BE-M260/EE-M255/NS-M206
Lecture - 19
Power and Data Telemetry

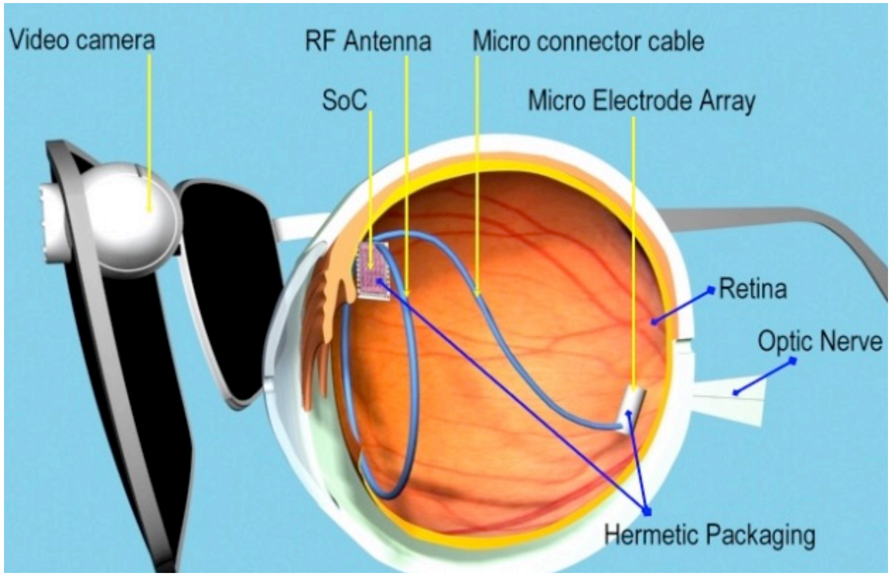
Wentai Liu©, PhD
Distinguished Professor
Department of Bioengineering/Electrical Engineering
UCLA
Email: wentai@ucla.edu
Web: www.seas.ucla.edu/IBR

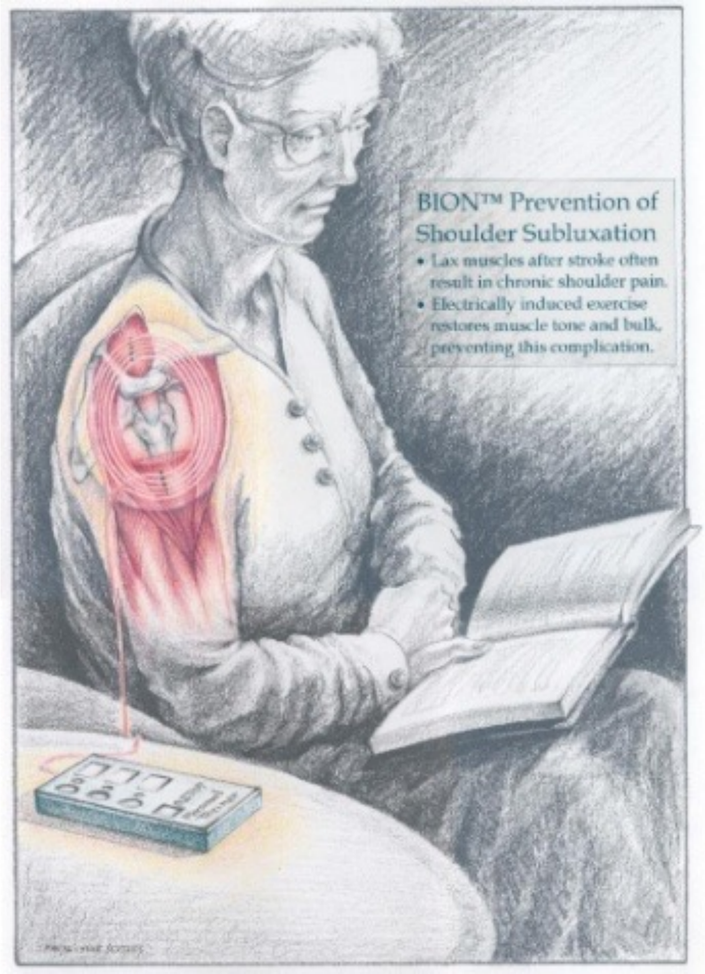
Outline

- Introduction – Telemetry
- Power telemetry
- Biomedical implants - various power requirement
- Power transfer - mechanisms and constraints
- Design methodology – inductive coupling
- Data telemetry
- Design example – fully integrated retinal implant
- Summary

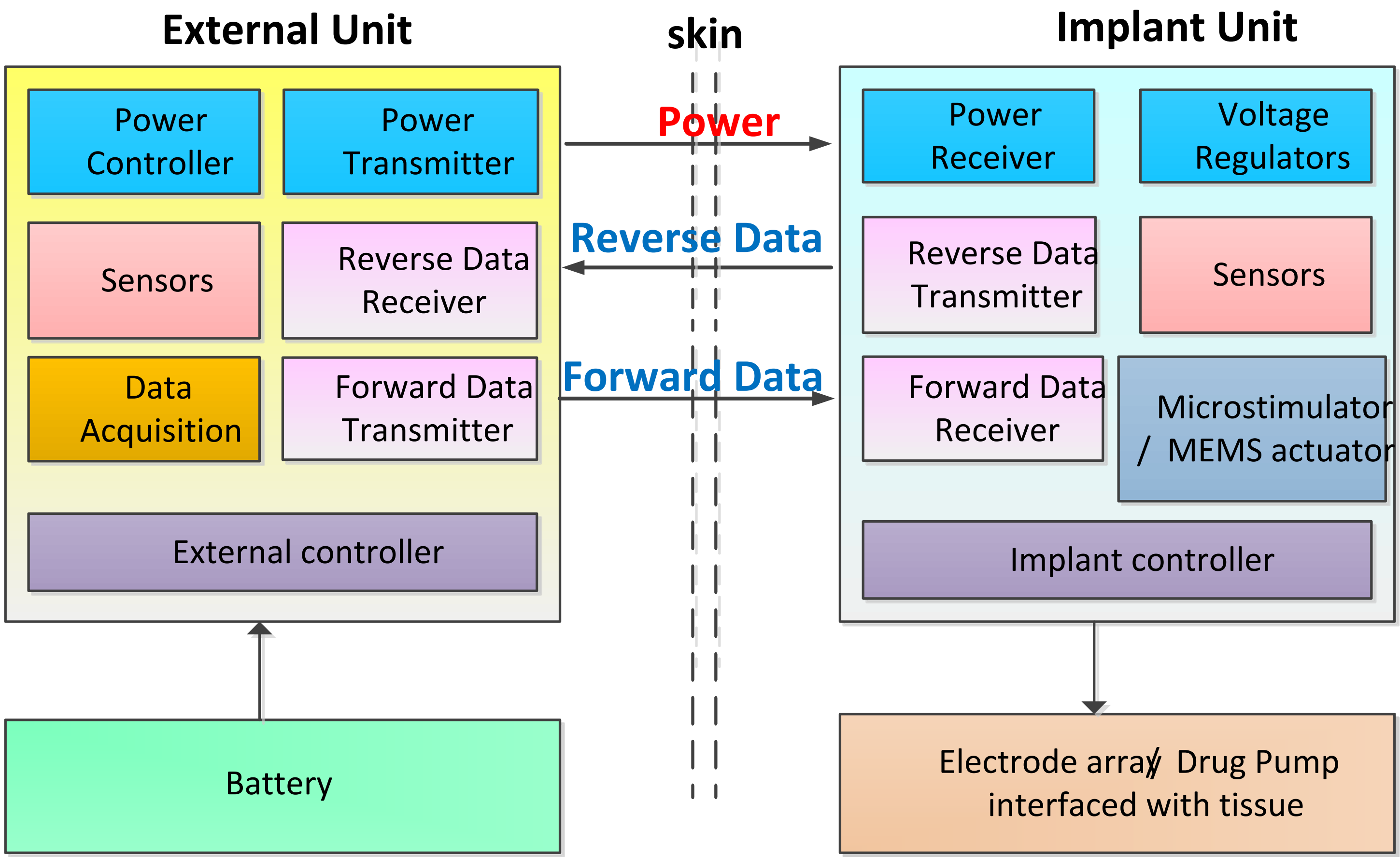
Role of Electronics in Medical Implants

- Main component of neural prosthetic devices implementing the diagnostic and therapeutic functions
  - Pacemaker
  - Cochlear implant
  - Neuromuscular prostheses
  - Retinal prostheses





Importance of Power and Data Transfer



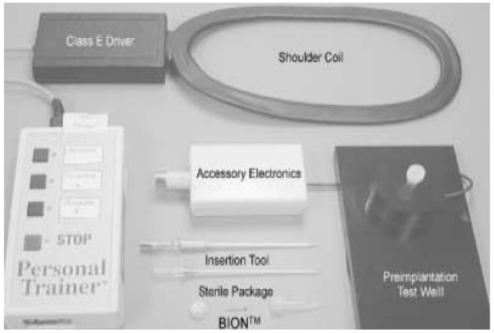
Power telemetry link: deliver energy for powering electronics

Data telemetry link: communicate information between the implant and external device

Categorized Applications

❑ High power, low forward and back data rate

BIONs: Muscle stimulation[1]

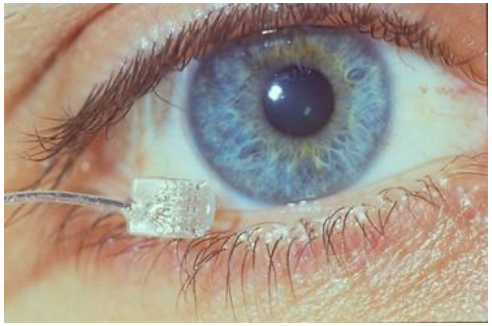


- **Power link**
- Inductive power link
- High power transmission (17V/0.2~30mA)
- **Data link**
- Inductive data link
- Data rate: 120kb/s forward data; 40kb/s back data
- Amplitude modulation (AM)

❑ High power, high forward data rate, low back data rate

Retinal prostheses: Visual stimulation[2]

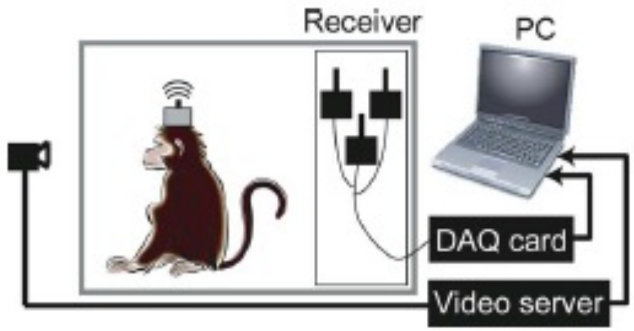
- **Power link**
- Inductive power link; high power transmission (~100mW)
- **Data link**
- Inductive data link
- Data rate: 2Mb/s forward data; 3.3kb/s back data
- Dual-band telemetry



Categorized Applications (Cont.)

❑ **High power, low forward data rate, high back data rate**

HermesC: Neural recording[3]



- **Power link**
- Battery
- High power consumption (63mW)
- **Data link**
- Data rate: preprogrammed forward data; 345kb/s back data modulated by 918MHz carrier
- Frequency-Shift Keying (FSK)

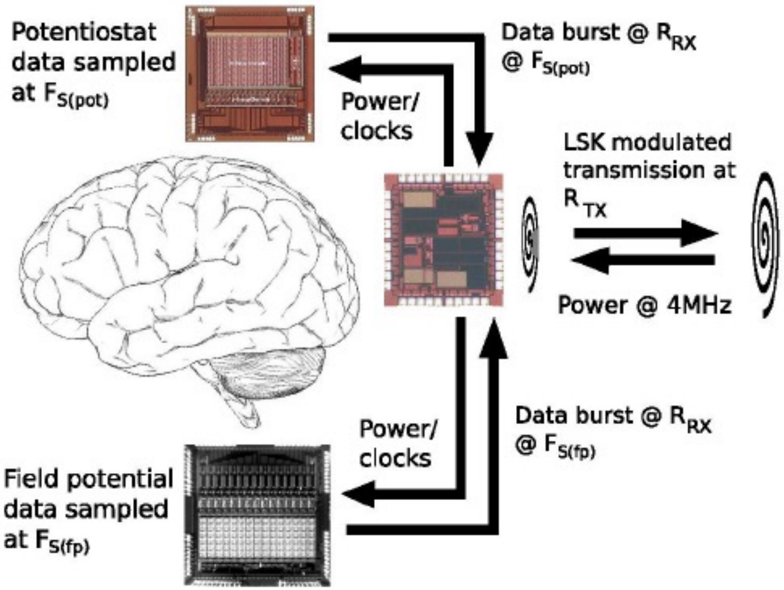
➢ **Low power is possible with efficient data transceiver such as UWB (left the burden to receiver located externally)**

Categorized Applications (Cont.)

❑ **Low power, low forward data rate, low back data rate**

Sensor network [19]

- **Power link**
  - ✓ Inductive link
  - ✓ Low power consumption (6mW)
- **Data link**
  - ✓ Data rate: no forward data; 4kb/s back data
  - ✓ Loading-Shift Keying (LSK)

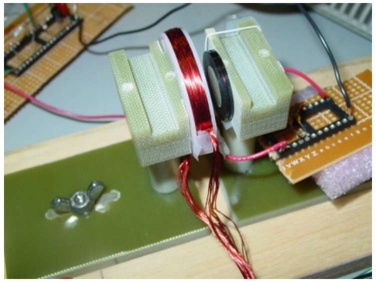


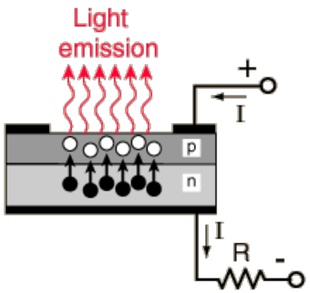
- **RFID**

Power Telemetry

Power Mechanism

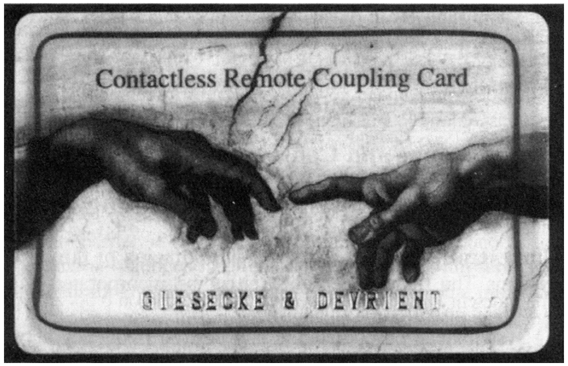
- Battery for Power
  - Easy to operate
  - Limited energy (pacemaker: ~10yrs)
- Physical Coupling
  - Capacitive link
  - Inductive link - Magnetically coupled
    - Theoretically unlimited life time
    - Design, implement, and implant issues
    - Safety concerns
- Optical link - Infrared and laser
  - Green energy
  - Limited efficiency associated with electrical-optical-electrical conversion
  - Safety concerns
- **Self-powered sensor network**
  - Pizoelectric, acoustic, biomotor, heat, etc.
  - Highly dependent on working environment (e.g. light, vibration)
  - Low power supply capability

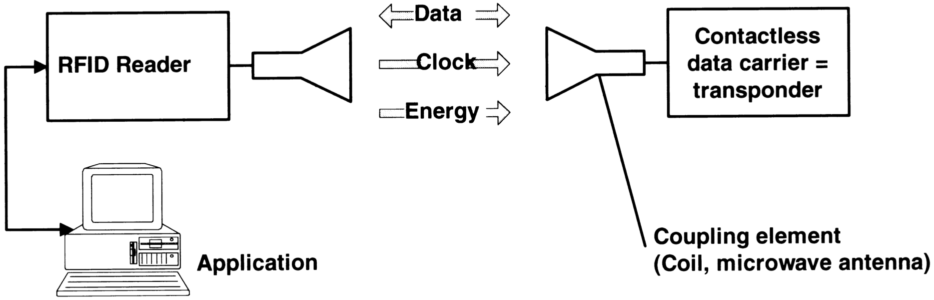


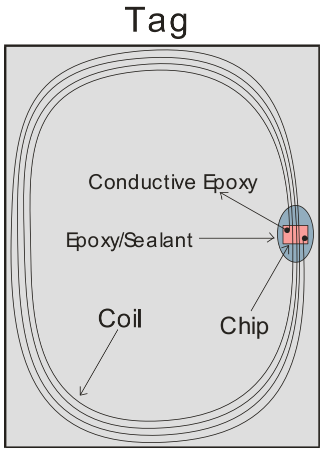


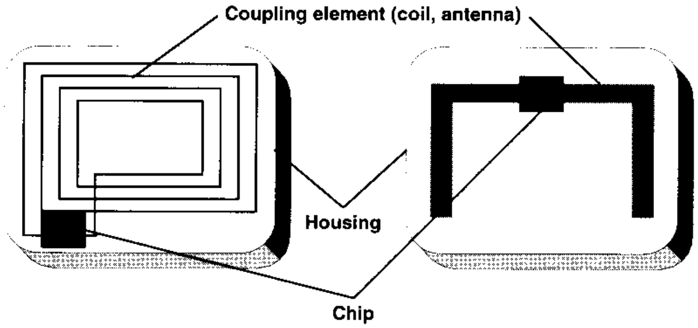
RF Tag/ID System

- Interrogator or "Reader"
  – Device used to read or read/write to the Tag: antenna, electronics and computer
- Transponder or "Tag"
  – Coupling device and chip, located on object to be identified



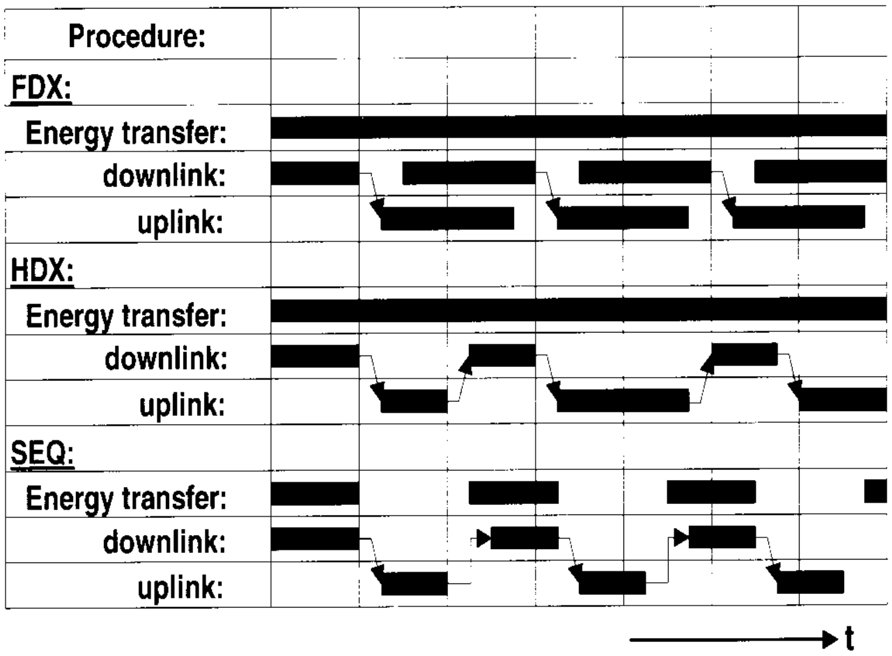






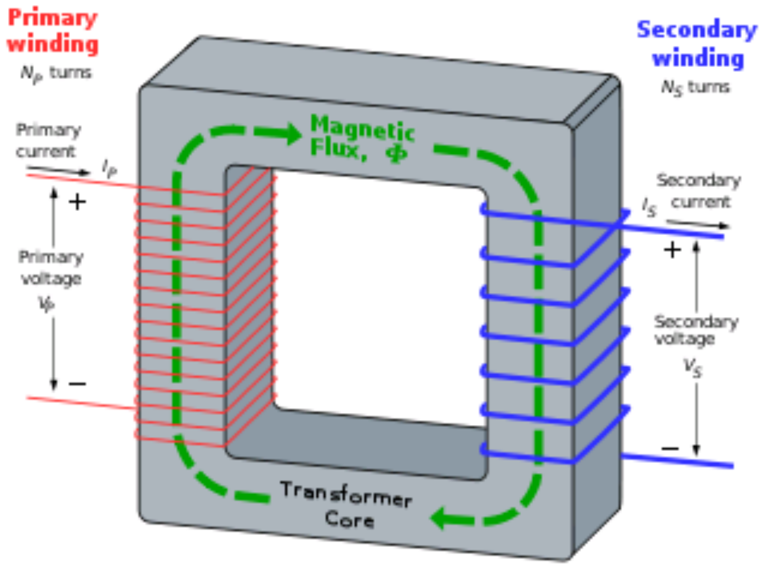
Communication Procedures

- Full-Duplex
  - Simultaneous ‘reader to tag’ and ‘tag to reader’ data flow
- Half-Duplex
  - Alternating ‘reader to tag’ and ‘tag to reader’ data flow
- Sequential
  - Alternating ‘reader to tag’ and ‘tag to reader’ data flow, with power transfer during ‘reader to tag’ communication



Power Mechanism – Inductive Link

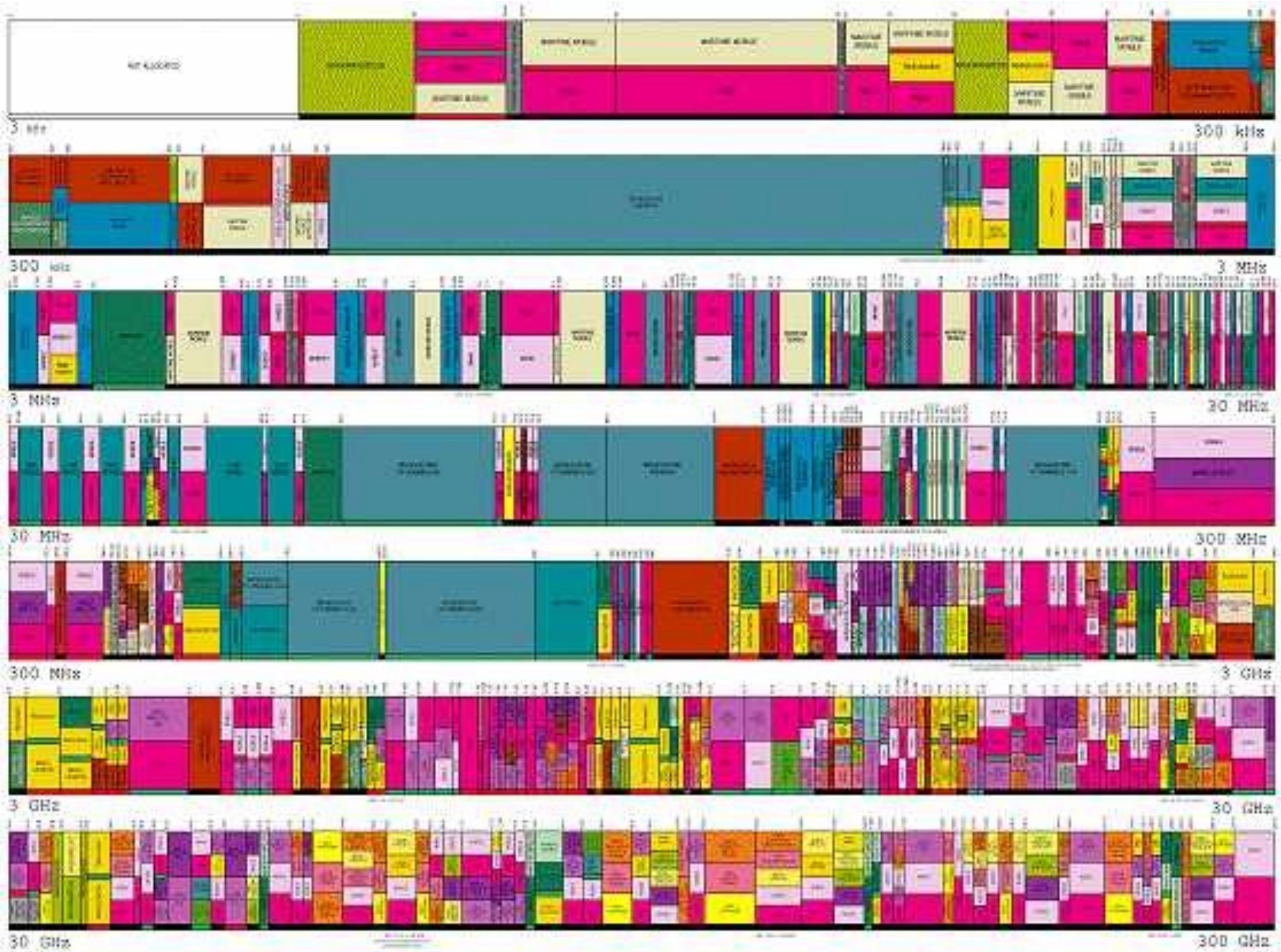
- **Inductive power link**
  - Most popular mechanism in implant applications
  - Theoretically unlimited life time
  - High efficiency if correctly design
  - Suitable for data transmission
  - Distance limitation
  - Orientation sensitive



Device Name	Medical condition or disease	Power Transmission	Data Transmission
Cochlear Implant [Sple99], [Zeng04]	Hearing disorder	Inductive [McD89], [Zier95]	Inductive [McD89], [Zier95]
Cardiac Pacemaker [Sand96]	Heart failure	Battery and Inductive [Sand96] [Nish98]	Inductive [Sand96]
Muscle Stimulator [Qi05], [Grant88]	Muscle (ex. Hand or foot) dysfunction	Inductive and/or battery [Loeb98] [Schul05]	Radio [Schul05] or Inductive [Loeb98]
Retinal Prosthesis [Humayun03a], [Riz97]	Eye disease	Inductive [Liu00]	Inductive [Liu00] or light [Gross99], [Waytt96]
Vagus Nerve Stimulator	Depression [Moor05]	Battery [Gub04]	Not available
Deep Brain Stimulation [Kan04]	Pakinson's disease [dbs-online]	Battery [dbs-online]	Not available
Neural Recording [Tak04], [Hao]	Motion control [Ser02] and others	Inductive [Nei05], [Hao]	RF wave [Tak04] [Nei05]

Power Delivery - Regulatory Issues

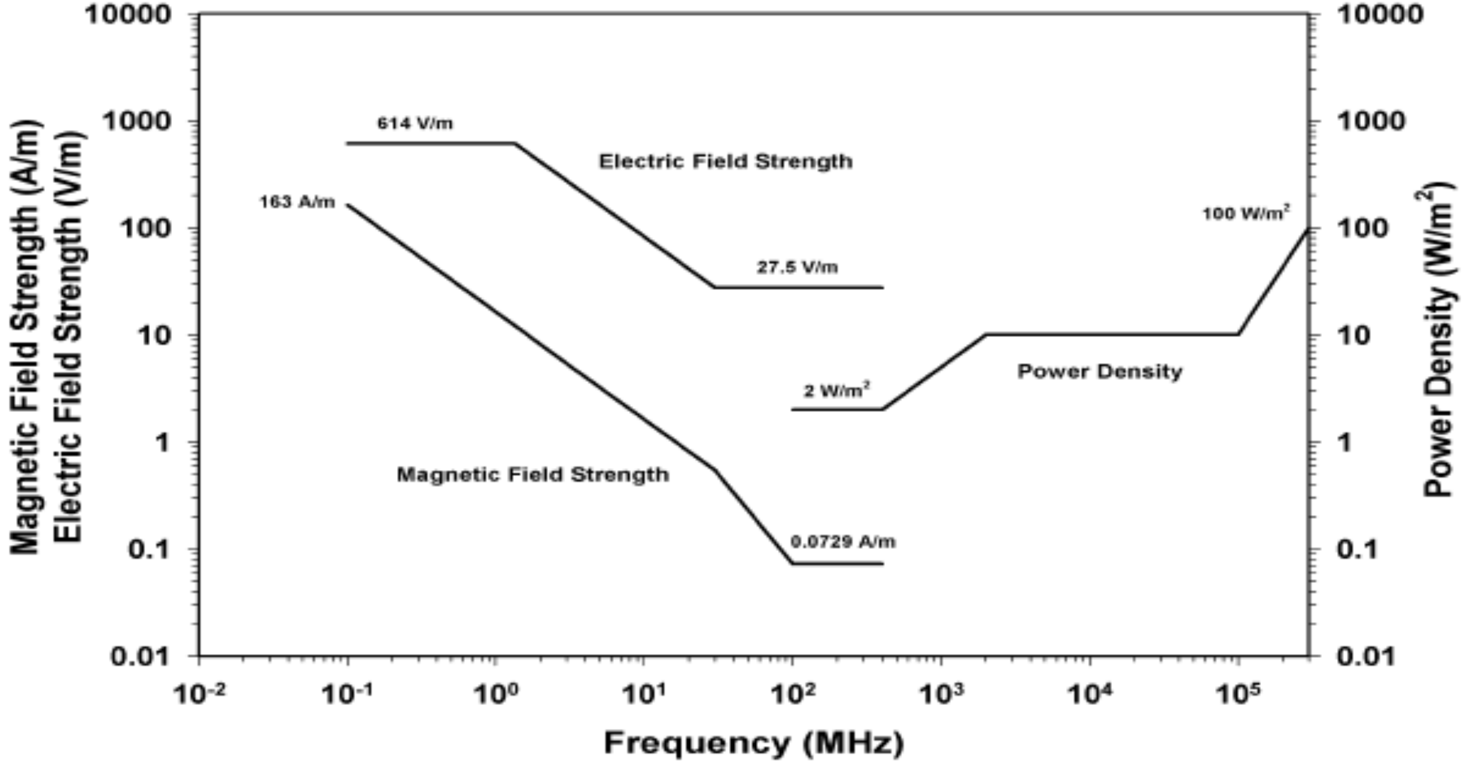
❑ Radio spectrum



Power Delivery - Regulatory Issues

- ❑ **FCC CFR-47-15 – EMI interference limit**
- ❑ **ANSI Z136.1 (Laser Safety Standards)**
- ❑ **Standard IEEE/ANSI C95.1-2005**

- Maximum permissible exposure (MPE): field strength
-



Power Link Design Issues – Regulatory Issues

- IEEE/ANSI C95.1-1999
- Heat generated by the E&M field may damage the tissue

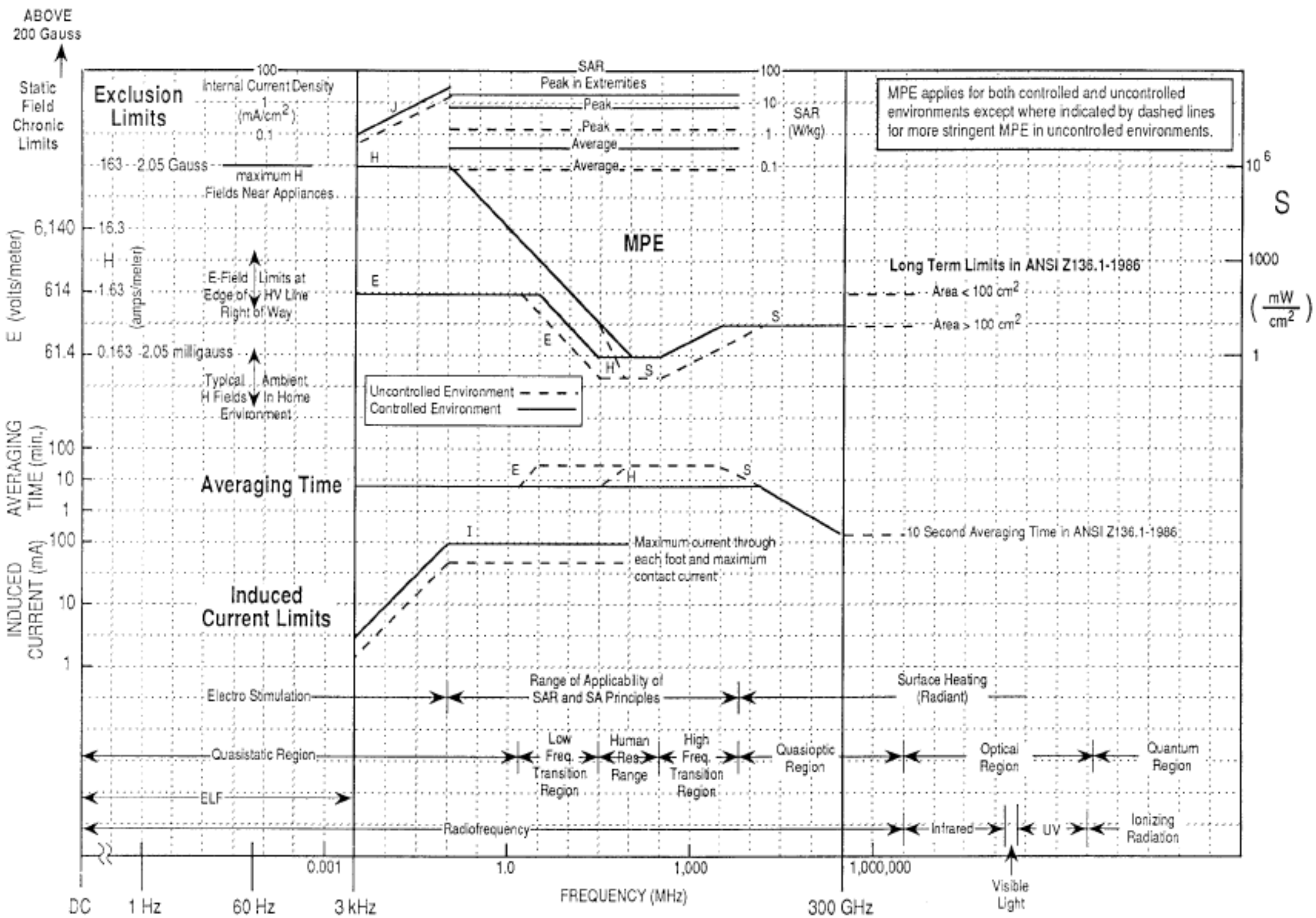


Figure E.1 — Capsule guide to the standard

Physical Principles of Inductively Coupling

- *Near Field* (distance < **$\lambda/2\pi$**) vs *Far Field*
- H field at point x for a short cylindrical coil (near field)

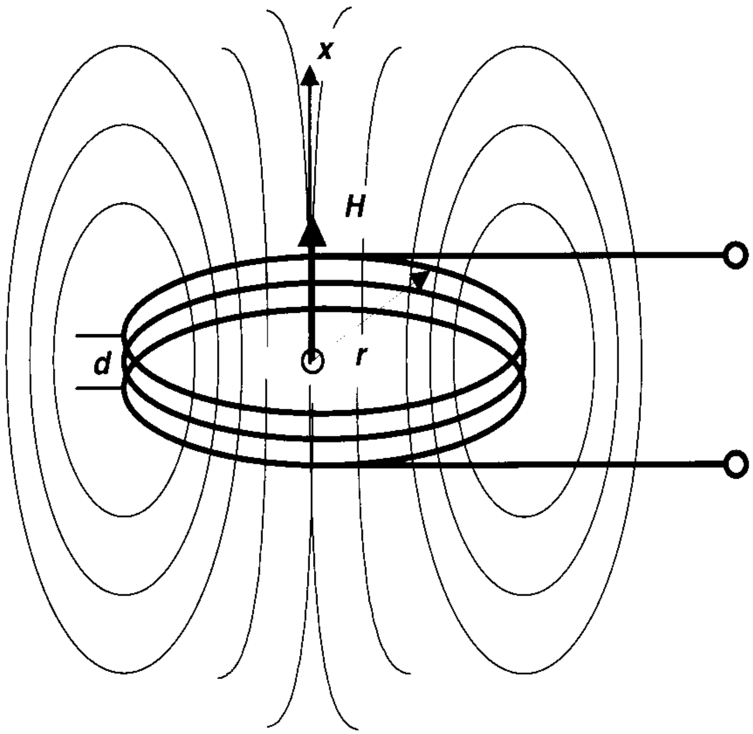
$$H = \frac{INr^2}{2\sqrt{(r^2 + x^2)^3}}$$

N: number of turns

r: circle radius

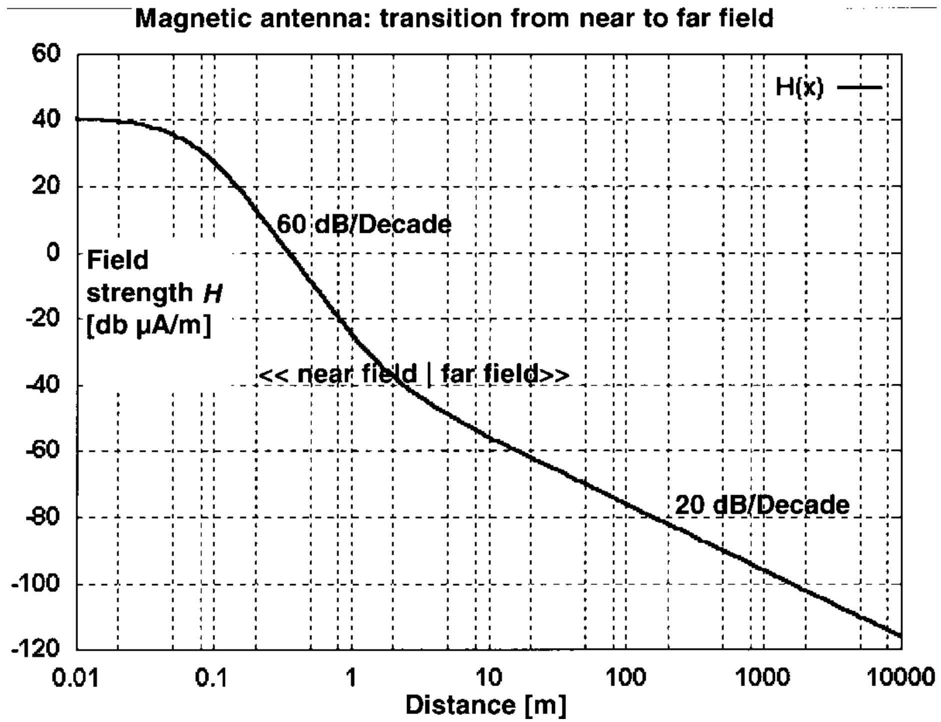
x: distance from center of coil in x-direction

Following conditions apply: d<<r and x<$\lambda/2\pi$ (near field solution)



H-field for Inductively Coupled Systems

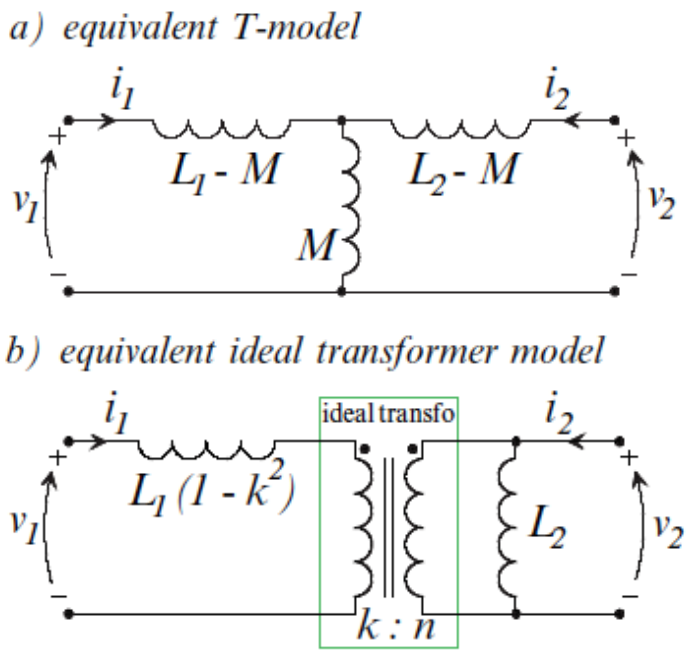
- Magnetic Coil
  - Used at *near field*
- Phase Array
  - *Used at far field*
- Near field boundary
  - 353m at 135kHz
  - 47m at 1MHz
  - 7.1m at 6.78MHz
  - 3.5m at 13.56MHz
  - 1.7m at 27.125MHz



Field strength H vs. distance at a frequency of 13.56Mhz

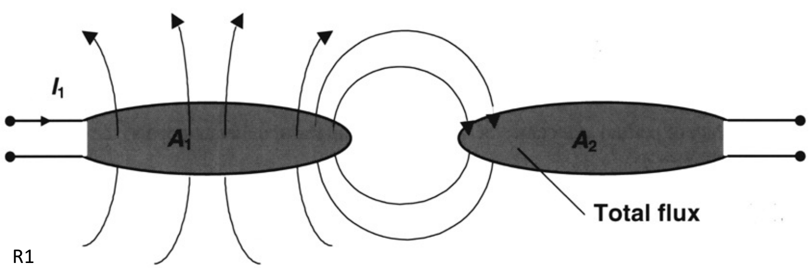
Simple Model for Mutual Coupling

- Basically just transformer action, but more complicated in real cases
- Many equivalent models [ref. 21]
- Mutual Inductance
  - How much of the flux is linked
  - Coupling coefficient – ratio of linked flux
- Self resonant frequency (f_T)
  - Behaves as a coil ($f < f_T$)
  - Otherwise as a capacitor

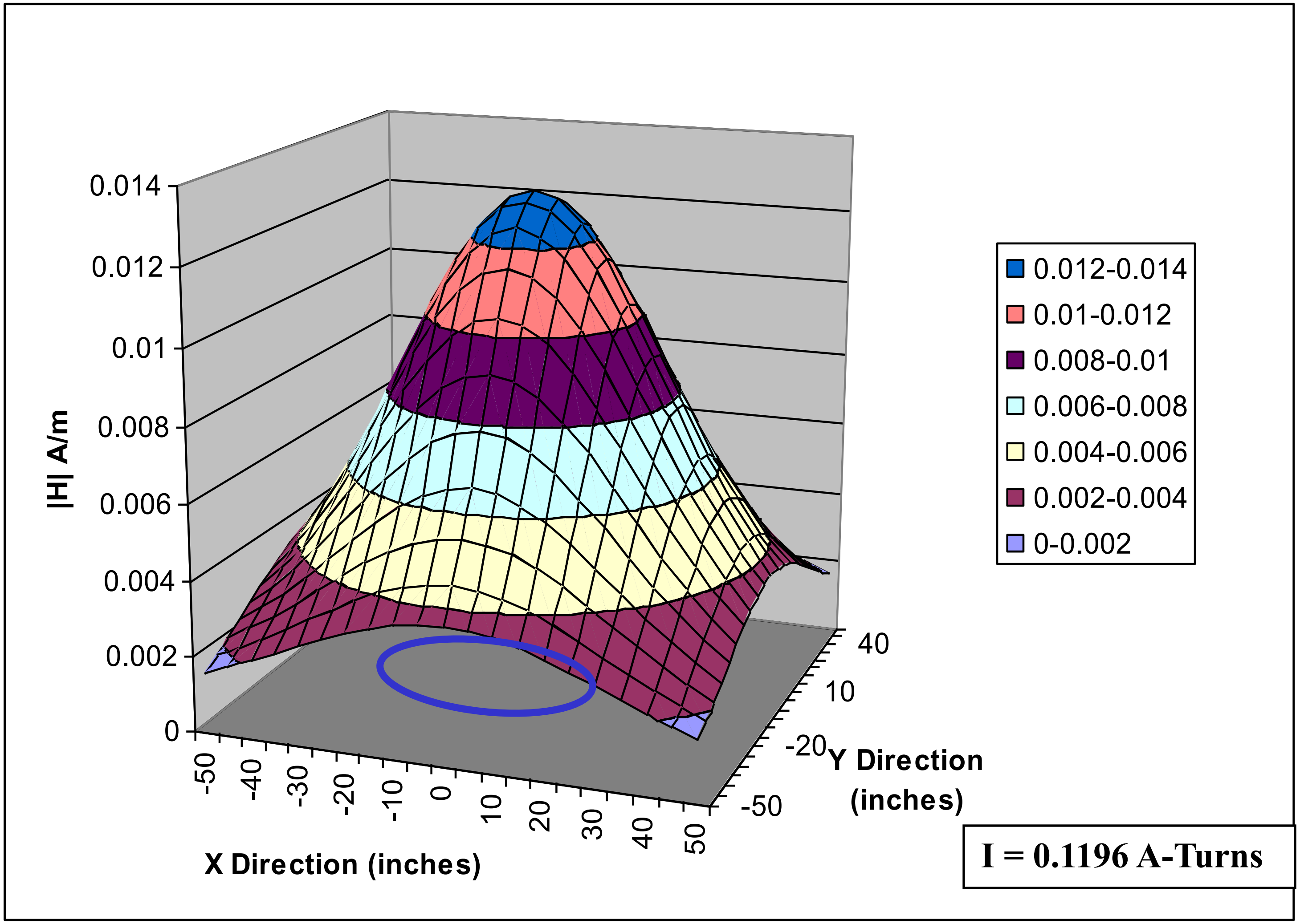


$$k = \frac{M}{\sqrt{L_1 L_2}}$$

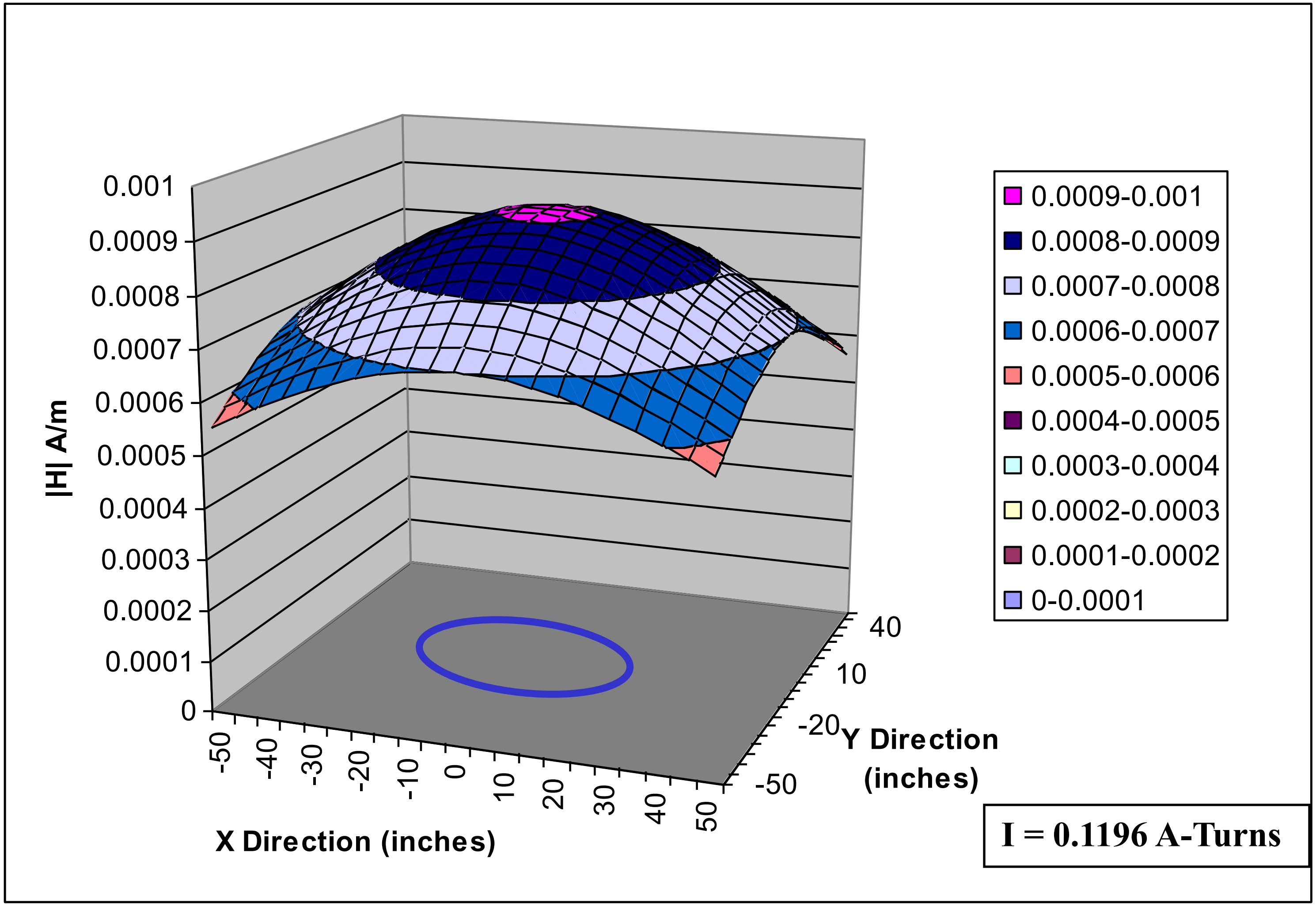
$$n = \sqrt{\frac{L_2}{L_1}}$$



Magnetic Field at 1m - 1m Loop

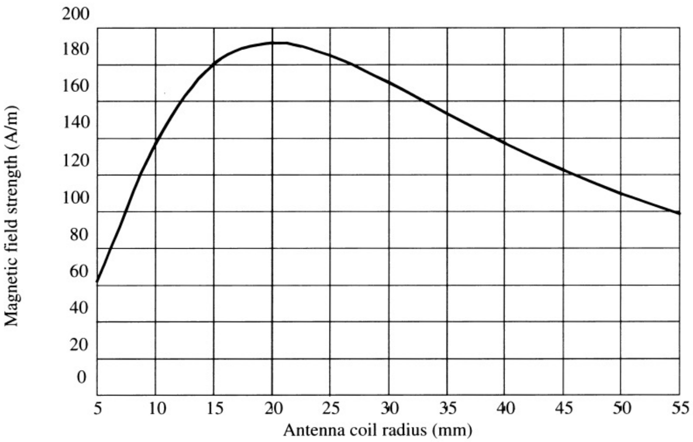


Magnetic Field at 3m - 1m Loop

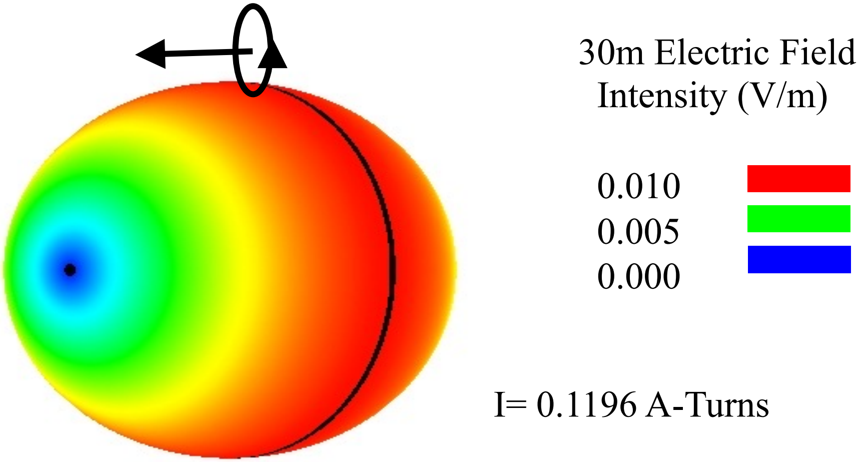


Inductive Coupling

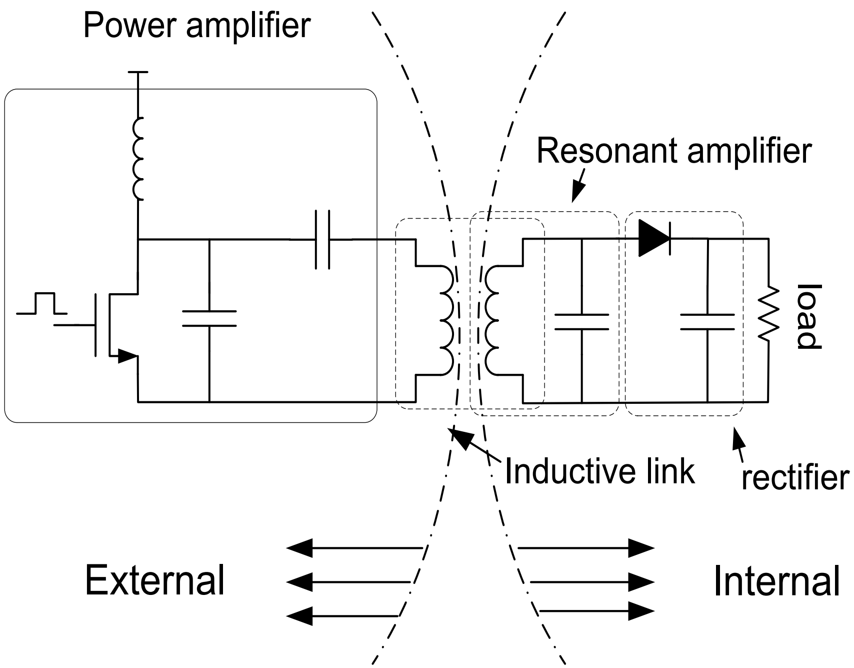
- Optimal antenna radius R for a given range Xmax is: R~Xmax
- Limiting factors to this solution
  - Minimum H-field required for operation
  - Physical size limits on coil loop
  - ANSI regulation (Specific Absorption Rate and magnetic field limit)
  - FCC regulation

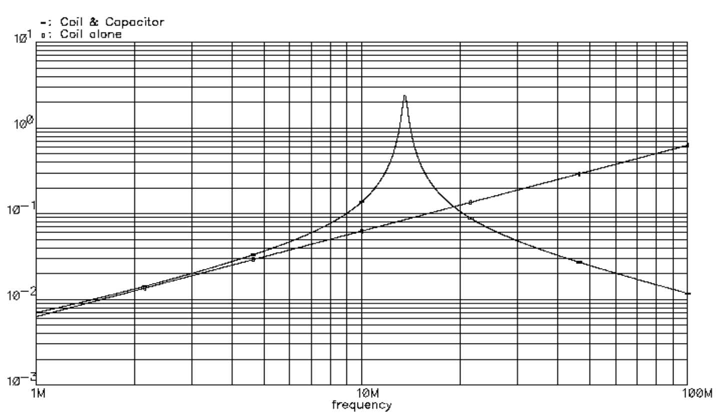


Field Strength H at a distance of x=20mm, where the coil radius R = 5 - 55mm



Inductive Power Link - Overview





Advantages

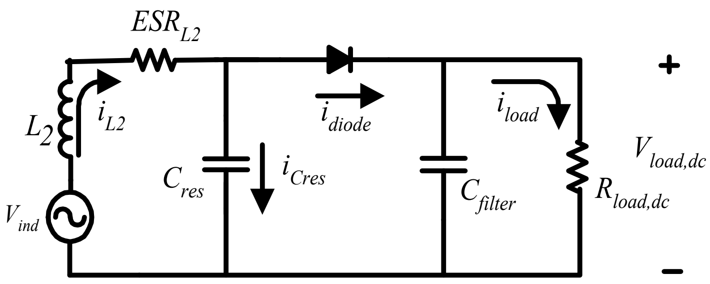
- Two separate units without hardwire connection
- Virtually infinite lifetime
- ***High voltage*** generation is possible via resonant amplification of the AC power
- Enables reverse data transmission to the primary side through load modulation

Disadvantages

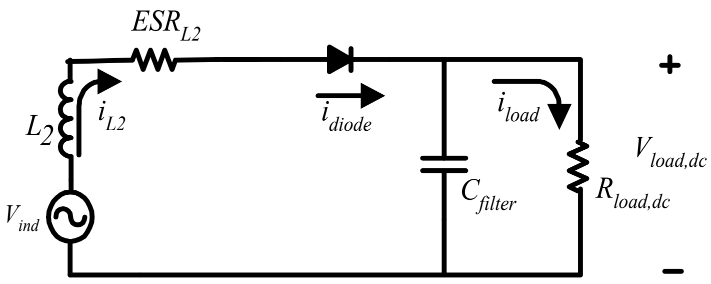
- Large sizes of coils are needed for efficiency
- Extremely inefficient for distances larger than 10 cm (less than 1%)
- Electromagnetic energy deposits in the body
- Susceptible to distance and load variations
- Power is transmitted only in the form of AC thus regulators are necessary for power recovery
- The orientation of the coils is critical

Power Link Design Issues - Two Topologies

Resonant



Non-resonant



- Uses parallel resonant circuit
- Can generate high voltage with a smaller magnetic field
- Resonant currents cause extra loss on the driver therefore needs thicker wires and thus larger space
- The resonant capacitor comes as an additional to the circuit and in most cases as an external component
- Should be used when high voltage is necessary from a small magnetic field

- Feeds the induced voltage directly to the load
- Needs larger magnetic fields
- Because the coil current is only the load current, the coil can be implemented by thin wires resulting in smaller coil area
- Should be used only when the coil size is extremely limited and should be refrained from otherwise

Inductive Link - Limitations

Coil sizes

- Biomedical compatibility on the secondary side
- Aesthetic and convenience issues on the primary side

Power dissipation on the coils

- Efficiency
- Overheating on the primary side and the secondary side

Circuit size

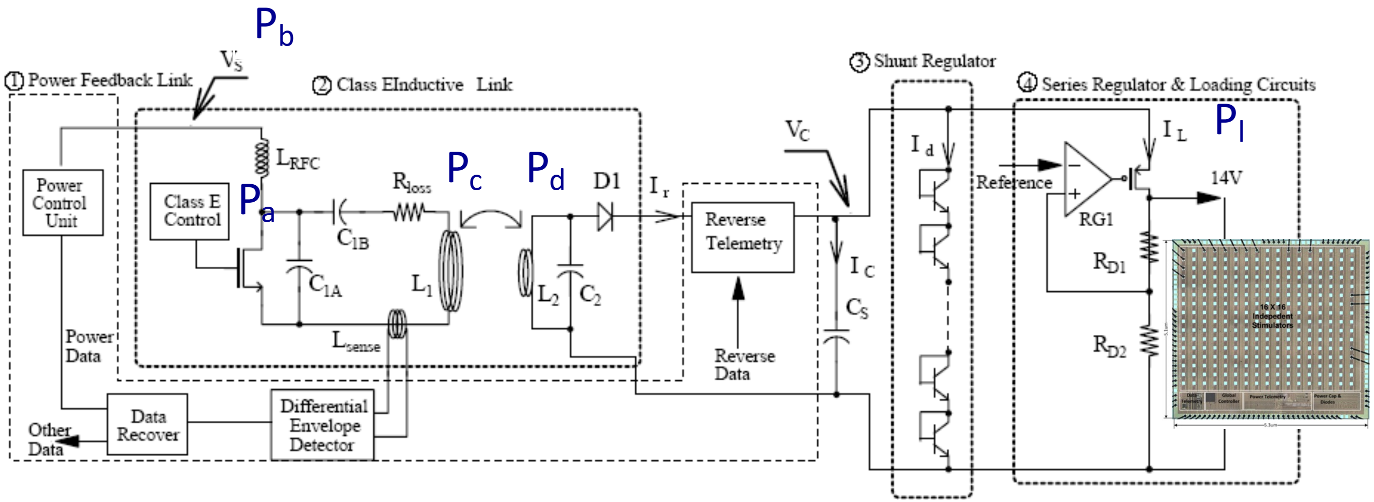
- Secondary side needs a number of circuit elements which sometimes have to be off-chip (i.e. resonant capacitor, filter capacitor, rectification diodes, etc.)
- Accommodate stimulation/recording requirements

Electrical and Magnetic field limitation

- High frequency E&M field causes heat generation on the tissue and is a health concern.

Optimal Design Problem – Power Link

- The design problem is to optimize the overall power efficiency subject to the constraints of H-field, E-field, Specific Absorption Rate, and physical dimensions.
- Critical factors – power transfer efficiency η_{coil} and $\eta_{rectifier/regulator}$



$$\text{Overall Efficiency} = \frac{P_a}{P_b} \times \frac{P_c}{P_a} \times \frac{P_d}{P_c} \times \frac{P_l}{P_d}$$

$$\eta_{battery} \times \eta_{power\text{-}amplifier} \times \eta_{coil} \times \eta_{rectifier/regulator}$$

Inductive Link Design Methodology

❑ Inductive link design issues

- Power and data interactions
- High efficient power amplifier design
- Coil design – external and implant sides
- Resonant amplification circuitry
- Rectifier/regulator
- Adaptive power control link
- Safety Issue

Optimal Inductive Link Design Principle

❑ **Power efficiency** is the critical factor for power link design

Approximation of power efficiency [4]

$$\eta = \frac{k^2 Q_1 Q_2}{[1+\sqrt{1+k^2 Q_1 Q_2}]^2}$$

η: power efficiency, defined as the power received by secondary side divided by the power extracted from primary battery

k: coupling coefficient between primary and secondary coils

Q_1, Q_2: quality factors of primary and secondary coils, respectively

- **η is a function of *k* and Q**

➡ **Maximize *k* and Q to obtain maximal power efficiency**

❑ Constraints

- **Coil size**: biomedical compatibility at the implant side
- **Power dissipation** on the coils: power efficiency and overheating
- **Off-chip components** at implant side (i.e. capacitors, diodes)
- **Regulatory compliance –** E/H- field, SAR

Design Methodology - Power/Data Telemetry

❑ Power/data telemetry [5]

- **For power link**: higher Q coil targets at higher power efficiency
- **For data link**: higher Q coil takes longer transition time

$$Q = 2\pi \cdot \frac{\text{energy stored}}{\text{energy dissipated in each cycle}}$$

➡ Higher Q, more stored power

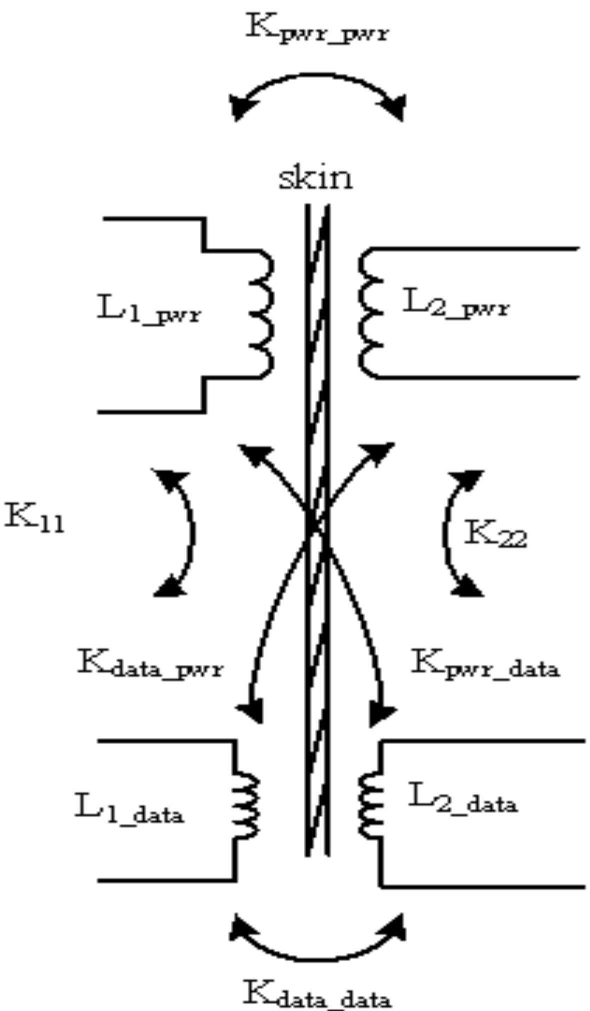
➡ Changing circuit condition, representing for data, takes longer time which results in lower data rate.

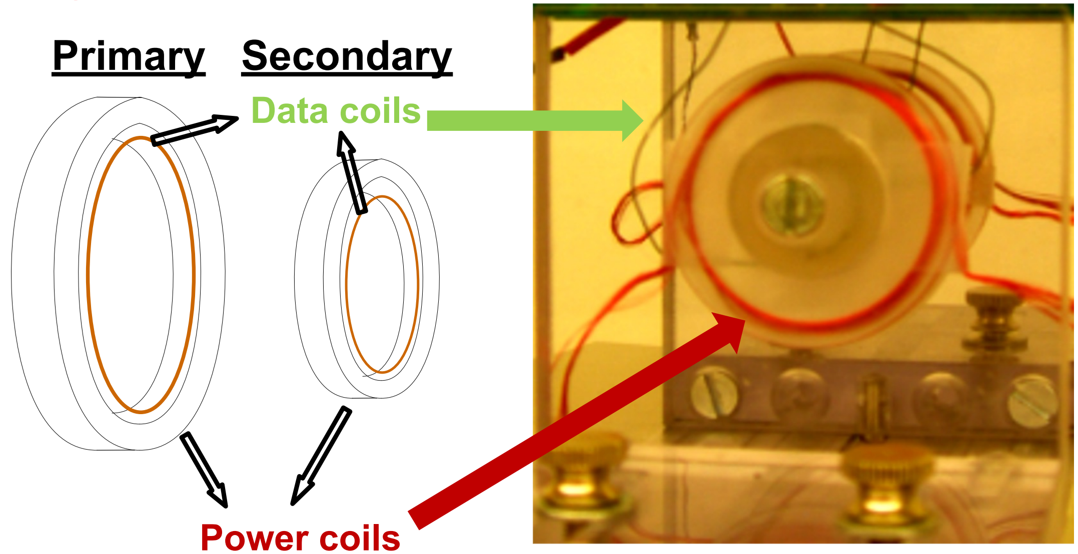
➢ **Solution**: **Dual-band telemetry**

1) Separated inductive coupling links are used as power and data transmission links
2) Higher Q coil for power link with lower working frequency
3) Lower Q coil for data link with higher working frequency

Design Methodology – Dual Band Telemetry

❑ Dual-band telemetry



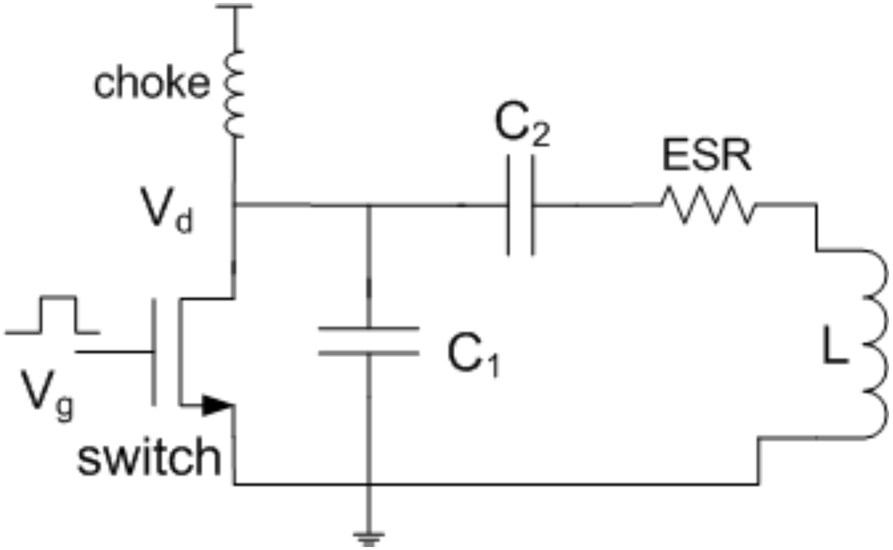


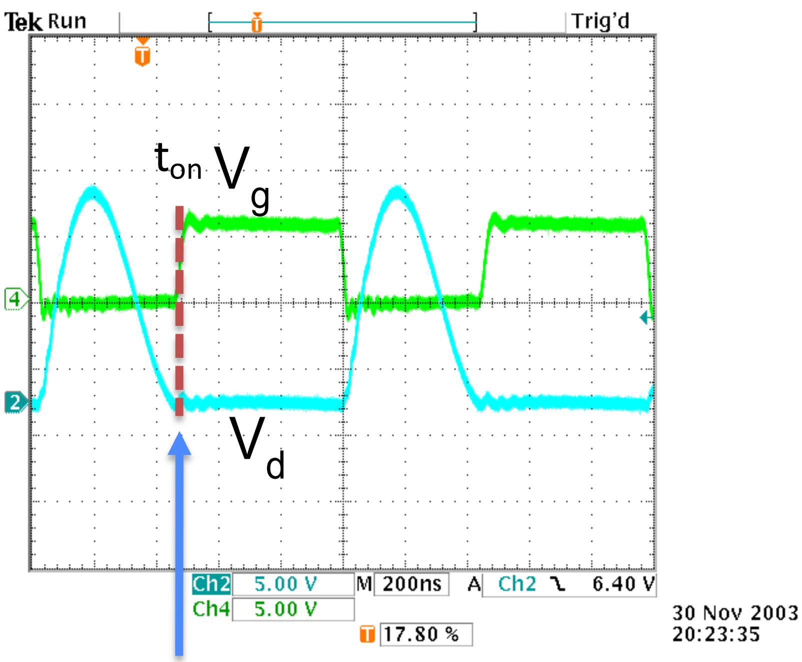
- 2 carrier frequencies; 4 coils; 6 coupling
- **Advantage**: High data rate and high power efficiency simultaneously
- **Disadvantage**: Strong power interference (PI) from power link to data link

Power interference (PI) cancellation scheme is needed for data receiver

Design Methodology - Power Amplifier

❑ Class-E power amplifier [6]





- **zero** turn-on voltage
- **zero** turn-on voltage derivative

▪ **Advantages**

1) Need only one active device
2) Theoretically 100% efficiency; practically 95% efficiency is achievable
3) Operates at low supply voltage

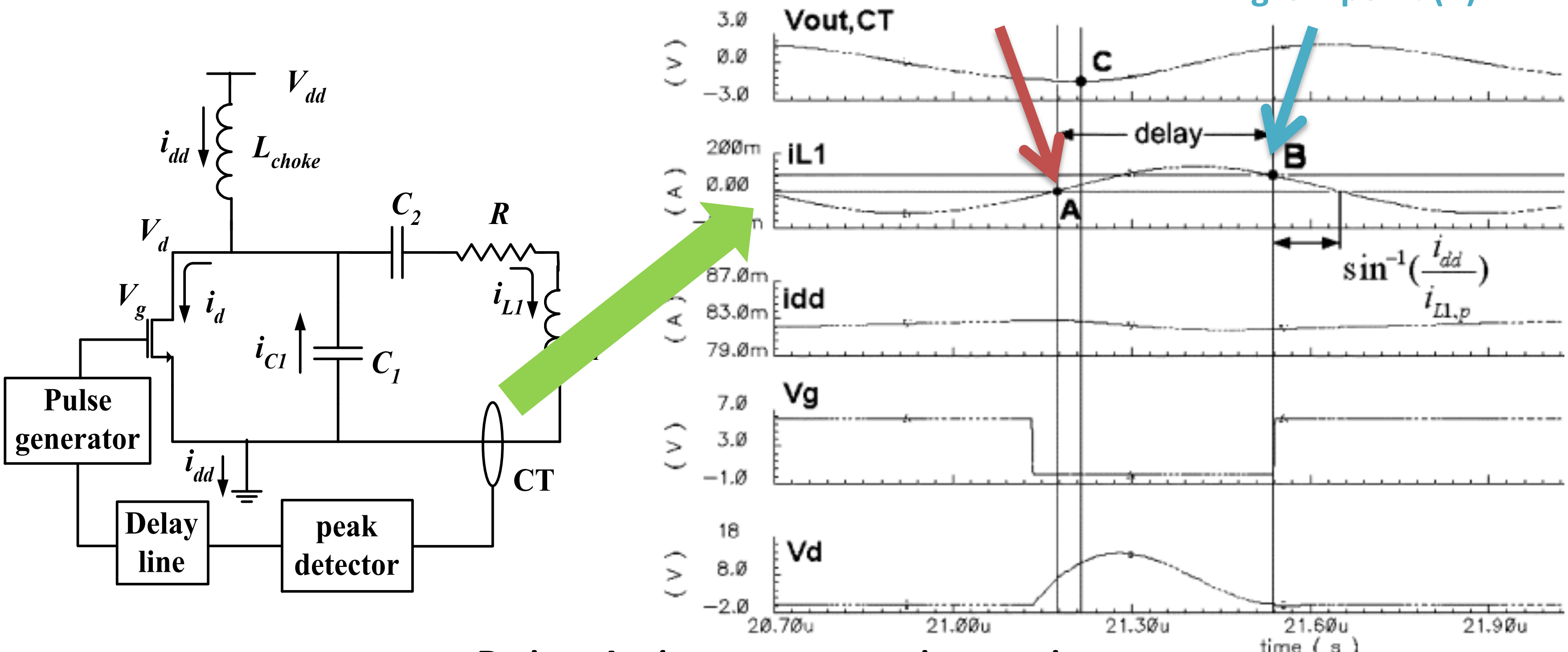
▪ **Disadvantages**

1) Subject to input frequency and component variations
2) C1 increases the switching loss under mistuned conditions

Design Methodology - Class-E Power Amplifier

❑ Closed-loop control Class-E amplifier[6]

- To increase the tolerance of the Class-E amplifier due to the component variations (e.g. inductance change)

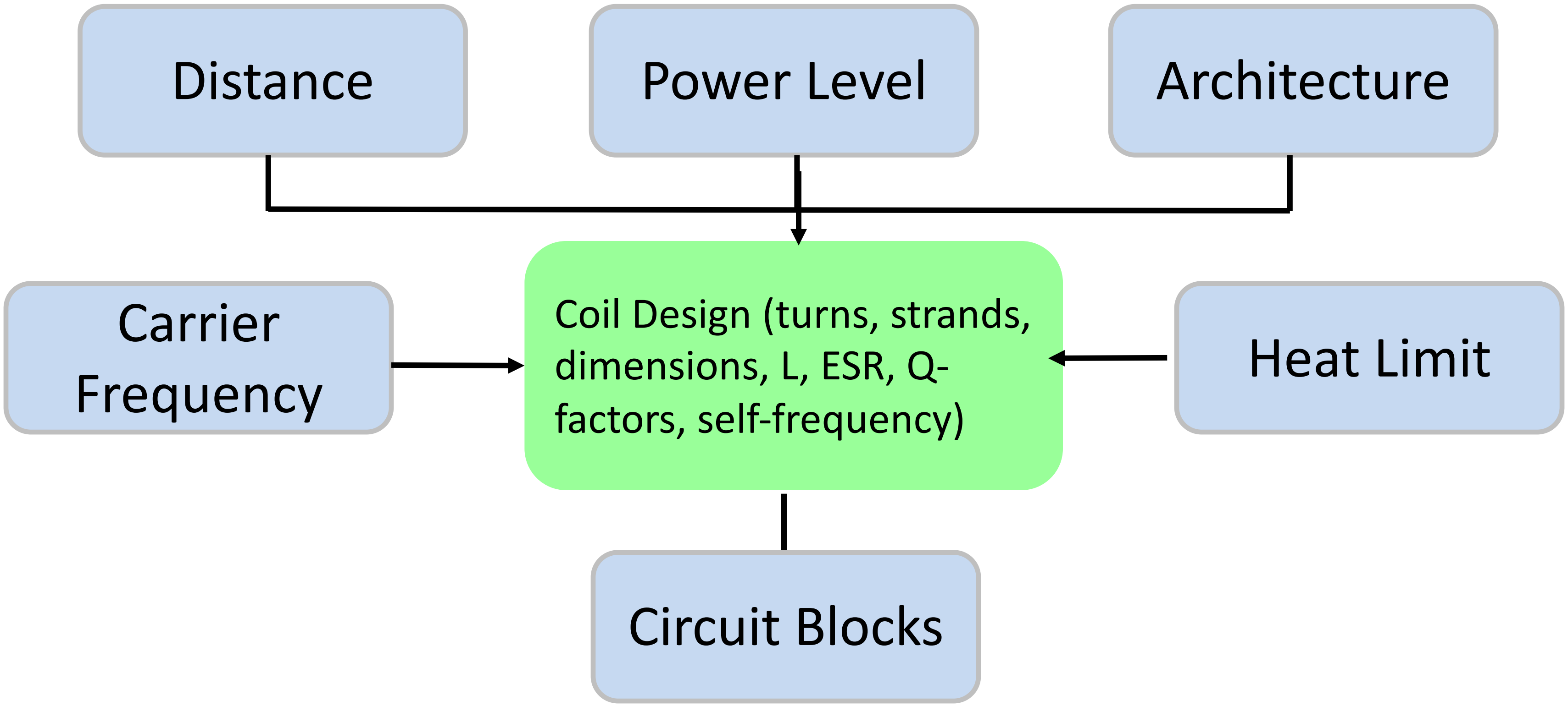


Point A: i_{L1} zero crossing point

Point B: $i_{C1} = 0$ → **V_g is turn on at this point**

$$\text{delay} = \frac{T}{2\pi}\left(\pi - \sin^{-1}\left(\frac{i_{dd}}{i_{L1,p}}\right)\right)$$

Design Methodology - Coil Design

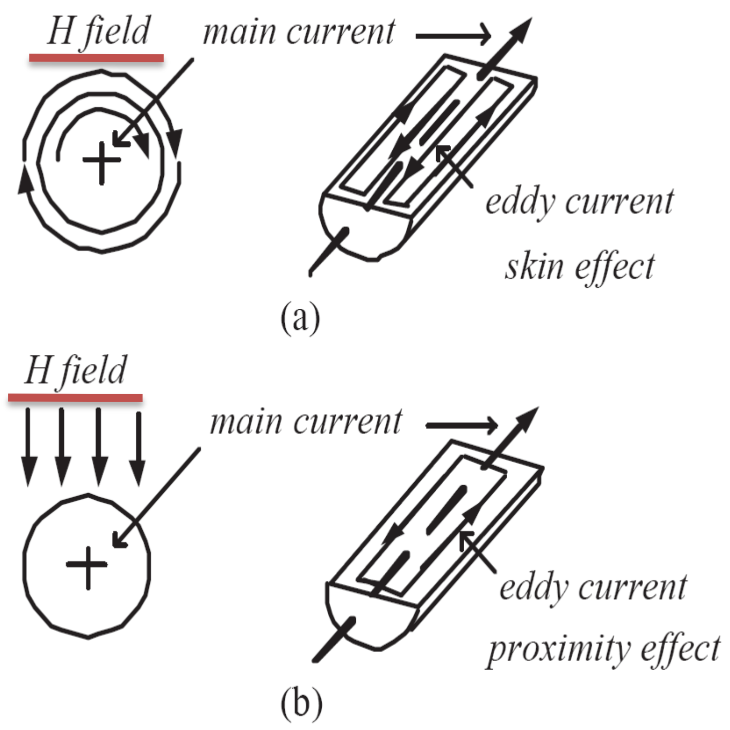


❑ Coil design

- Most critical component with respect to power efficiency
- Most critical component related to transmission range

Coil Design - Frequency Dependence Effects [7]

❑ Skin and Proximity effect



Skin effect

Current density near the surface of the conductor is greater than that at its core

Proximity effect

Magnetic field generated by one inductor induces eddy current in adjacent conductors, altering the overall distribution of flowing currents

➢ **Coil characteristics at high frequency is much more complex**

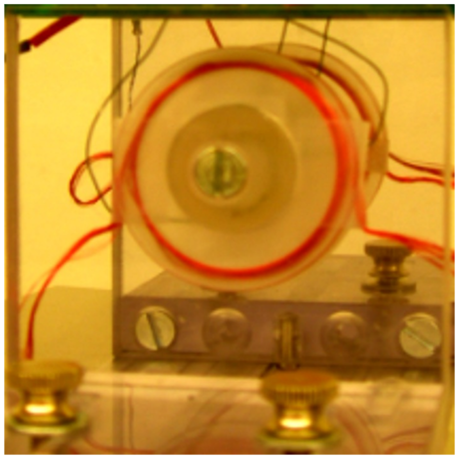
Design Methodology - Coil Design Paramters

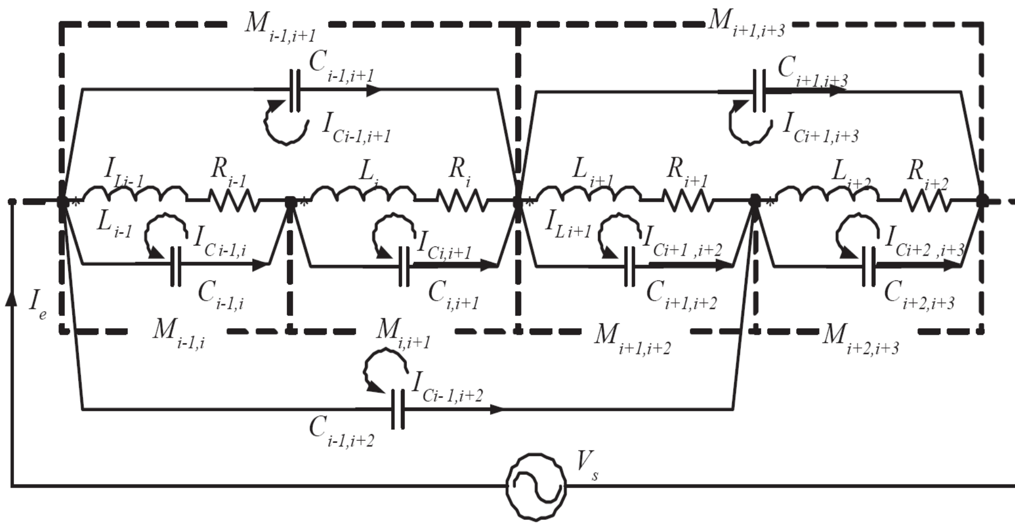
- **Coil design parameters** [7]
  - *Self-resonant frequency (f_{self})*
  - *Inductance*
  - *Effective serial resistance (ESR)*
  - *Quality Factor – Q*
  - *Coupling coefficient - K*
  - *Power amplifier parameters - such as Class-E*

- **Coil design app available in Biomimetric Research Lab at UCLA**
  - *Support 3-D shape and geometry*
  - *Accurately calculate the parameters*

Coil Design - Advanced Coil Model (1) [7]

❑ Distributive equivalent model





- ***Self-resonant frequency (f_{self})*** **– analytical solution**

$$\omega_{self} = \frac{A \pm B}{G}$$

$$A = R_i \angle 90^\circ \sum_{p<k} C_{p,k}(k-p)$$

$$B = \sqrt{\frac{1}{1-\alpha} 4L_i \sum_{p<k} C_{p,k}(k-p)^2 - R_i^2 \left[\sum_{p<k} C_{p,k}(k-p)\right]^2}$$

$$G = 2L_i \sum_{p<k} C_{p,k}(k-p)^2.$$

➢ **Coil should be designed to work at frequency less than self-resonant one in order to guarantee good inductive performance**

Coil Design - Advanced Coil Model (2) [7]

- ***Inductance*** **– analytical solution**

$$L_{eff} = \frac{L_{DC}}{1 - \frac{f^2}{f_{self}^2}}$$

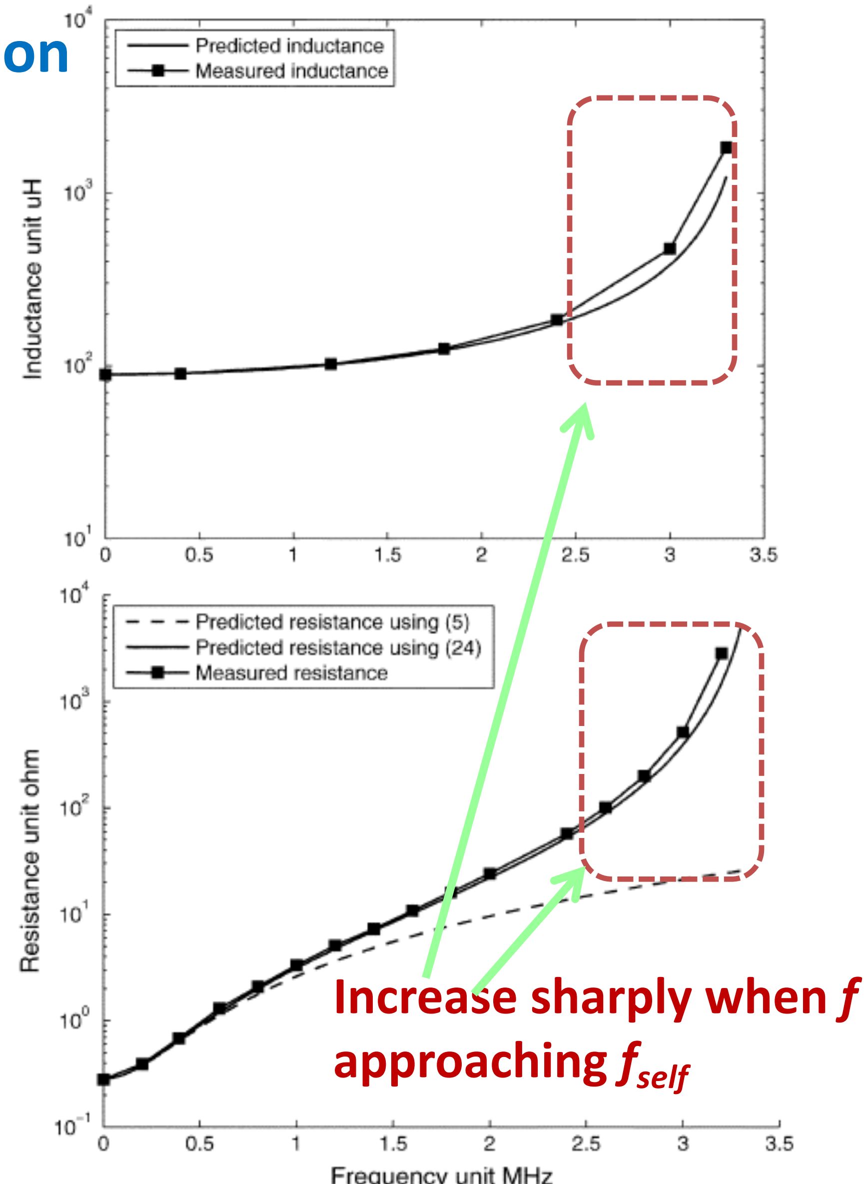
$$L_{DC} = N^2 L_{unit}$$

- ***Effective serial resistance (ESR)*** **– analytical solution**

$$ESR = \frac{R_{AC}}{(1 - \frac{f^2}{f_{self}^2})^2}$$

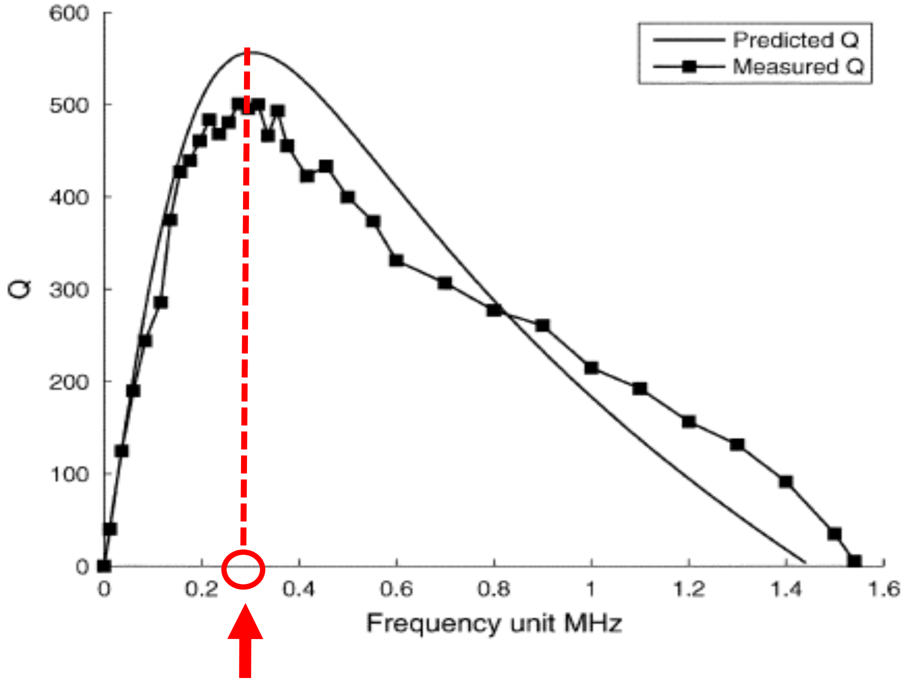
$$R_{AC} = R_{DC}(1 + \frac{f^2}{f_h^2})$$

$$f_h = \frac{2\sqrt{2}}{\pi r_s^2 u_0 \sigma \sqrt{N_t N_s \eta \beta}}$$



Coil Design: Advanced Coil Model (3) [7]

- ***Quality factor (Q)*** **– analytical solution**



$$Q(f) \approx 2\pi f L \left(1 - \frac{f^2}{f_{\text{self}}^2}\right) \Big/ R_{\text{DC}} \left(1 + \frac{f^2}{f_h^2}\right)$$

$$f_h = \frac{2\sqrt{2}}{\pi r_s^2 \mu_0 \sigma \sqrt{N_t N_s \eta \beta}}$$

F_{opt} - Optimal frequency for Q

Power carrier selection should take into consideration of f_{opt} !

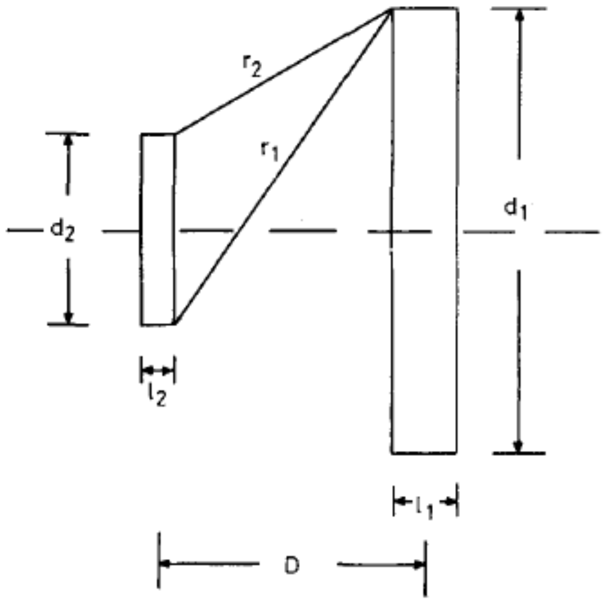
Coil Design - Advanced Coil Model (4)

- ***Coupling coefficient (k)*** **– no analytical solution but software package exists for any given 3D geometry**

  K is a major parameter that influences power efficiency

  1) defined by the flux coupling of two inductor loops
  2) is a function of **geometry** and **distance** of two inductor loops

For simple configurations such as parallel inductor loop [4][20]



$$k = \frac{d_1^2 d_2^2}{\sqrt{d_1 d_2}\left(\sqrt{d_1^2 + D^2}\right)^3} \quad \text{for } d_1 > d_2$$

Coupling between these two coils is maximized when

$$d_1^2 = d_2^2 + 4D^2$$

Optimal Design Problem – Power Link

- **Optimal design based on one equation with multiple variables to find out the optimal value of L_1, d_1, L_2, d_2**

- **Here are useful equations [21]**

$$k = \frac{d_1^2 d_2^2}{\sqrt{d_1 d_2}\,(\sqrt{d_1^2 + D^2})^3} \quad \text{for } d_1 > d_2$$

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2 + \dfrac{Q_2}{Q_{load}}} \times \frac{1}{1 + \dfrac{Q_{load}}{Q_2}}$$

$$\eta^{opt} = \frac{k^2 Q_1 Q_2}{\left[1 + \sqrt{1 + k^2 Q_1 Q_2}\right]^2} \quad \text{if}$$

$$Q_{load}^{opt} = \frac{Q_2}{\sqrt{1 + k^2 Q_1 Q_2}} = \frac{R_{load}}{\omega L_2^{opt}}$$

$$L_2^{opt} = \frac{R_{load}\sqrt{1 + k^2 Q_1 Q_2}}{\omega Q_2}$$

Optimal Design Problem – Power Link

➢ Example

$$d_1^2 = d_2^2 + 4D^2$$

$$d_2 = 0.5cm,\ D = 5cm,\ d_1 = 10cm,\ \text{L2=1uH}$$

$$\text{Q}_1 = 70,\ Q_2 = 70,\ R_{load} = 2.4K\Omega,\ Q_{load} = \frac{R_{load}}{\omega L_2} = 200$$

$$k = \frac{d_1^2 d_2^2}{\sqrt{d_1 d_2}(\sqrt{d_1^2 + D^2})^3} = 0.007 = 0.7\%$$

$$\eta^{opt} = \frac{k^2 Q_1 Q_2}{\left[1 + \sqrt{1 + k^2 Q_1 Q_2}\right]^2} = 0.056 = 5.6\%$$

$$Q_{load}^{opt} = \frac{Q_2}{\sqrt{1 + k^2 Q_1 Q_2}} = \frac{R_{load}}{\omega L_2^{opt}}$$

$$L_2^{opt} = \frac{R_{load}\sqrt{1 + k^2 Q_1 Q_2}}{\omega Q_2}$$

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2 + \frac{Q_2}{Q_{load}}} \times \frac{1}{1 + \frac{Q_{load}}{Q_2}} = \frac{0.25}{1 + 0.25 + \frac{70}{200}} \times \frac{1}{1 + \frac{200}{70}} = 0.022 = 2.2\%$$

Optimal Design Problem – Power Link

Example

$$d_1^2 = d_2^2 + 4D^2$$

$$d_2 = 0.5cm,\ D = 2cm,\ d_1 = 4cm,\ \mathrm{L}_2 = 1uH$$

$$\mathrm{Q}_1 = 70,\ Q_2 = 70,\ R_{load} = 2.4K\Omega,\ \omega\text{=2MHz},\ Q_{load} = \frac{R_{load}}{\omega L_2} = 200$$

$$k = \frac{d_1^2 d_2^2}{\sqrt{d_1 d_2}\left(\sqrt{d_1^2 + D^2}\right)^3} = 0.04 = 4\%$$

$$\eta^{opt} = \frac{k^2 Q_1 Q_2}{\left[1 + \sqrt{1 + k^2 Q_1 Q_2}\right]^2} = 0.5 = 50\%$$

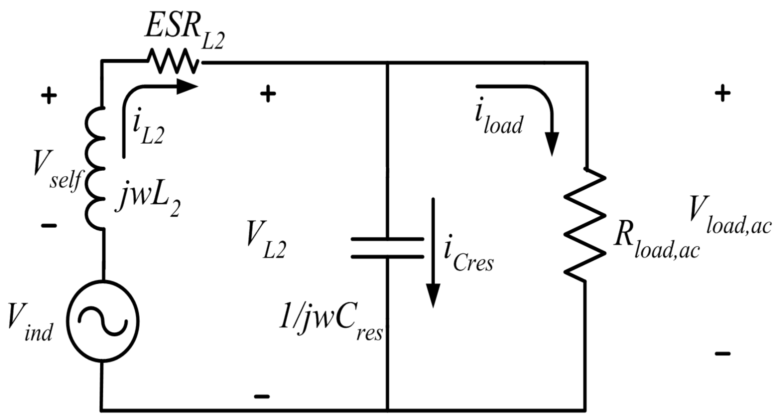
$$Q_{load}^{opt} = \frac{Q_2}{\sqrt{1 + k^2 Q_1 Q_2}} = \frac{R_{load}}{\omega L_2^{opt}}$$

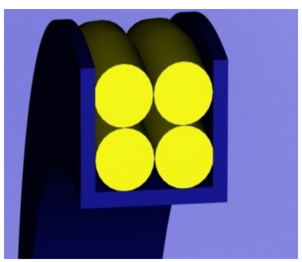
$$L_2^{opt} = \frac{R_{load}\sqrt{1 + k^2 Q_1 Q_2}}{\omega Q_2}$$

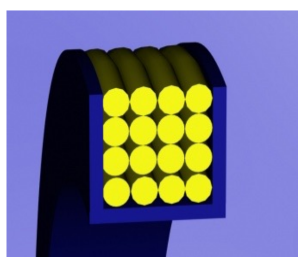
$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2 + \frac{Q_2}{Q_{load}}} \times \frac{1}{1 + \frac{Q_{load}}{Q_2}} = \frac{8}{1 + 8 + \frac{70}{200}} \times \frac{1}{1 + \frac{200}{70}} = 0.22 = 22\%$$

Coil Design: Design Tradeoff

Coil design tradeoff







Neglecting skin effect

N_1=4	N_1=16
L_1=L	L_1=L*16
ESR_{L2}=R	ESR_{L2}=16*R

Very Small L_2

$$\frac{1}{\omega C_{res}} << R_{load,ac}$$

$$i_{load} << i_{Cres}$$

$$i_{L2} = i_{Cres} \propto \frac{1}{1/\omega C_{res}} = \frac{1}{\omega L_2}$$

$$ESR_{L2} \propto \sqrt{L_2}$$

$$loss = i_{L2}{}^2 \times ESR_{L2} \propto \frac{1}{L_2\sqrt{L_2}}$$

$$Q_s = \frac{\omega L_2}{ESR_{L2}} = \sqrt{L_2}$$

$$V_{ind} = \frac{V_{load,ac}}{Q_s} = \frac{1}{\sqrt{L_2}}$$

$$H_{ind} \propto \frac{V_{ind}}{N_2} \propto \frac{1}{L_2}$$

Very Large L_2

$$\frac{1}{\omega C_{res}} >> R_{load,ac}$$

$$i_{load} >> i_{Cres}$$

$$i_{L2} = i_{load} = cons$$

$$ESR_{L2} \propto \sqrt{L_2}$$

$$loss = i_{L2}{}^2 \times ESR_{L2} \propto \sqrt{L_2}$$

$$Q_p = \frac{R_{load,ac}}{\omega L_2} \propto \frac{1}{L_2}$$

$$V_{ind} = \frac{V_{load,ac}}{Q_p} \propto L_2$$

$$H_{ind} \propto \frac{V_{ind}}{N_2} \propto \frac{L_2}{\sqrt{L_2}} \propto \sqrt{L_2}$$

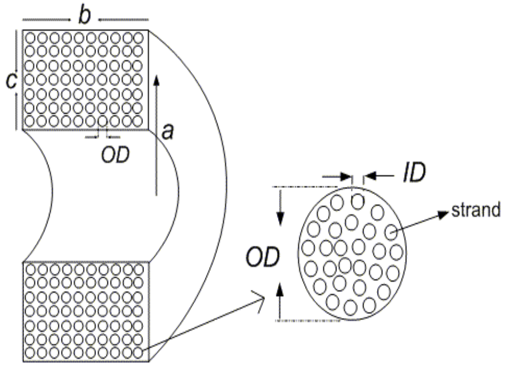
Optimums exist for the loss and H-field between two extremes

Coil Design: Procedure (1)[5,6]

◆ 1 - Select the optimal coupling parameters

Specify the geometry constraints including secondary coil diameter and targeting distance, then select primary coil diameter using

$$d_1^2 = d_2^2 + 4D^2$$

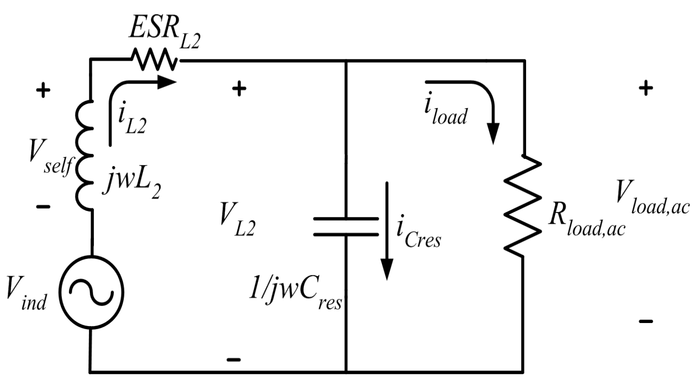


◆ 2 - Conduct the secondary coil design (by received power and voltage level)

- Calculate unit inductance (1 turn) of L_1 and L_2 - L_{2unit} and L_{1unit}
- Plot both figures of loss and H field vs L_2 based on equations below

$$loss = \frac{V_{load} \times 2\pi a \times \rho}{\omega^2 L_{2unit}^2 \times N_2^2 \times b \times c \times K_s}$$

$$H_{ind} = \frac{V_{load}[1 + (j\omega C_{res} + \frac{1}{R_{load}})(ESR_{L2} + j\omega L_2)]}{N_2 \pi^2 a^2 2 f \mu_0}$$



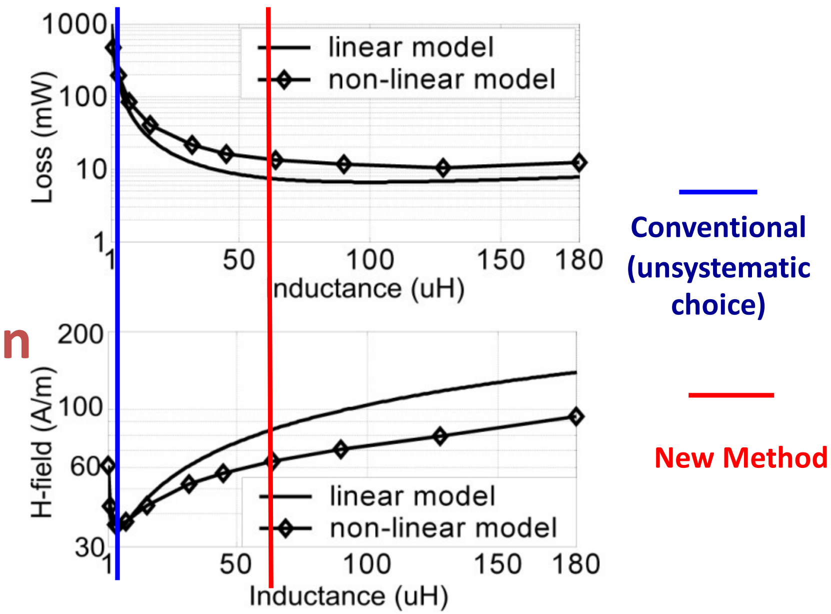
Linear Model (without diode)

Coil Design: Procedure (2)

◆ 2. Secondary coil design (cont'd)

- Select large inductance L_2 with H field under safety limit
- Determine N_2 using $L_2 = N_2^2 L_{2unit}$
- Induced voltage on L_2 is

$$V_{ind} = \frac{V_{load}}{[1 + (j\omega C_{res} + \frac{1}{R_{load}})(ESR_{L2} + j\omega L_2)]}$$



- **V_{ind} is then related to primary side design**

◆ 3. Primary coil design (given V_{ind})

- Calculate primary side loss vs L_1

$$V_{ind} = \omega M I_{L1}$$

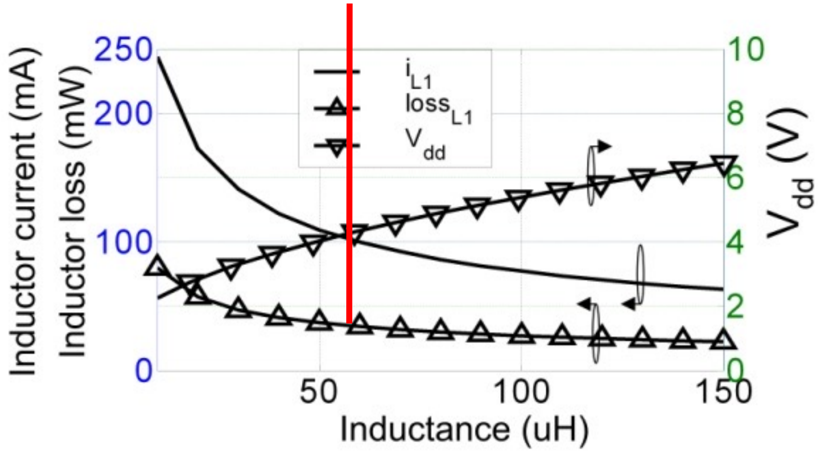
$$i_{L1} = \frac{V_{ind}}{\omega \times k \times \sqrt{L_1 \times L_2}}$$

$$\text{loss}_{L1} = \frac{V_{\text{ind}}^2}{\omega^2 k^2 L_2} \times \frac{2\pi a \times \rho}{K_s \times L_{1,\text{unit}} \times b \times c} \times \left(1 + K_c \left(\frac{\frac{b \times c \times K_s}{\sqrt{\frac{L_1}{L_{1,\text{unit}}} \pi (\frac{ID}{2})^2}} \times ID}{2\sqrt{\frac{b \times c}{\pi \sqrt{\frac{L_1}{L_{1,\text{unit}}}}}}} \right)^2 \left(\frac{ID\sqrt{f}}{0.262} \right)^4 \right)$$

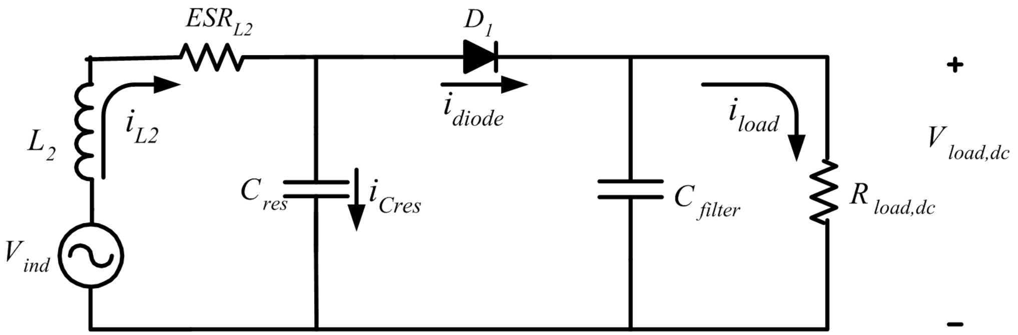
Coil Design: Procedure (3)

◆ 3. Primary coil design (Cont'd)

- ➢ Use simulation (Spice) method to determine required battery voltage by Class E amplifier *vs* L_1
- ➢ Select the inductance corresponding to battery supply voltage
- ➢ Determine N_1 using $L_1 = N_1^2 L_{1unit}$



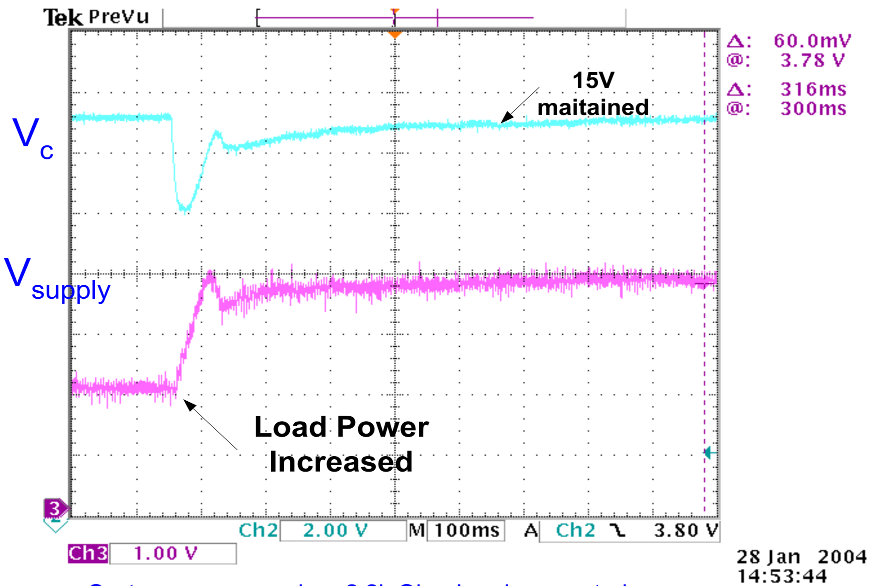
❑ Comments



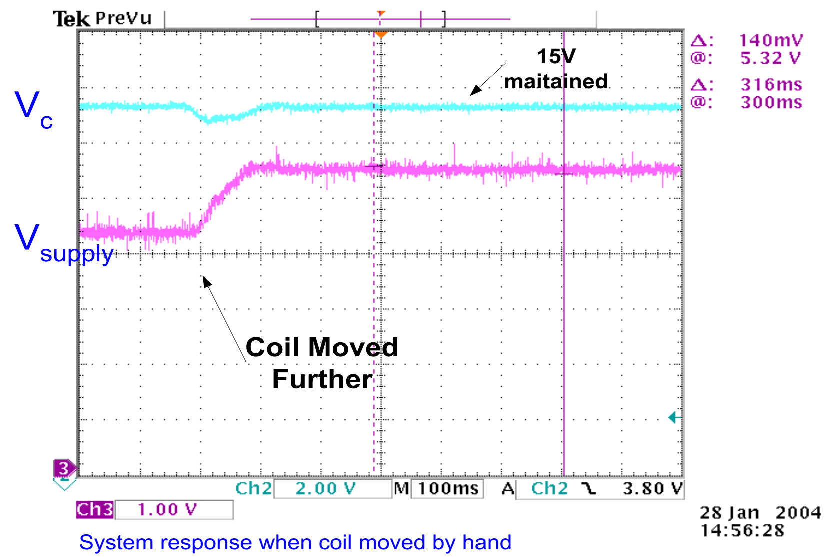
Non-linear Model (with diode)

- ➢ Non-linear model is constructed if more accuracy is needed to extract current and voltage for linear model
- ➢ Litz wire is essential for the secondary coil to effectively reduce ESR

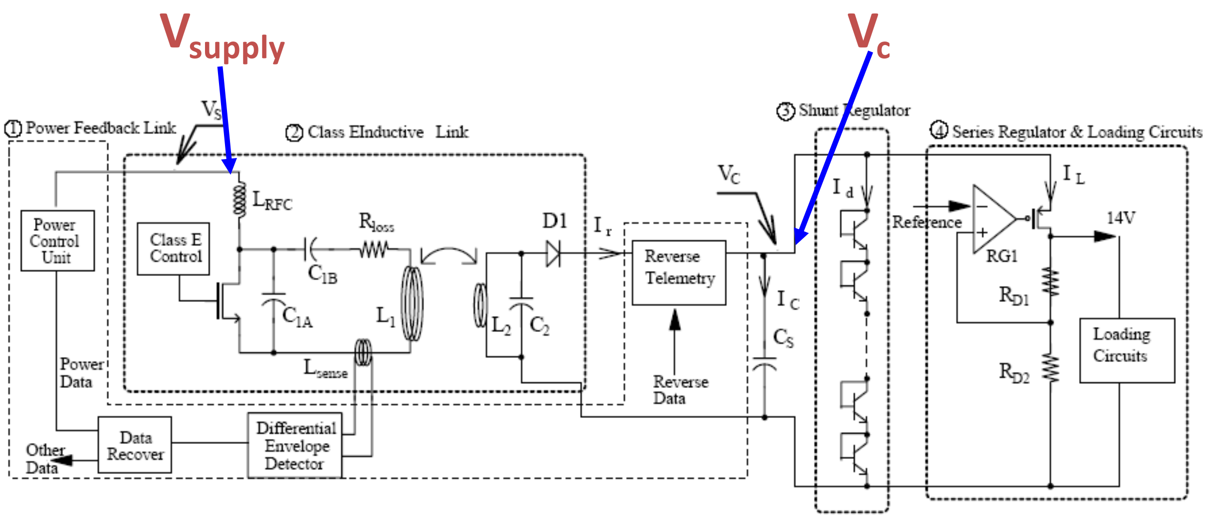
Design Procedure (4) – Adaptive Power Control[8]



System response when 2.2k Ohm Load connected
Vc - Voltage on storage capacitor (before regulated)
Vs - Controlled supply voltage to Class-E amplifier



System response when coil moved by hand
Vc - Voltage on storage capacitor (before regulated)
Vs - Controlled supply voltage to Class-E amplifier



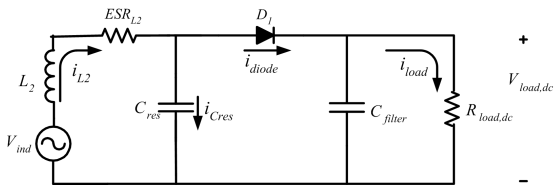
Reversed telemetry

Designed for Retinal Prosthesis

System can maintain preset value (Vc) at the secondary side under all loading conditions and coil distance changes

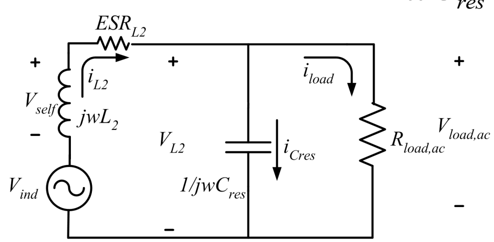
Summary - Coil Design Methodology

Non-linear model (2nd coil)



- Accurate
- Can be analyzed only via SPICE
- Time consuming analysis

Linear model: $R_{load,ac} >> \frac{1}{\omega C_{res}}$



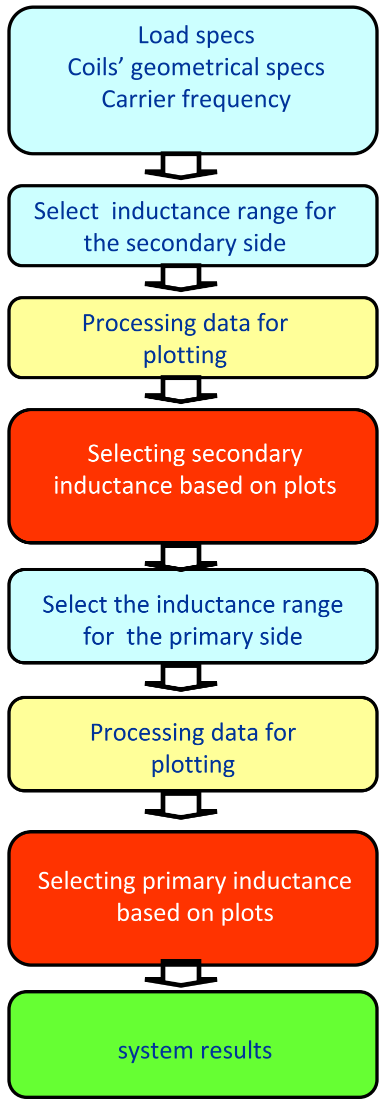
- Only valid for specific region
- Easier to analyze

Primary coil:

$$i_{L1} = \frac{V_{ind}}{\omega \times k \times \sqrt{L_1 \times L_2}}$$

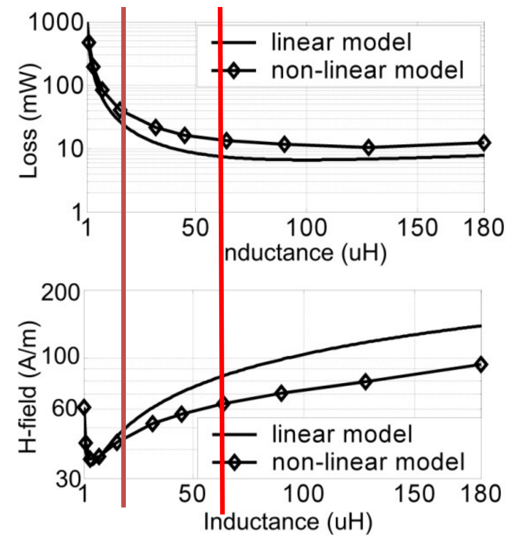
$$V_{dd} = V_o + \sqrt{\frac{P_{out} \times R}{0.577}} = V_o + \frac{\omega k \sqrt{L_1 L_2}}{V_{ind} \times 0.76} P_{out}$$

Semi-automated coil design software using linear model



Output Plots

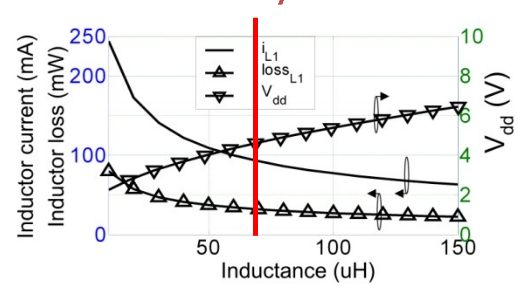
Secondary side



Conventional

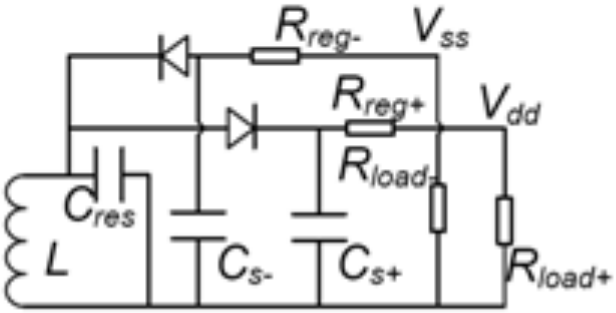
New Method

Primary side

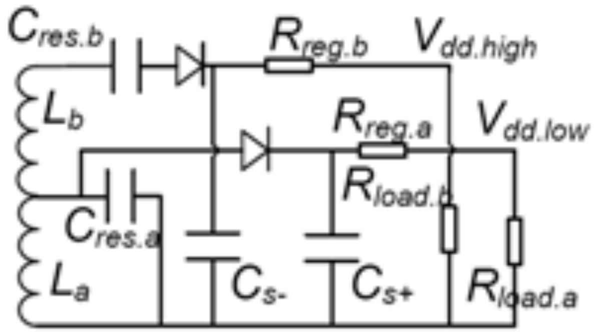


Design Methodology: Rectifier Design

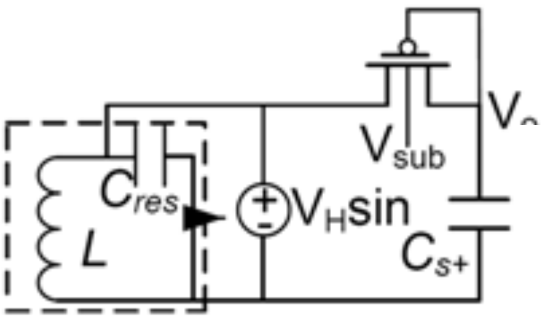
❑ Rectifier topology



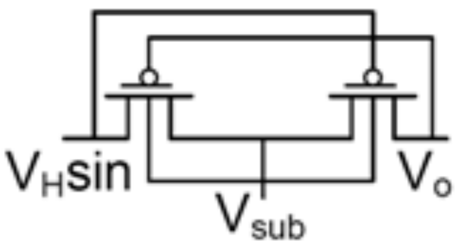
Full wave

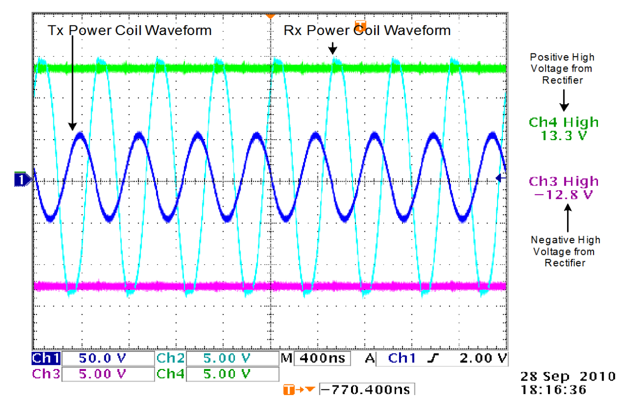


Cascoded



Diode-connected





Cross-coupled PMOS Diodes

Design Example – Coil and Power Link

System Specs

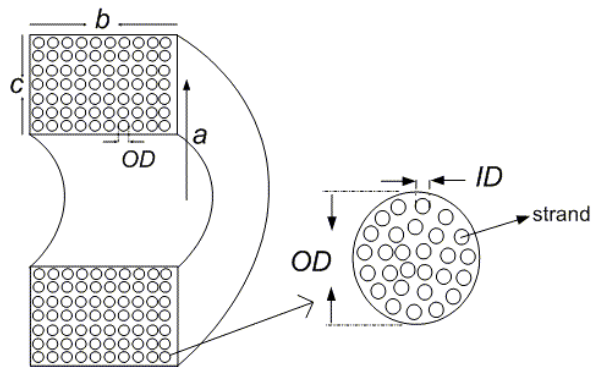
load	250mW at 16Vdc
secondary coil	a, b, c= 1 , 0.05 , 0.2 (cm)
primary coil	a, b, c= 1.8 , 0.50 , 0.4 (cm)
distance	0.7cm (inside to inside)
frequency	1MHz

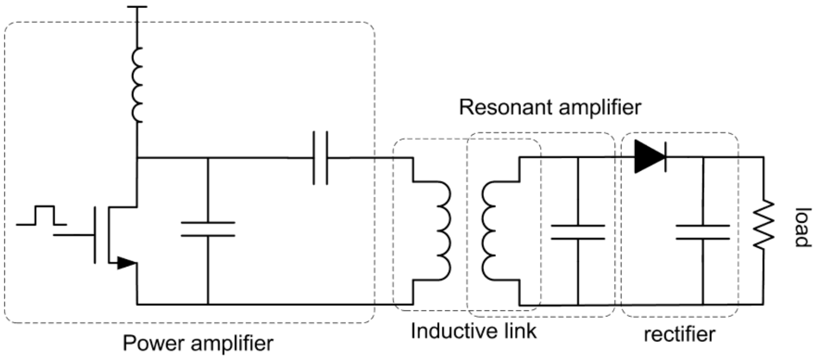
System parameters

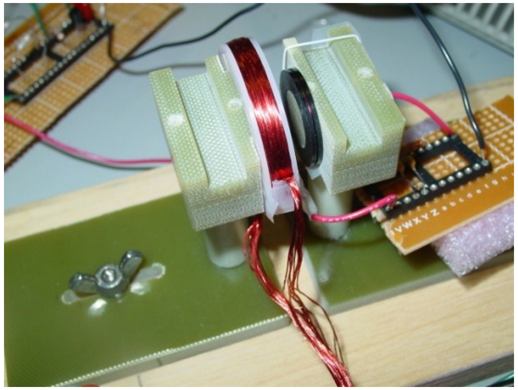
Rload :	1 kohm	Pload=250mW
Vload :	16Vdc	
Cfilter, Cres, C1, C2 :	100E3, 270, 660, 377 (pF)	
L1, L2, Lchoke :	69, 60, 230 (uH)	
N1, N2:	37, 40	
Ns1, Ns2:	4, 150	
switch:	IRF510N (MOSFET)	
Nominal frequency :	1 MHz	

Results

Experimental results including the class-E amplifier				
d(mm)	k	Pin(mW)	Pout(mW)	efficiency(%)
7	0.16	333	250	**67.34**
2	0.24	342	250	**65.12**
15	0.08	452	250	**51.16**





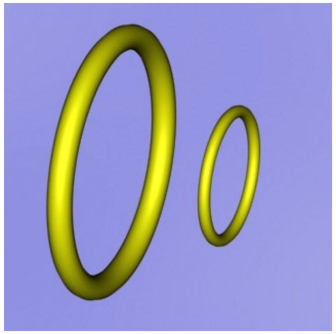


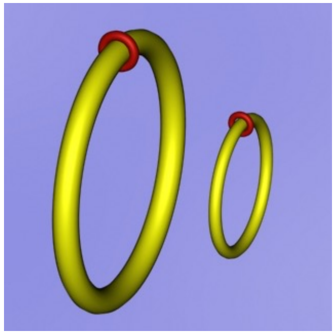
Inductive Link for Data -- Coils

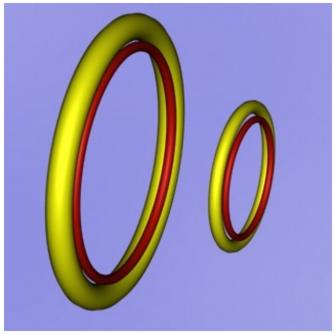
Inductive link can send data too!

Two interesting approaches

- Implement data transfer over power carrier on the same link
  - Less components, critical in implantable applications
  - But difficult to optimize since data link and power link normally have contradicting requirements
    - Frequency
    - System Q
- Transfer data on a separate link
  - Interference between power and data link
  - Orthogonal or parallel







Inductive Link for Data -- Modulation

ASK

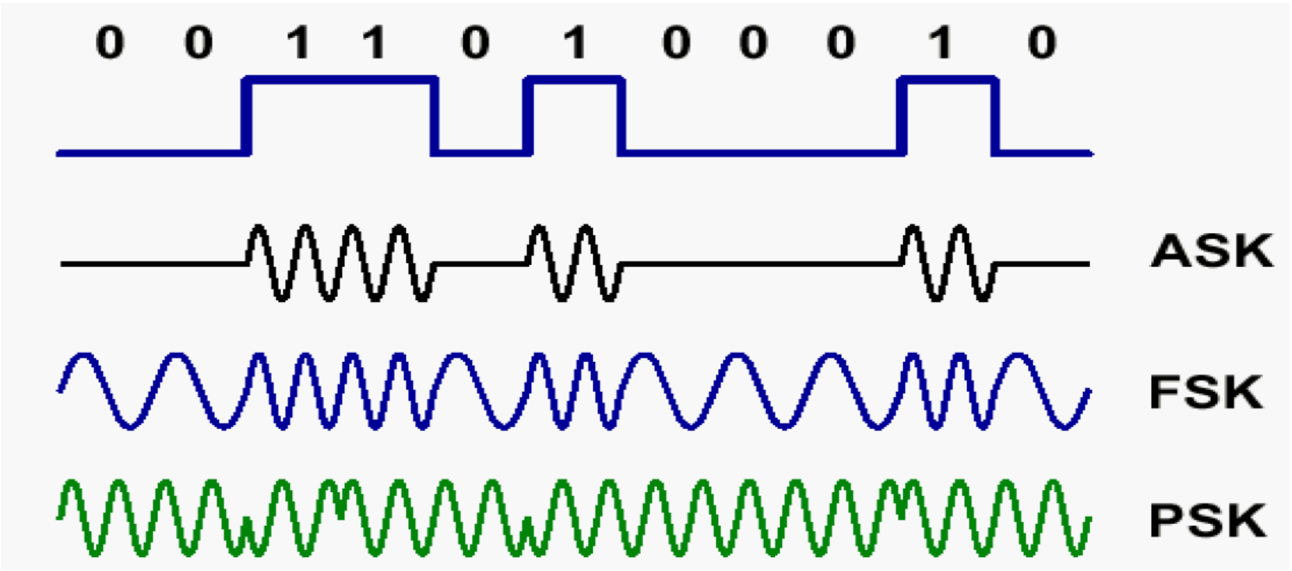
- Mostly used
- Easy to implement
- Hard to get high data rate as carrier frequency limited
- Sensitive to coil misplacements
- ~ 1Mbps achieved

FSK

- Recently some efforts are made on FSK to achieve higher data rate
- Still constrained by system Q and implementing complexity

PSK

- No published results on implantable system yet

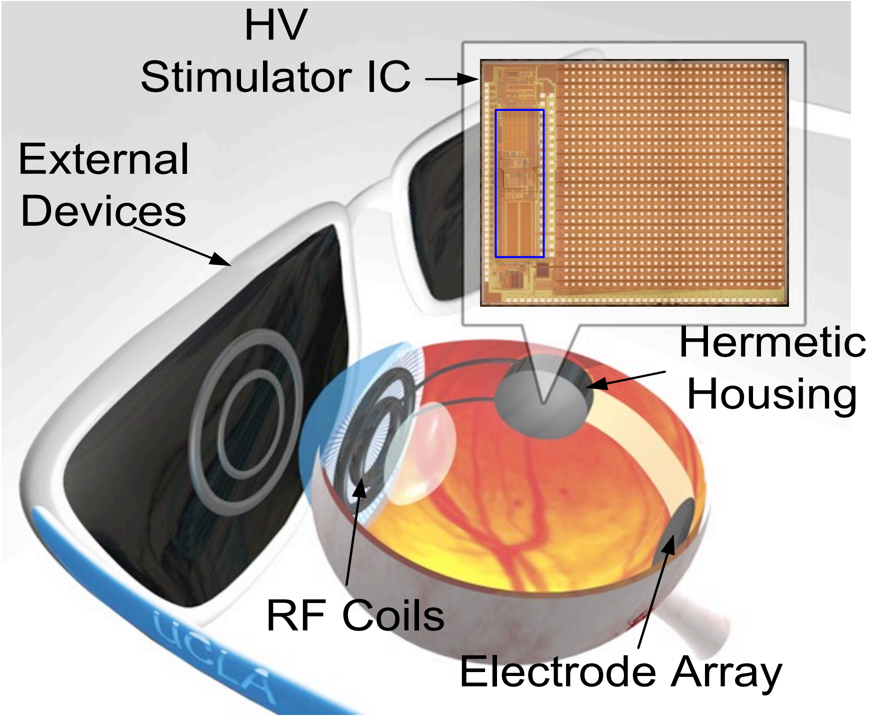


Power Link Example – Integrated Solution

❑ Retinal Prosthesis[22]

- Eyeglass-mounted camera captures images
- Image is down-sampled, gray-scaled, and encoded
- Power and image data are wirelessly transmitted to the implant
- Stimulator IC generates electrical pulses to electrodes
- Patient "perceives" light from the remaining cells in the retina

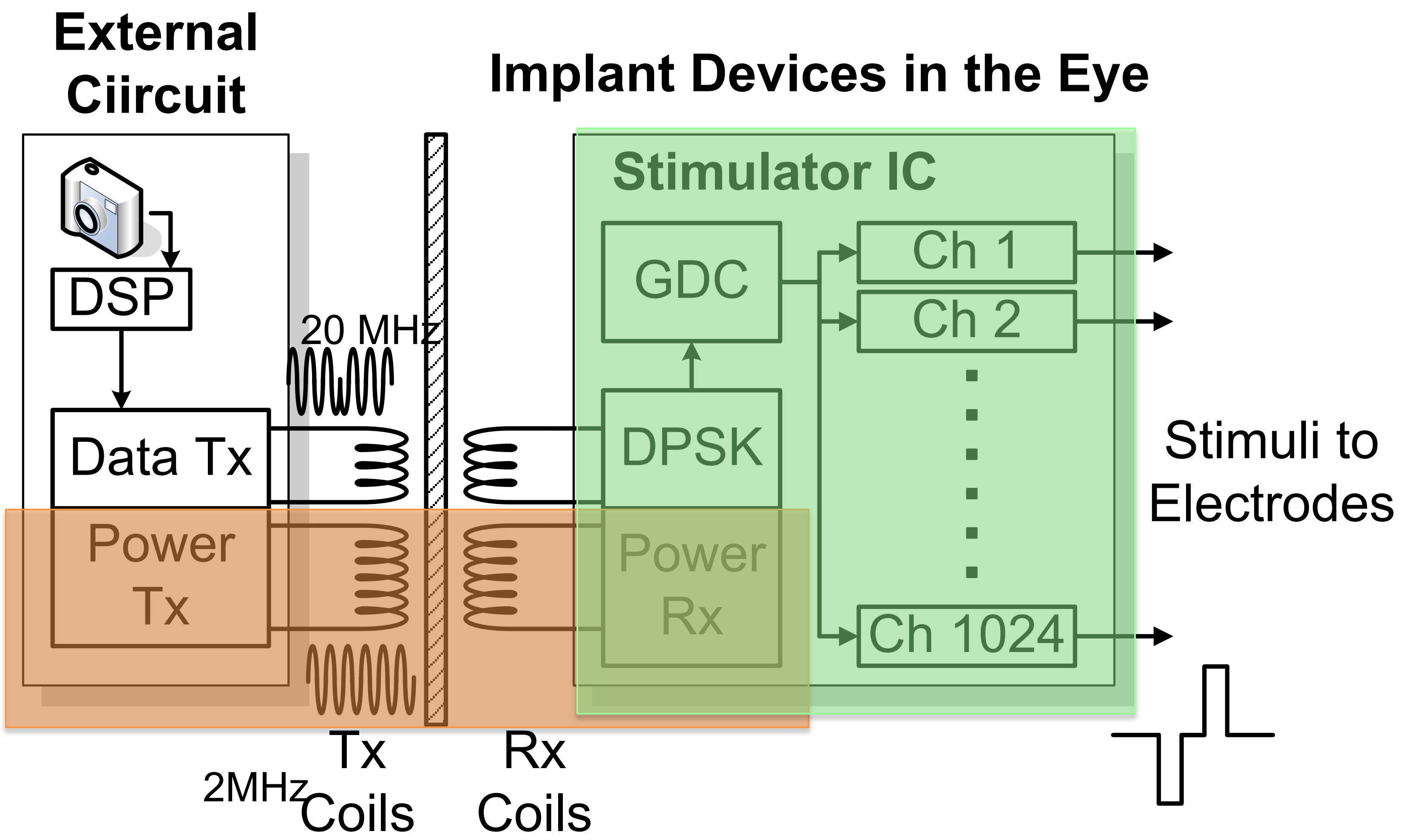
Concept of epi-retinal prosthesis



➢ **Power driven by scaling of stimulation channel**

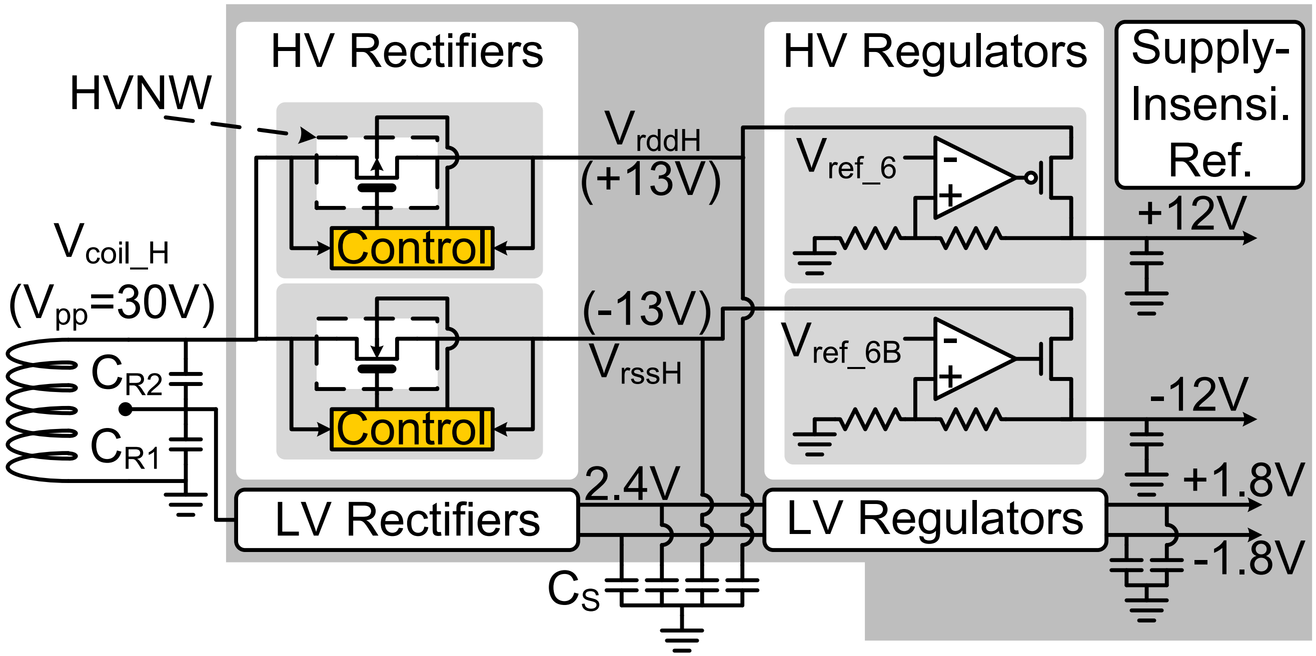
- high number of channels is needed
- high compliance voltage is required and thus impose technology constraints

System Architecture – SoC Solution [22][23]



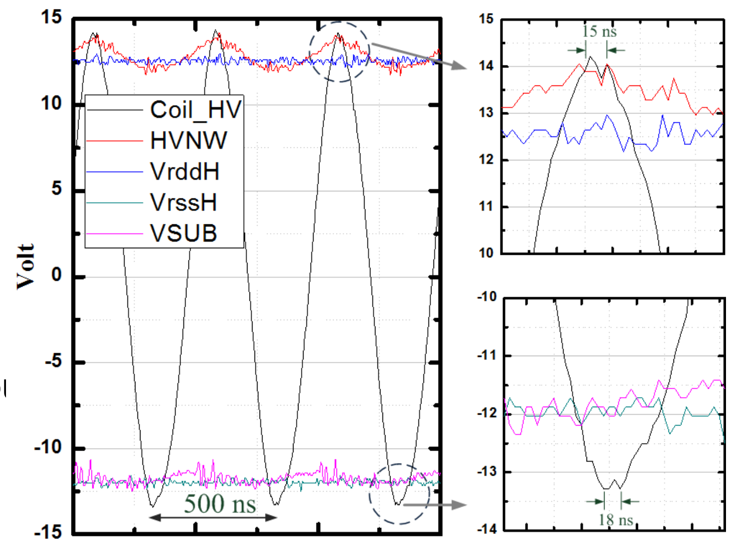
Retinal Prosthesis – Integrated Power Link[23]

- The world first ***SoC power link*** that takes two AC voltages via a coil and produces four DC voltages at power >***100mW***
  - ***Transistor***-based rectifier without off-chip diodes
  - Precisive timing-controlled rectifier with linear regulator
  - Maximize power transfer efficiency by elliminating reverse leakage during the turn-on of rectifying switches

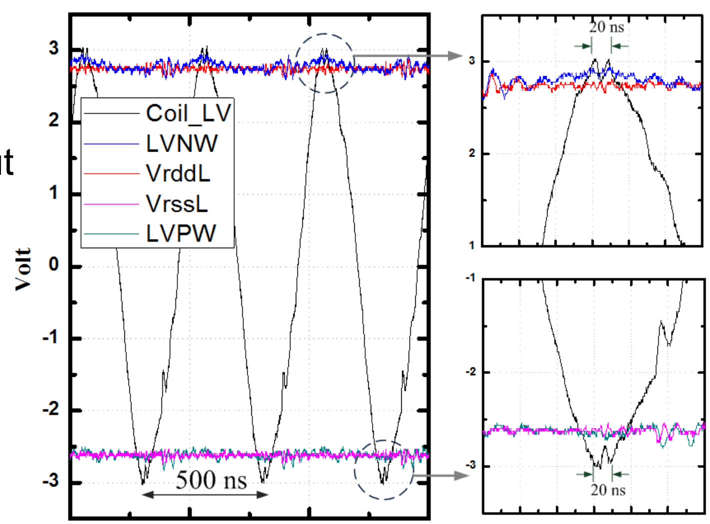


Retinal Prosthesis – Integrated Power Link [23]

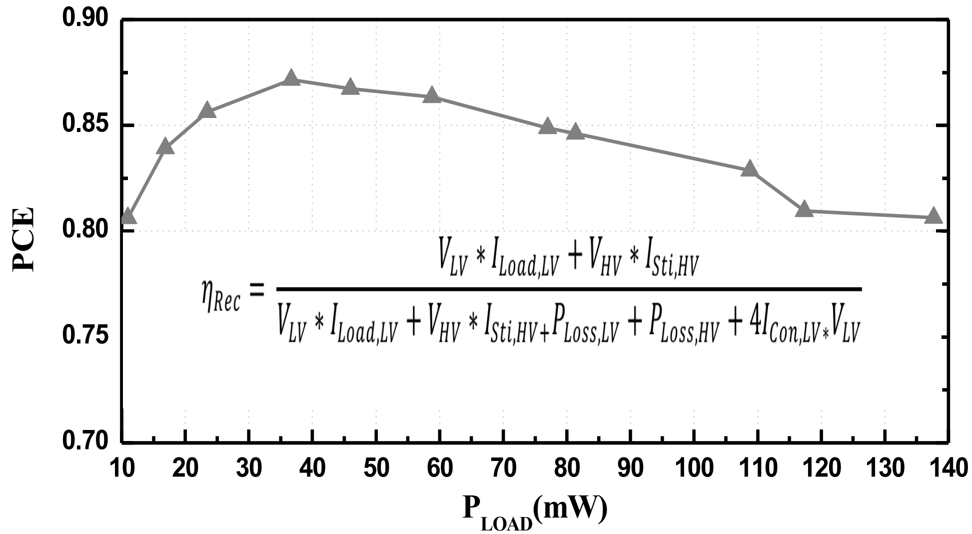
HV outp



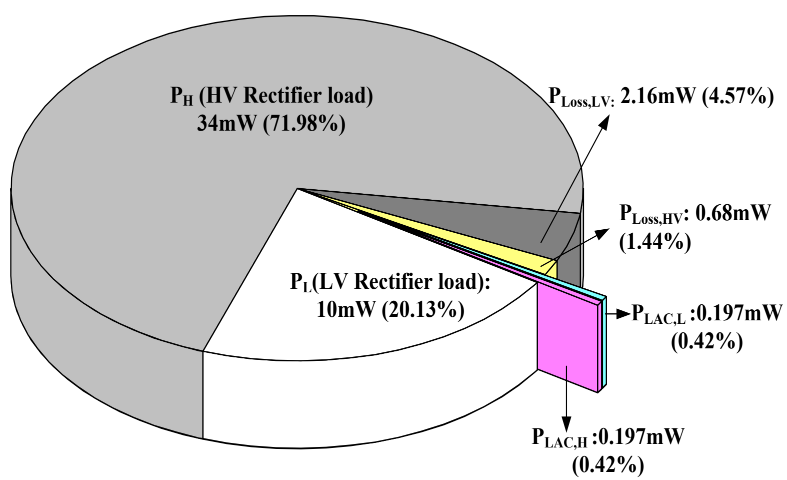
LV output



Power Conversion Efficiency (PCE)



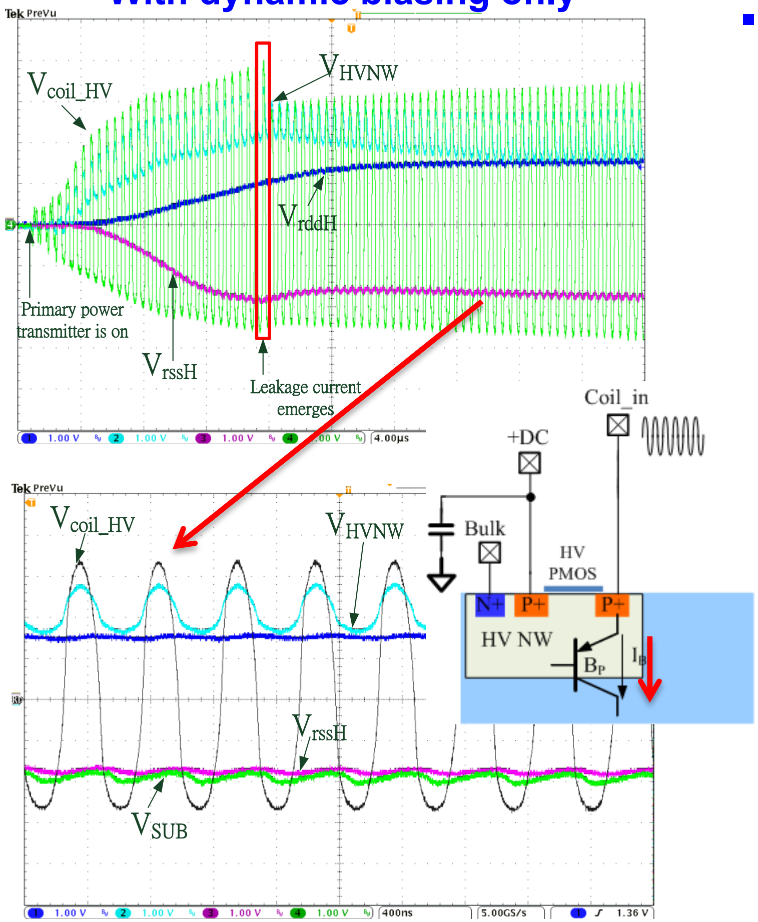
Power consumption pie chart



Retinal Prosthesis – Integrated Power Link [23]

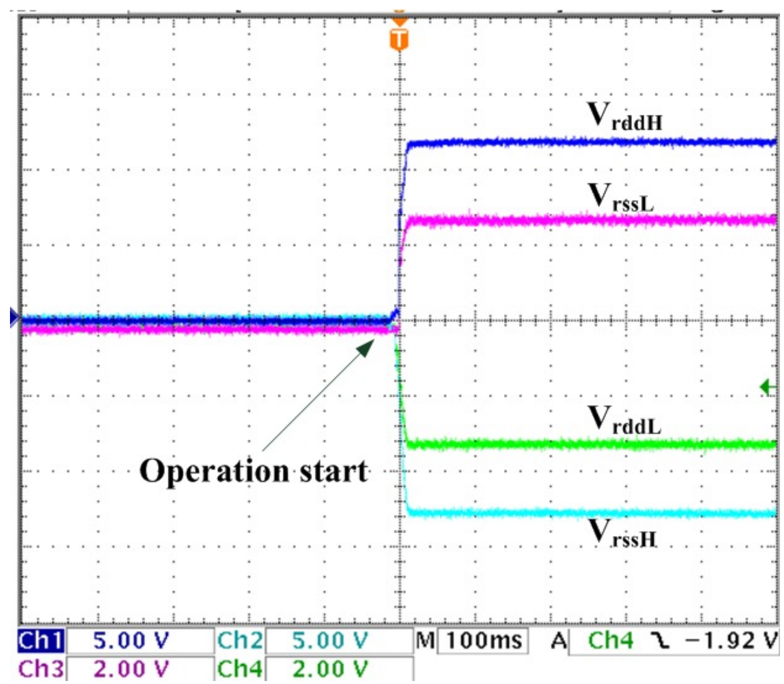
❑ In-vivo power link test results

With dynamic biasing only



- Conventional dynamic biasing can not be applied to HV process and start-up fails due to substrate leakage current !

With controller on



Retinal Prosthesis – Integrated Power Link [23]

Comparison

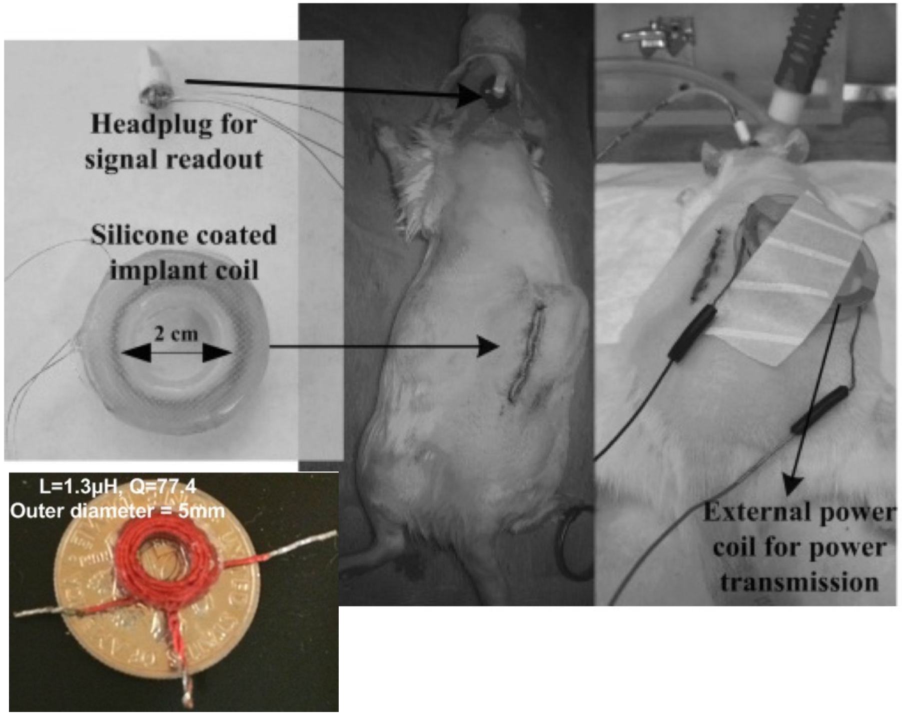
	Cha (TCAS I 12)	Ghovanloo (ISSCC12)	Sawan (TBCAS 12)	This work
CMOS Tech. (μm)	0.18	0.5	0.8	0.18
Rectifier Out (V)	1.33	3.1	3.3, 14.8 (2 levels)	±2.43,±12 (4 levels)
RX Coil Voltage (V)	1.5	3.7	22.4	3 (LV) 14 (HV)
Load (mW)	1.8(est.)	19.2(est.)	14.8(est.)	19.9 (LV) 98.9(HV)
PCE	81.9	77	N/A	81.19

	Substrate leakage current prevention scheme	Operation condition	Effectiveness in HV process
Prior works	Dynamic biasing	$V_{TH} < V_{diode}$	N/A
This work	Mixed-voltage gate controller	$V_{TH} > V_{diode}$	Yes

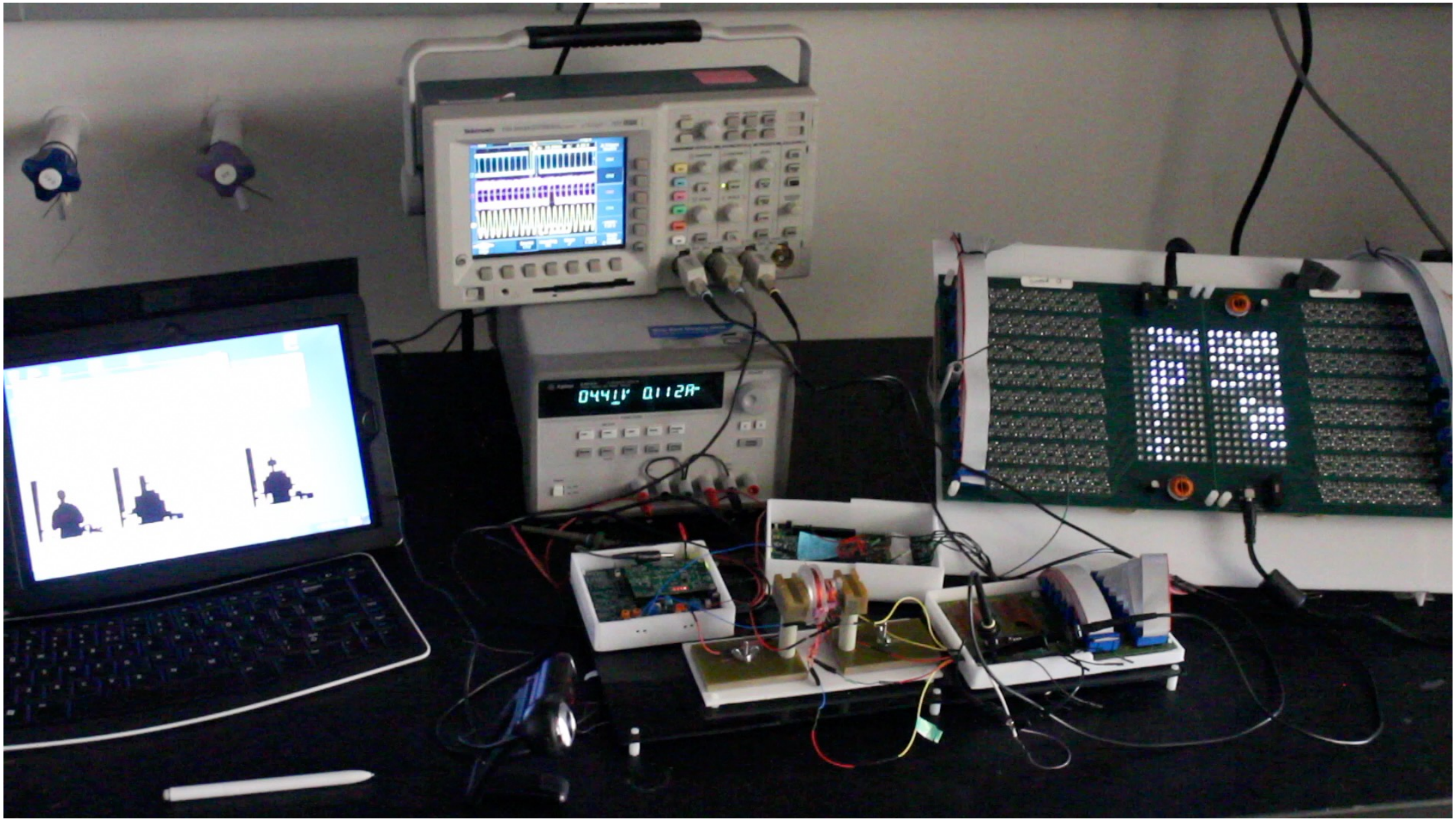
In Vivo Test – Integrated Power Link [23]

- test the longevity of the implanted coil
- verify the start-up and leakage current prevention schemes

	Inductance	Quality Factor
Before coating	2.85 μH	83.06
After coating	2.88 μH	82.73
after implanted for 2 month	2.76 μH	79.95



Demo [22]



Summary

- Power telemetry is discussed to support various biomedical implants with various power and voltage levels
- Generic system architecture for power telemetry is presented
- Critical blocks and their constraints for a power telemetry are discussed
- A rigorous design procedure for power telemetry with design parameters is presented
- Automated design procedure is available at my Lab
- An integrated power link with on-chip rectifier and regulator is implemented at TSMC high voltage CMOS (an ***IP block***)
- A retinal implant with the integrated on-chip power link is also demonstrated
- Data telemetry can also be implemented by inductive link

Reference

[1] G. E. Loeb et al, RF-Powered BIONs™ for Stimulation and Sensing, IEEE Engineering in Medicine and Biology Society, Volume. 2, pp.4182–4185, 2004

[2] K. Chen et al, An Integrated 256-Channel Epiretinal Prosthesis, Journal of Solid-State Circuits (JSSC), Volume. 45, pp.1946-1956, September 2010

[3] Cynthia A. Chestek et al, HermesC: Low-Power Wireless Neural Recording System for Freely Moving Primates, IEEE Transactions on Neural Systems and Rehabilitation Engineering, volume. 17, pp. 330-338, August 2009

[4] W. H. Ko et al, Design of radio-frequency powered coils for implant instruments, Med. Biol. Eng. Comput-15, pp. 634–640, 1977

[5] G. Wang et al, A dual band wireless power and data telemetry for retinal prosthesis, in Proc. Int. Conf. IEEE Eng. Med. Biol., pp.4392–4395, 2006

[6] G. A. Kendir et al, An Optimal Design Methodology for Inductive Power Link with Class-E Amplifier, IEEE Transactions on Circuits and Systems – I, vol. 52, pp. 857 – 866, 2005

[7] Z. Yang and W. Liu, Inductor modeling in wireless links for implantable electronics, IEEE Trans. Magn., vol. 43, no. 10, pp.3851–3860, 2007

[8] G. Wang et al, Design and Analysis of an Adaptive Transcutaneous Power Telemetry for Biomedical Implants, IEEE Transactions on Circuits and Systems – I, vol. 52, pp. 2109 - 2117, 2005

[9] T. G. Ryan et al, Pacemaker Telemetry System, U.S. Patent 5 350 411, 1994

[10] Stimulation Strategies, IEEE Trans. On Neural Systems and Rehabilitation, vol. 3, pp.112-116, 1995

Reference (Cont.)

[11] W. Liu et al, A Neuro-Stimulus Chip with Telemetry Unit for Retinal Prosthetic Device, IEEE Journal of Solid-State Circuits, vol. 35, no. 10, pp. 1487-1497, 2000

[12] M. Ghovanloo et al, A Wideband Frequency-Shift Keying Wireless Link for Inductively Powered Biomedical Implants, IEEE Transactions on Circuits and Systems, vol. 51, no. 12, pp. 2374–2383, 2004

[15] M. Zhou et al, A Non-Coherent DPSK Data Receiver with Interference Cancellation for Dual-Band Transcutaneous Telemetry, IEEE Journal of Solid-State Circuits, vol. 43, no. 9, pp. 2003-2012, 2008.

[16] N. Ortamanns, et al., A 232 channel epiretina stimulator ASIC, JSSC, pp. 2946-2959, 2007

[17] P. R. Troyk, and M. A. K. Schwan, "Closed-loop class E transcutaneous power and data link for MicroImplants," *IEEE Trans. Biomed. Eng.*, vol. 39, no. 6, pp. 589-599, Jun. 1992

[18] Z. Yang, et al., Wireless power and data telemetry for wearable and implantable electronics, in *Wireless Area Body Network* (Editor M. Yuce), Pan Stanford Publisher, 2011

[19] K. Nikita (editor), Handbook of Biomedical Telemetry, John Wiley and Sons, 2014

[20] K. Finkenzeller, RFID-Handbook, Wiley, 2003

[21] K. van Schuglenbergh and R. Puers, Inductive powering, Basic Theory and Application to Biomedical Systems, Springer, 2009

[22] K. F. Chen, Y. K. Lo, Z. Yang, J. D. Weiland, M. S. Humayun, and W. T. Liu, "A System Verification Platform for High-Density Epiretinal Prostheses," *IEEE Trans. Biomed. Circuits Syst.*, vol. 7, pp. 326-337, Jun 2013.

[23] Y. K. Lo, *Bioelectronic Circuit and System Design for Epi-Retinal and Neural Prostheses*, PhD Dissertation, Bioengineering Department, UCLA, 2014