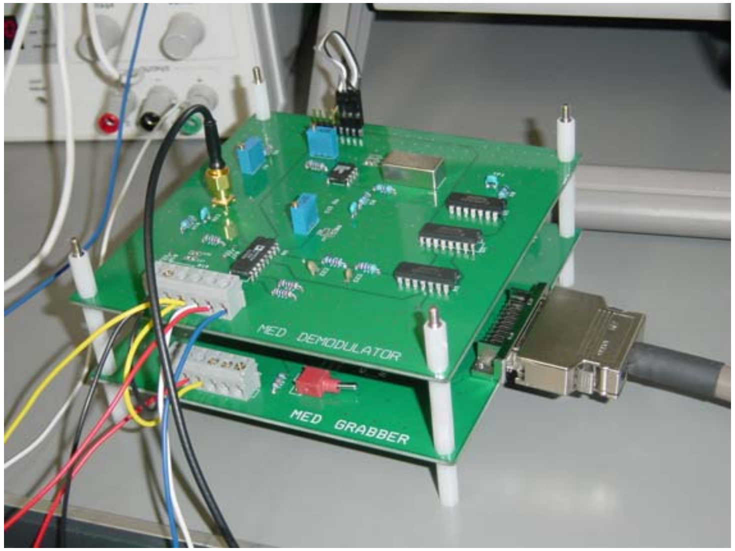
Wireless block
Chip occupied Area 0.04mm^2

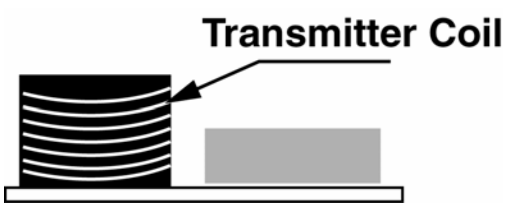
Experimental Setup

Miniaturized Camera Module



Demodulator

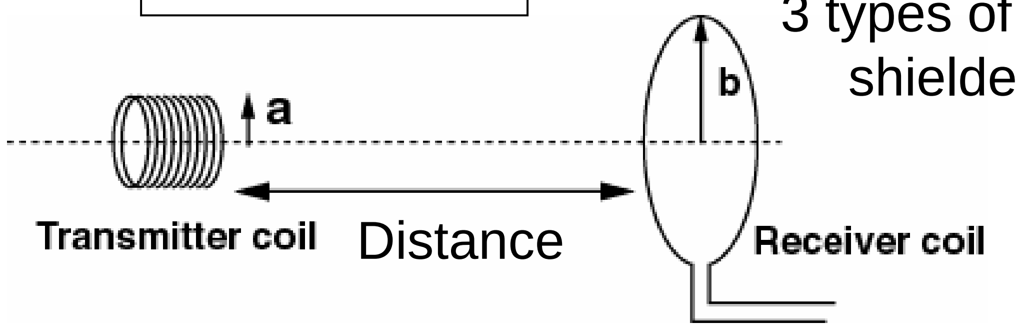




Carrier frequency
20MHz
Symbol rate
2.5Msymbol/s
BPSK modulation

3 types of Receiver coil
shielded loop 1Turn
2xb=10cm
20cm
40cm

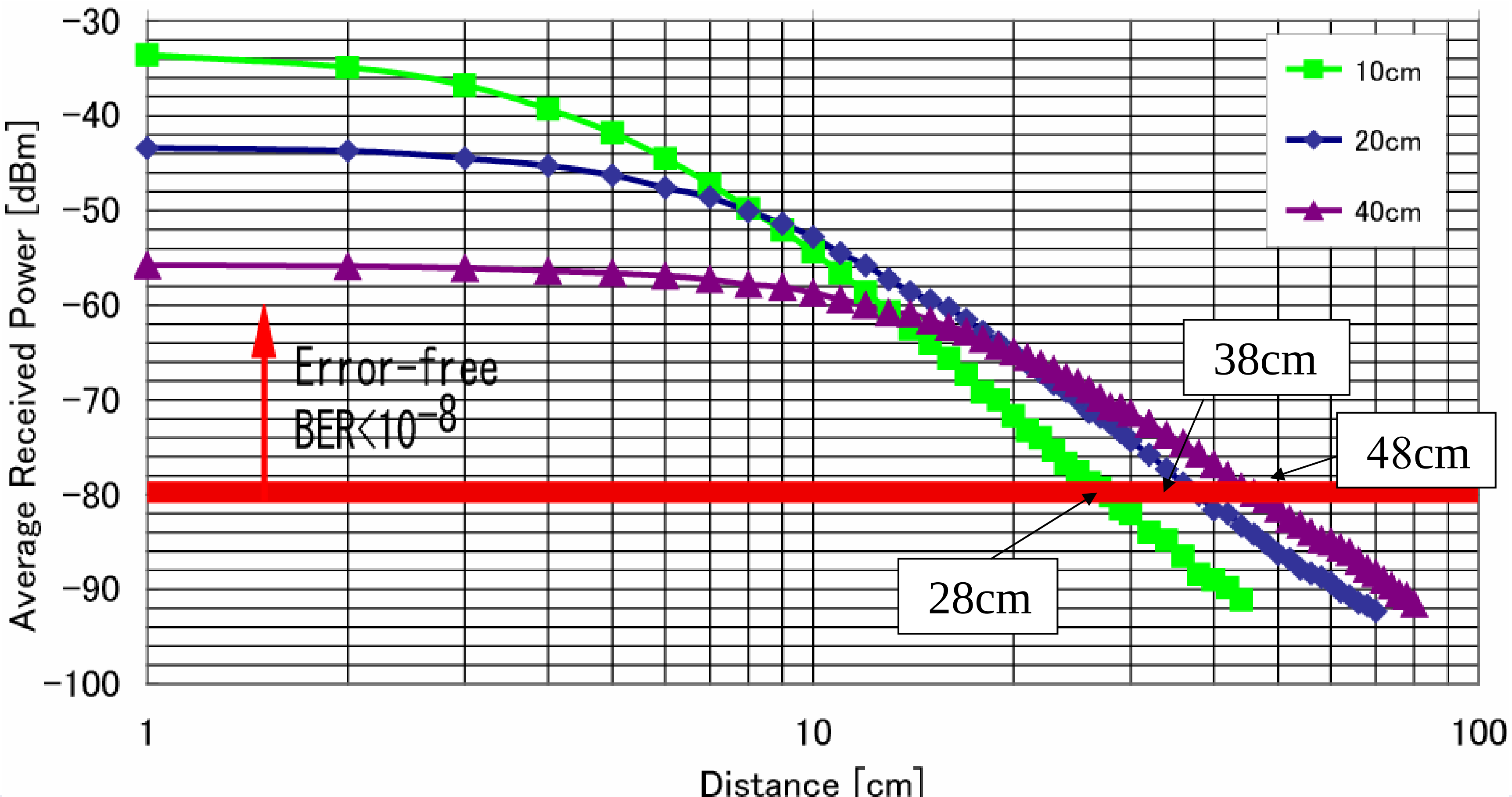
Transmitter coil
N=10Turn
2xa=10mm
inductance 1uH



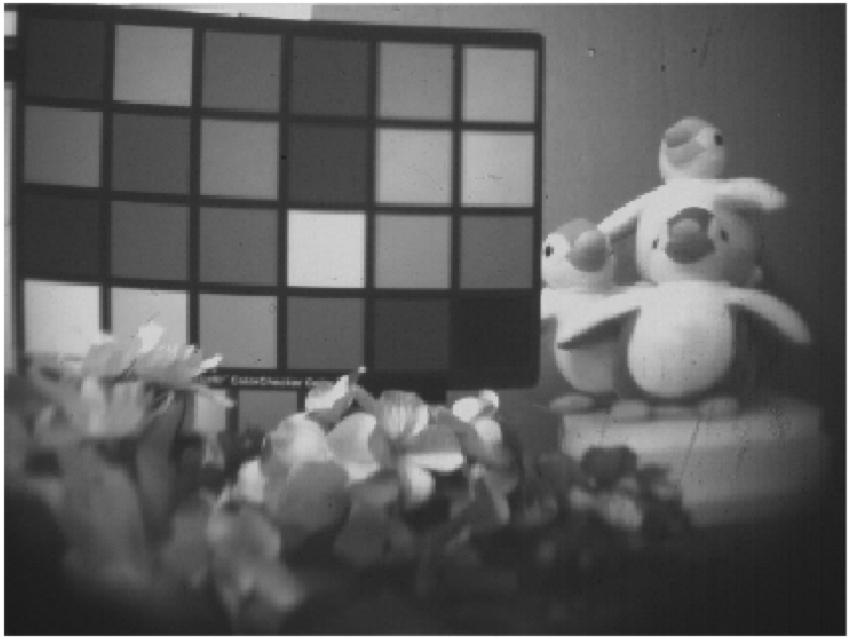
Average Received Power
as a function of the communication distance

Minimum Received Power
= -174dBm + 10logBw + NF + SNR
= -80dBm

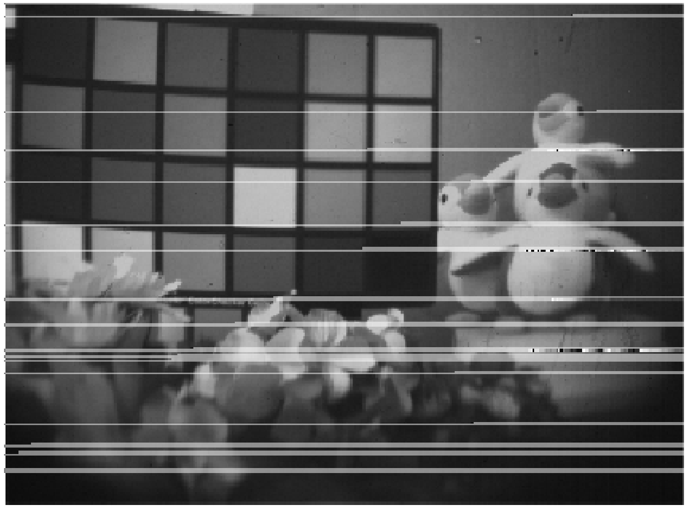
Bw = 2.5MHz
NF = 10dB
SNR = 20dB



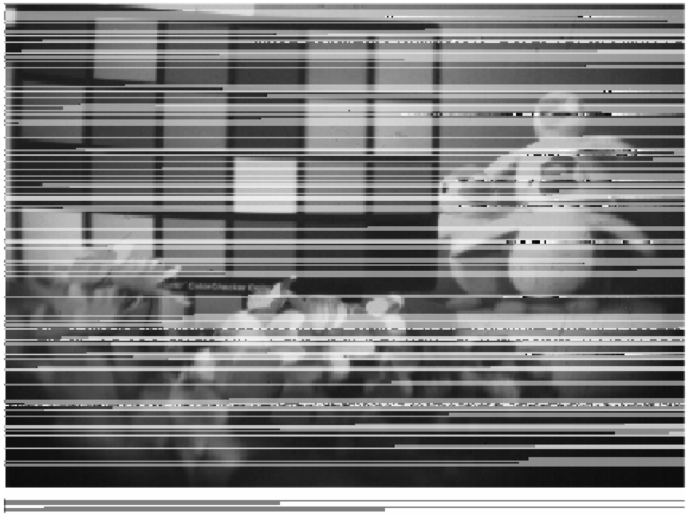
Captured Image



(a)-80dBm



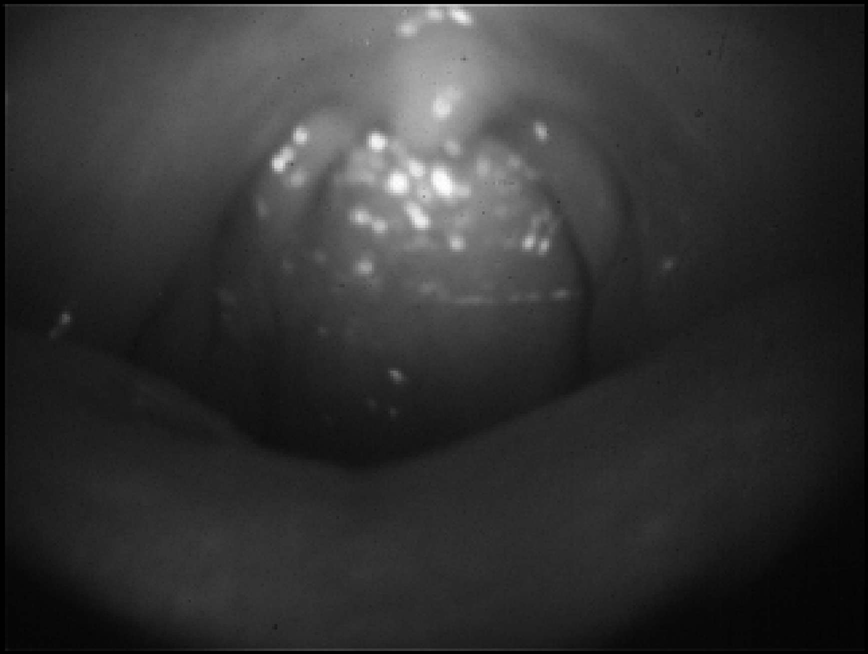
(b)-87dBm



(c)-90dBm

Error-free image transmission over a distance of 48cm

Sample Movie



2frame/s
QVGA
320 x 240
10bit resolution

The chip specifications and the measured performance summary

Technology		0.25μmCMOS 1P4M
Chip Size		4.84(H)mmx4.34(V)mm
Supply Voltage		2V
Array Size		320(H)x240(V) QVGA
Pixel Size		10μmx10μm
Fill Factor		54.9%
ADC Resolution		10bit
Frame Rate		2fps
Modulation Method		BPSK
Carrier Frequency		20MHz
Bit Rate		2.5Mbps
Measured Power Consumption	Analog	950μW
	Digital	250μW
	Transmitter	1.4mW
	Total	2.6mW

Total
2.6mW

Transmitter power: 1.4mW @ 2.5Mbps 0.56nJ/bit !!
Maximum transmission distance 48cm

Summary

- A simple but efficient transmitter design which introduces the concept of class-F amplifiers into an inductive data link is proposed.

- An experiment of image data transmission has been successfully performed using the implemented chip.

- The result of the transmitter power consumption is 1.4mW at data transmission rate of 2.5Mbps

- Error-free data transmission over a distance of 48cm. The energy consumption of 0.56nJ/bit is achieved.