SPIE Micro+Nano Materials, Devices and Applications, Sydney, Australia

# Wirelessly Powered Micro-Spectrometer for Neural Probe-Pin Device

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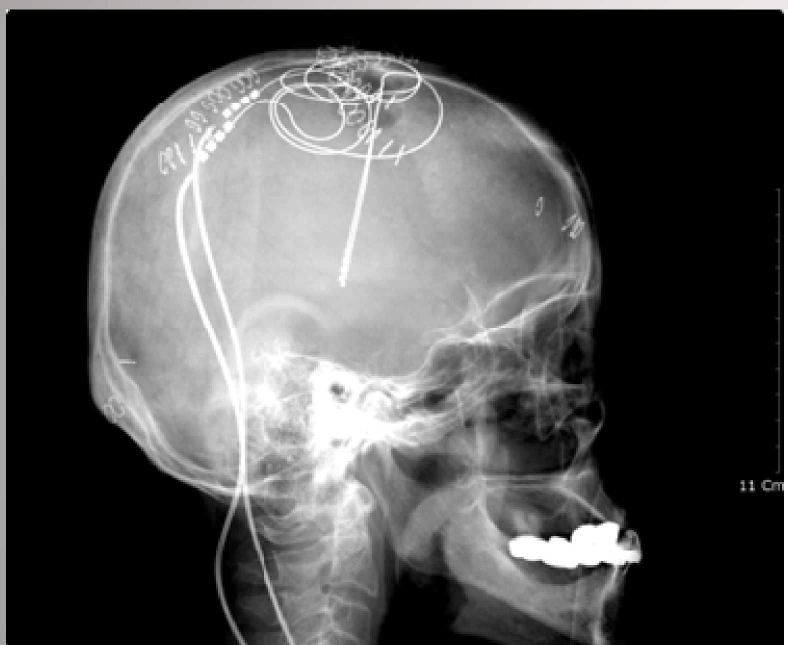
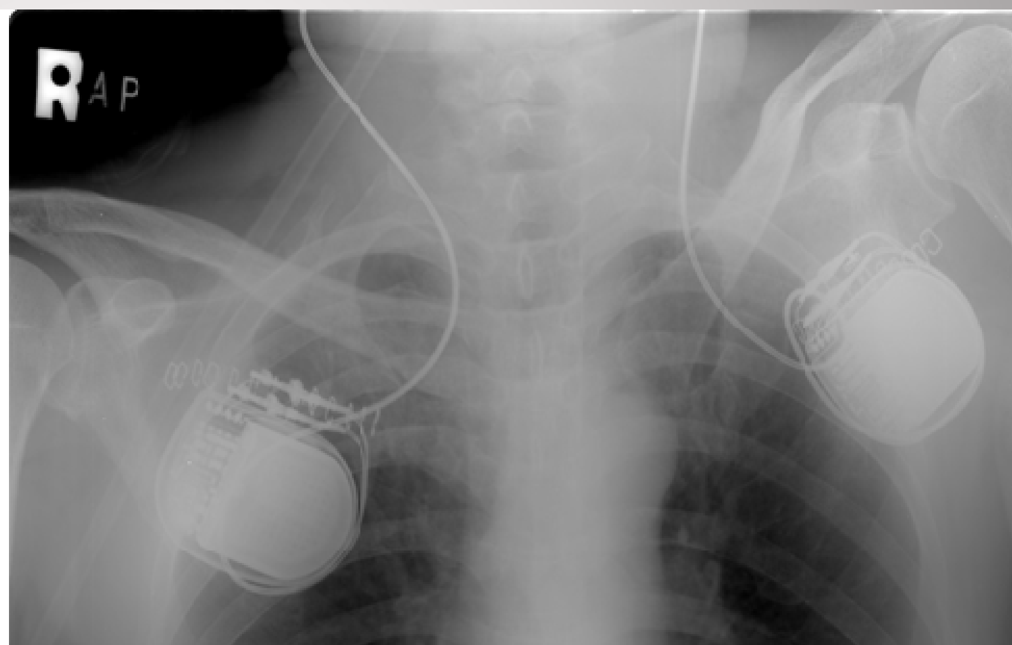
# Implanted Probes & Batteries

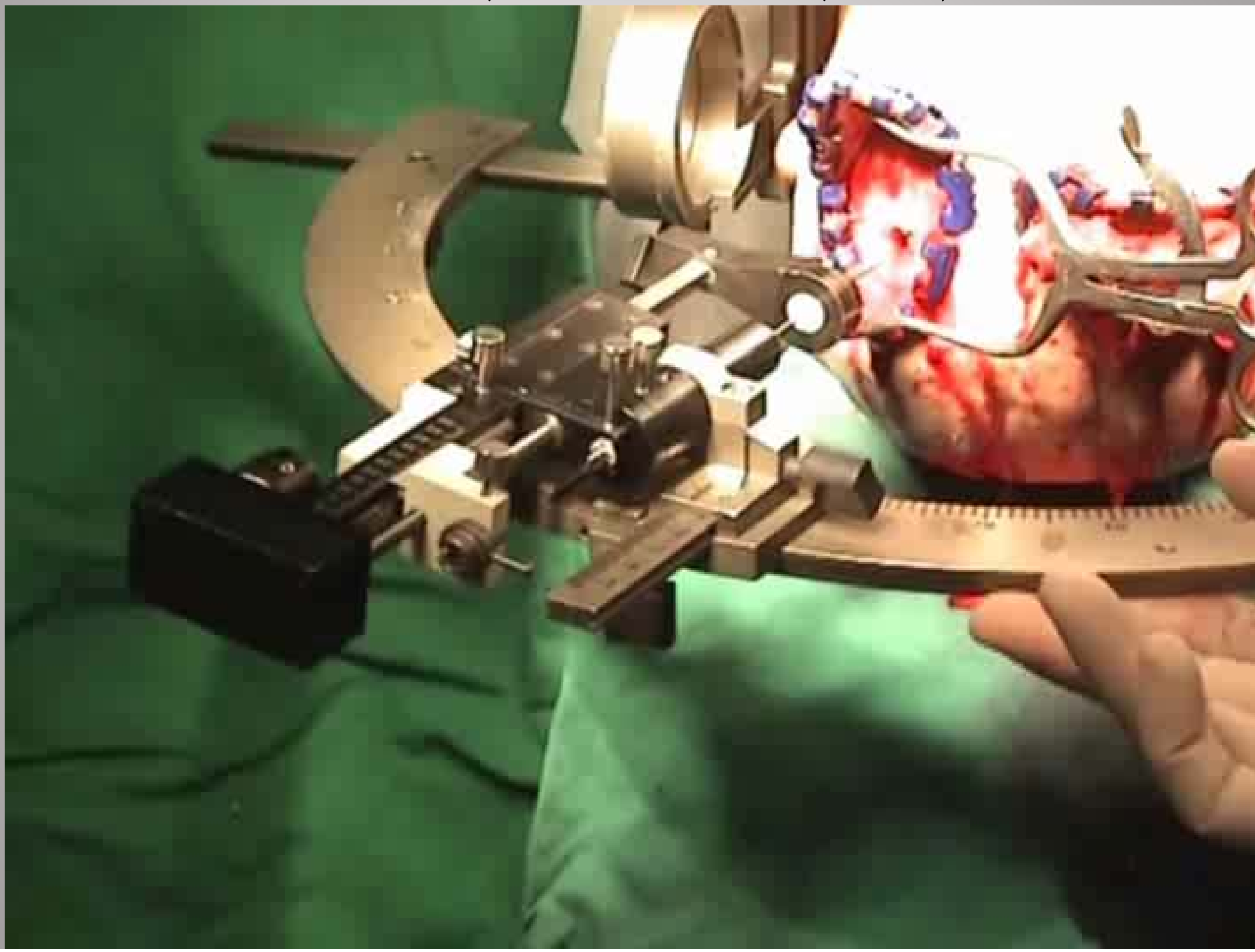



Source: Dr. Uhn Lee, Gacheon Medical School, Incheon, Korea

# DBS Implantation

Source: Dr. Uhn Lee, Gacheon Medical School, Incheon, Korea



# Current Limitations

**Power Source:** Implanted battery with tether line

- Painful and cumbersome
- Battery life: 3-5 years
- Power-line vulnerable to disconnection

**Performance:** Jolt suppression voltage only

- Diagnosis and search of anomaly required
- A single function

# New Approach: Probe-Pin Device

**Power Source:** Wirelessly powered

- Micro-coil with train of magnetic pulses
- Rectenna array for microwave coupling

**Performance:** Integrated multi-functionality

- Diagnosis and search of anomaly required
- Multi-functions integrated
  - Jolt suppression voltage
  - Brain temperature
  - Brain pressure
  - Neuro-electricity
  - Neuro-chemistry by micro-spectrometer

Logic Circuit for Monitoring, Control, & Data Acquisition

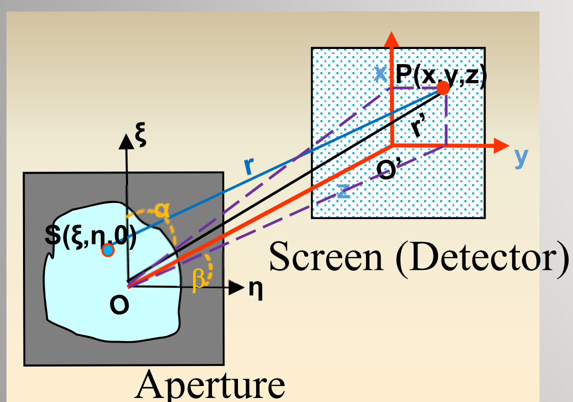
# Approximation of Diffraction Phenomena

Augustin Fresnel (1788-1827)
(Public domain media from Wikimedia Commons)

- Optical situation when light passes a spot, **S**(η,ξ,0) at a coordinate (η,ξ,0) on an aperture and illuminates a point, **P**(x,y,z) at a coordinate (x,y,z) on a screen.
- According to **Huygens's Principle**, the electric field at a far point **P**, is obtained by adding each point of the light's wave-front surface, the electric field strength at point **P**, *u*(**P**) can be written by the integration of tiny electric fields from all spots like **S** in the aperture.

$$u(P) = \frac{iA}{\lambda}\iint \frac{e^{-ikr}}{r}\, d\xi\, d\eta$$

Where λ = wavelength, k = wavenumber of light.




Note that while the distance $r$ is a temporary variable for integration, the distance $r'$ is a fixed engineering parameter of a given instrument that does not change over the integration.

Approximation with r'

$$u(P) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S(\xi,\eta,0)\exp[ik(l\xi + m\eta)]\, d\xi\, d\eta \qquad z > \frac{a^2}{\lambda}$$

where $r \cong r' - (l\xi + m\eta)$, $l = \frac{x}{r'} = \cos\alpha;\ m = \frac{y}{r'} = \cos\beta$

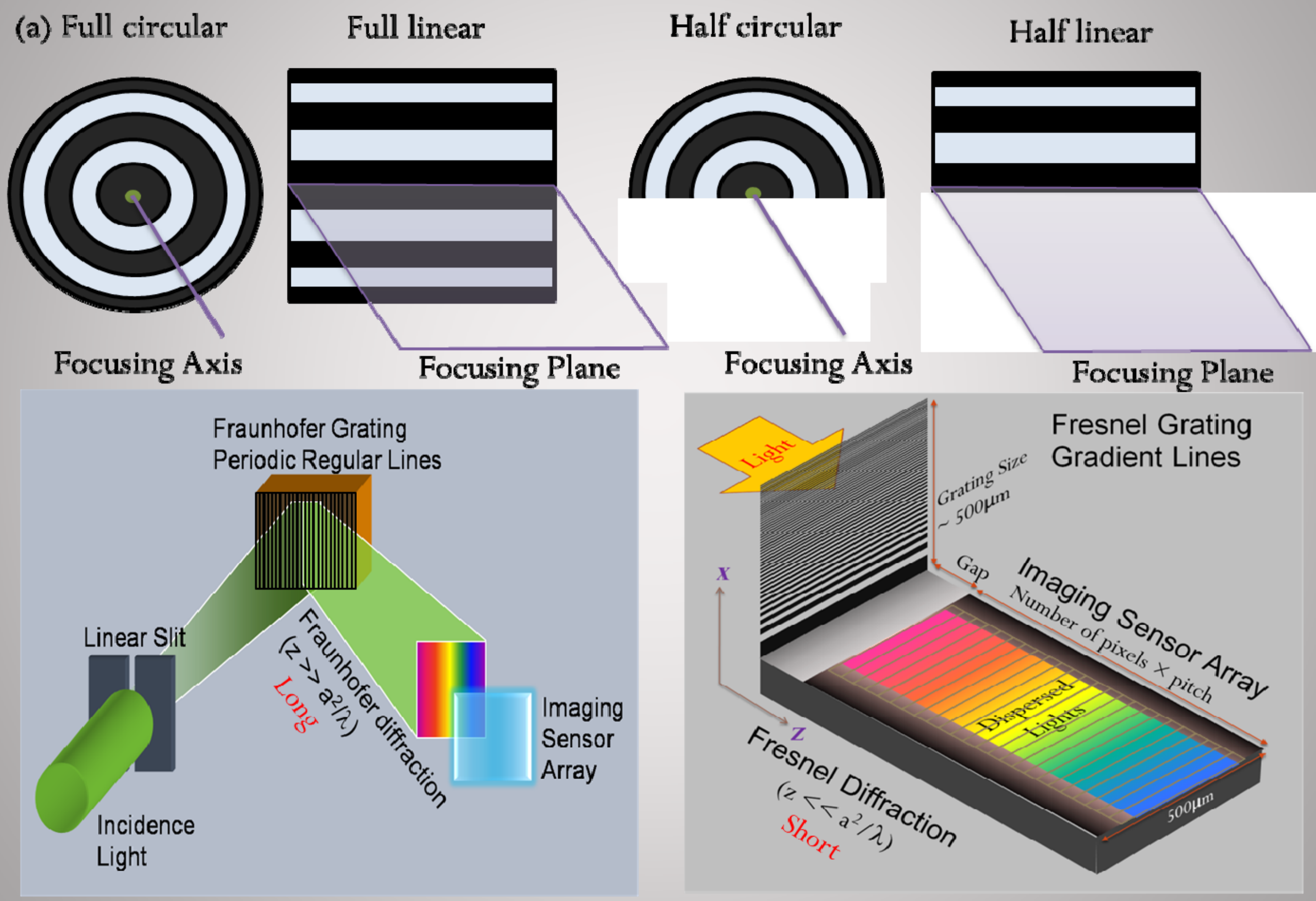
Fraunhofer Terms

$$r = r' - \frac{x\xi + y\eta}{r'} + \left[-\frac{(x\xi + y\eta)^2}{2r'^3} + \frac{\xi^2 + \eta^2}{2r'}\right] + \cdots$$

Fresnel Terms

$$u(P) = \frac{i}{\lambda z}\exp[-ikz]\iint S(\xi,\eta,0)\exp\left\{\frac{-ik}{2z}\left[(x-\xi)^2 + (y-\eta)^2\right]\right\} d\xi\, d\eta \qquad a < z < \frac{a^2}{\lambda}$$

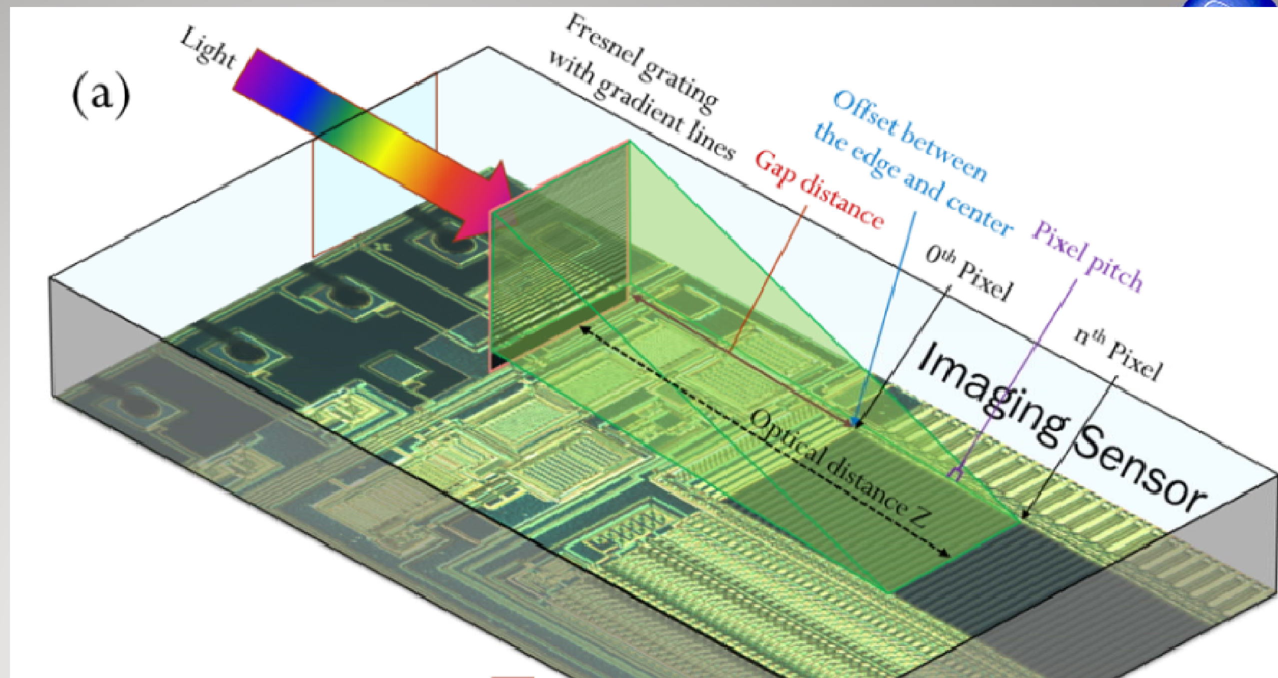
# Linear Fresnel Spectrometer




(b) Conventional Fraunhofer Spectrometer

(c) Linear Fresnel Spectrometer

# Pixel Number, Energy and Wavelength




Optical distance Z = gap distance between Fresnel grating and the edge of the 0th pixel + pixel pitch/2 + (pixel number × pixel pitch)

Then, the wavelength of the photon on the $n_{th}$ pixel (pixel number = n) with the Optical distance Z is determined by: Wavelength = $K^2/Z$, where K is a Fresnel grating size constant such that,

$$K = \frac{R}{\sqrt{L}}$$

$$Wavelength = \frac{K^2}{Z} = \frac{K^2}{gap + PixelNumber * PixelPitch}$$

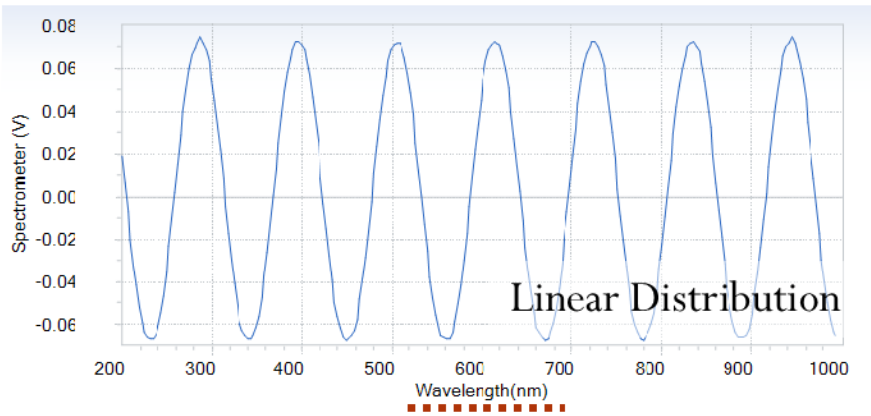
$$= \frac{R^2}{L \times (gap + PixelNumber * PixelPitch)}$$

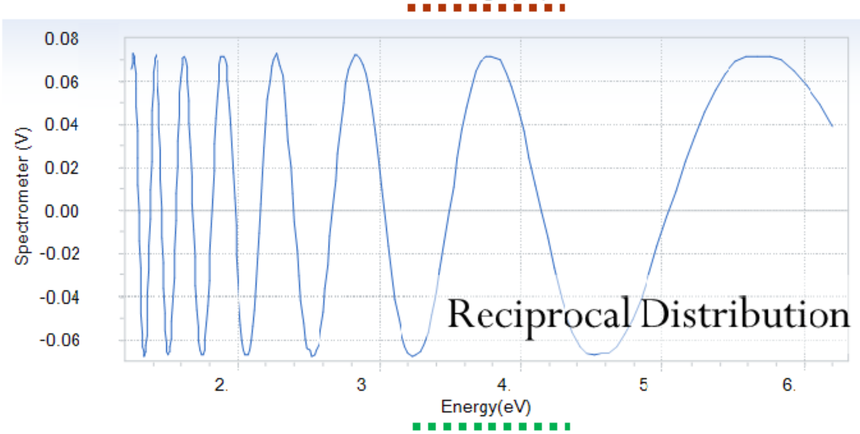
$$Energy = \frac{hcLZ}{R^2} = \frac{hcL}{R^2}(gap + PixelNumber * PixelPitch)$$

where L is the number of gradient rings (circular grating) or gradient lines (linear grating) and R is the radius of a circular grating or the height of a linear grating.

# Pixel to Wavelength/Energy Conversion

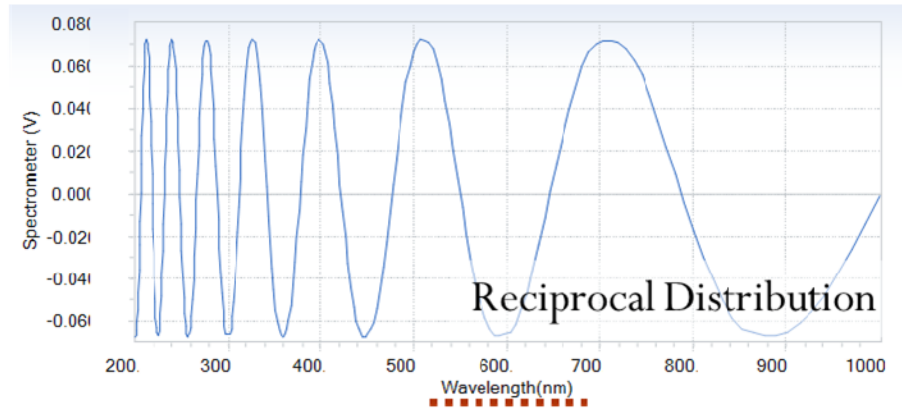
## Fraunhofer Spectrometer (Conventional)

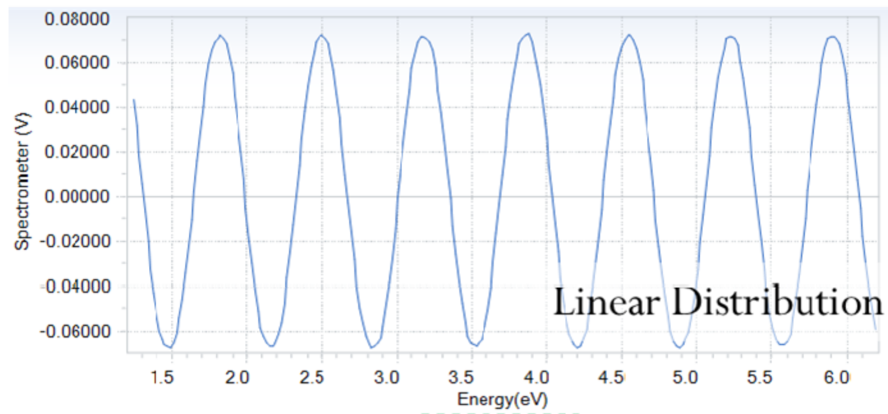



Fraunhofer spectrometer's sampling is linear to the **wavelength scale** (λ= hc/E).

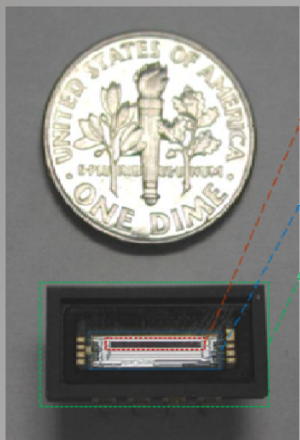
## Fresnel Spectrometer (New)




Fresnel spectrometer's sampling is linear to the **energy scale** (E=hc/λ).

# Spectrometer Chip

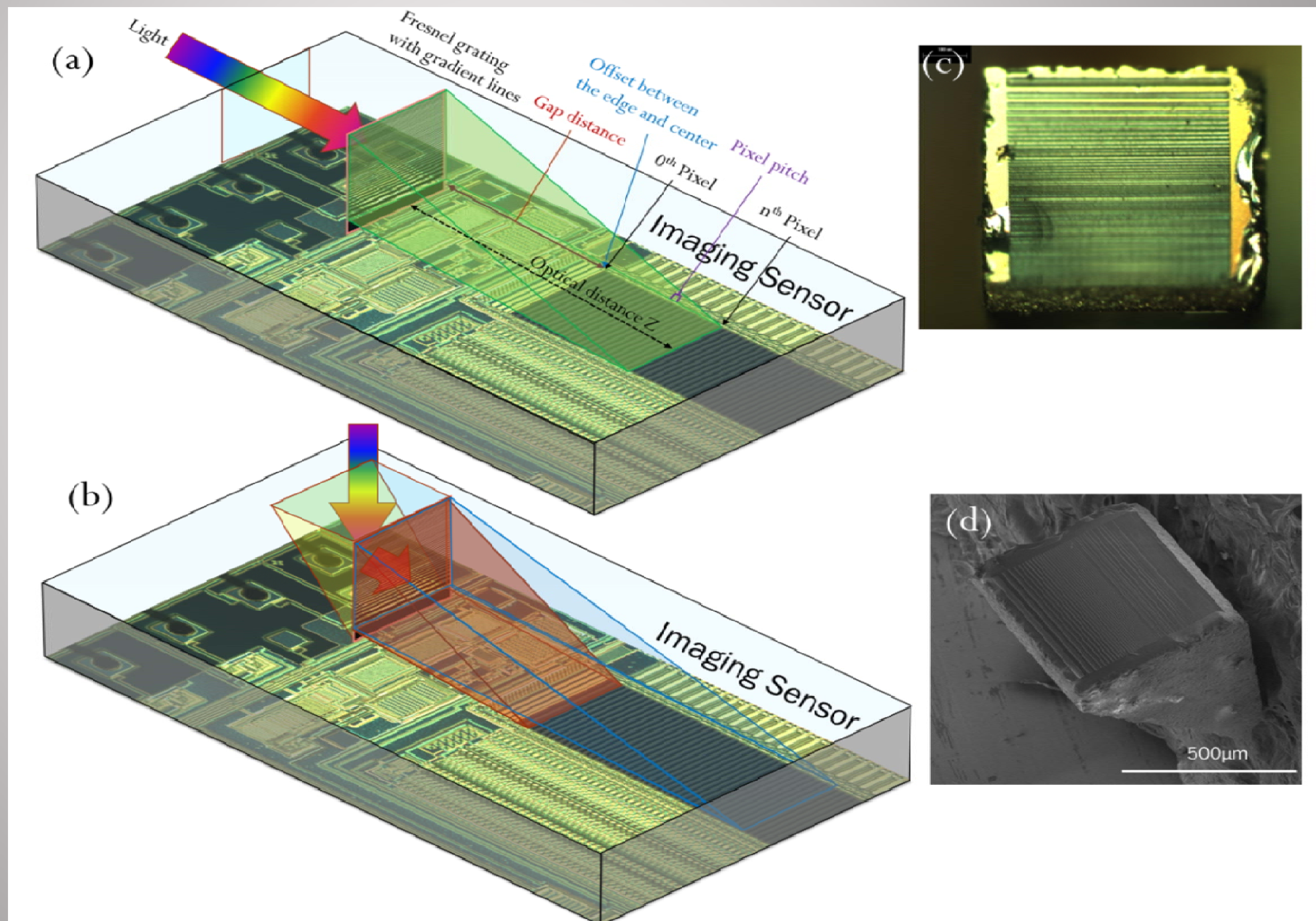


Dimension

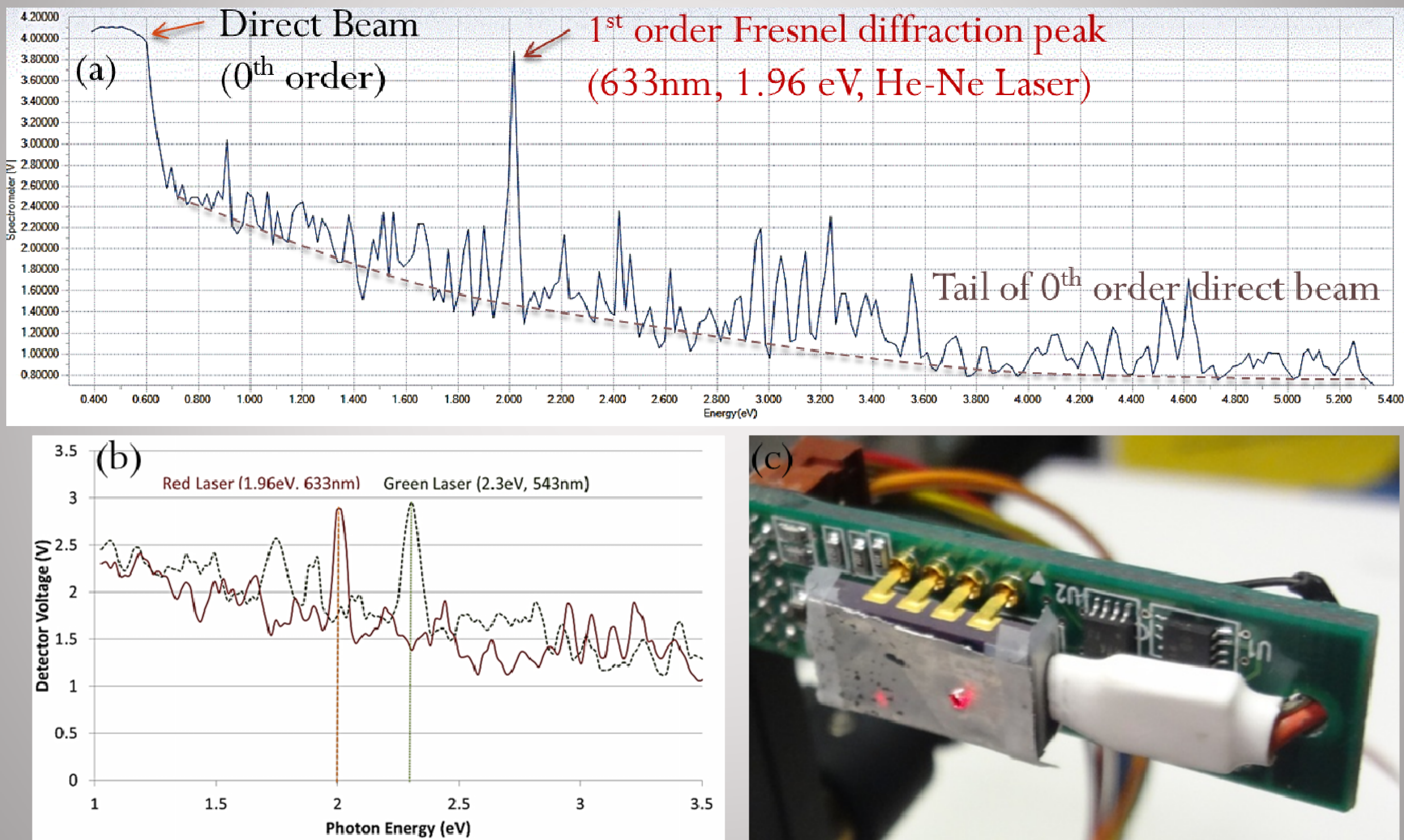
1. Active Area: 6.4mm x 0.5mm (Spectrum Area)

2. Die Size: **9.5mm x 2.5mm**

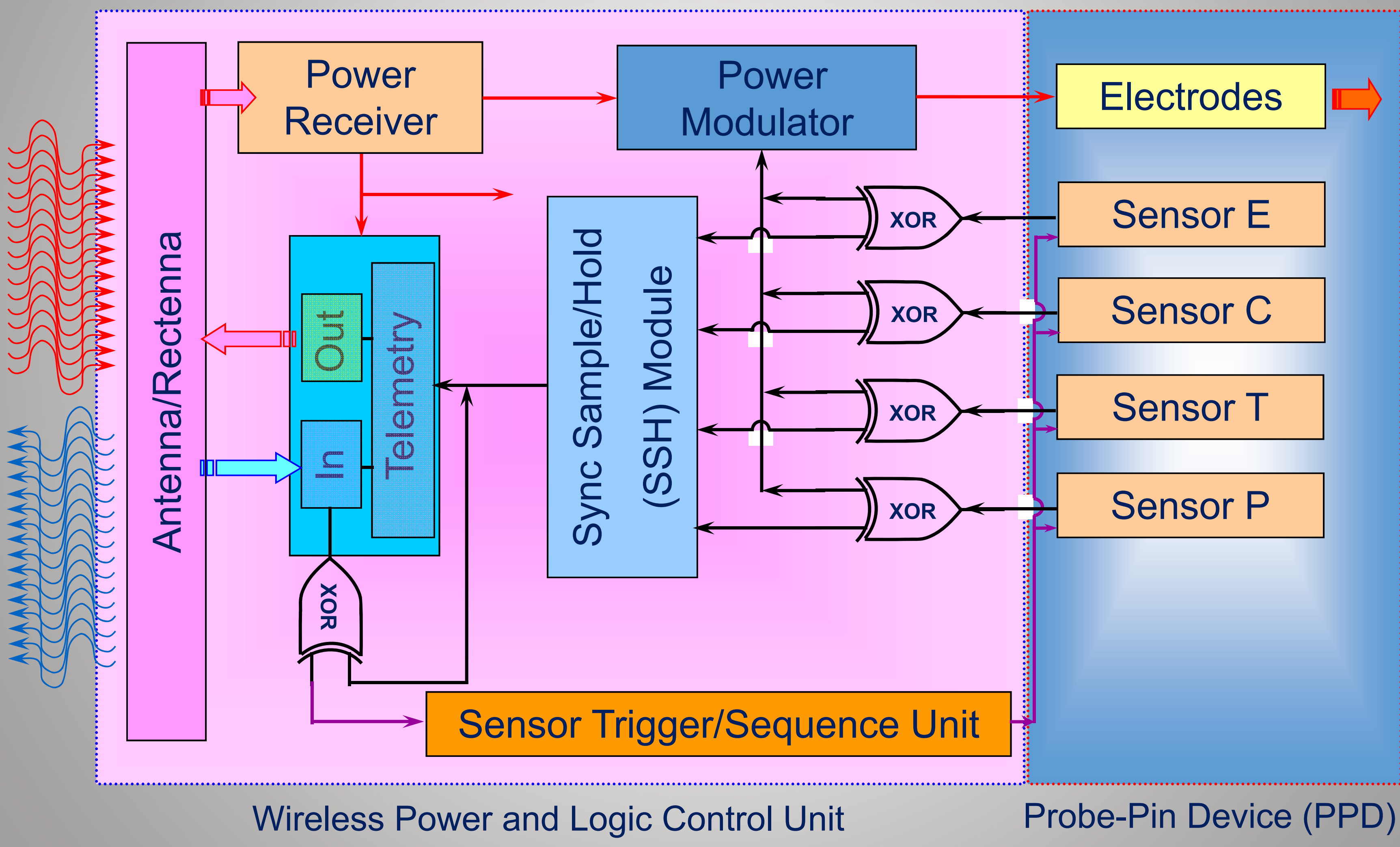
3. Packaging: 15.8mm x 7.87mm



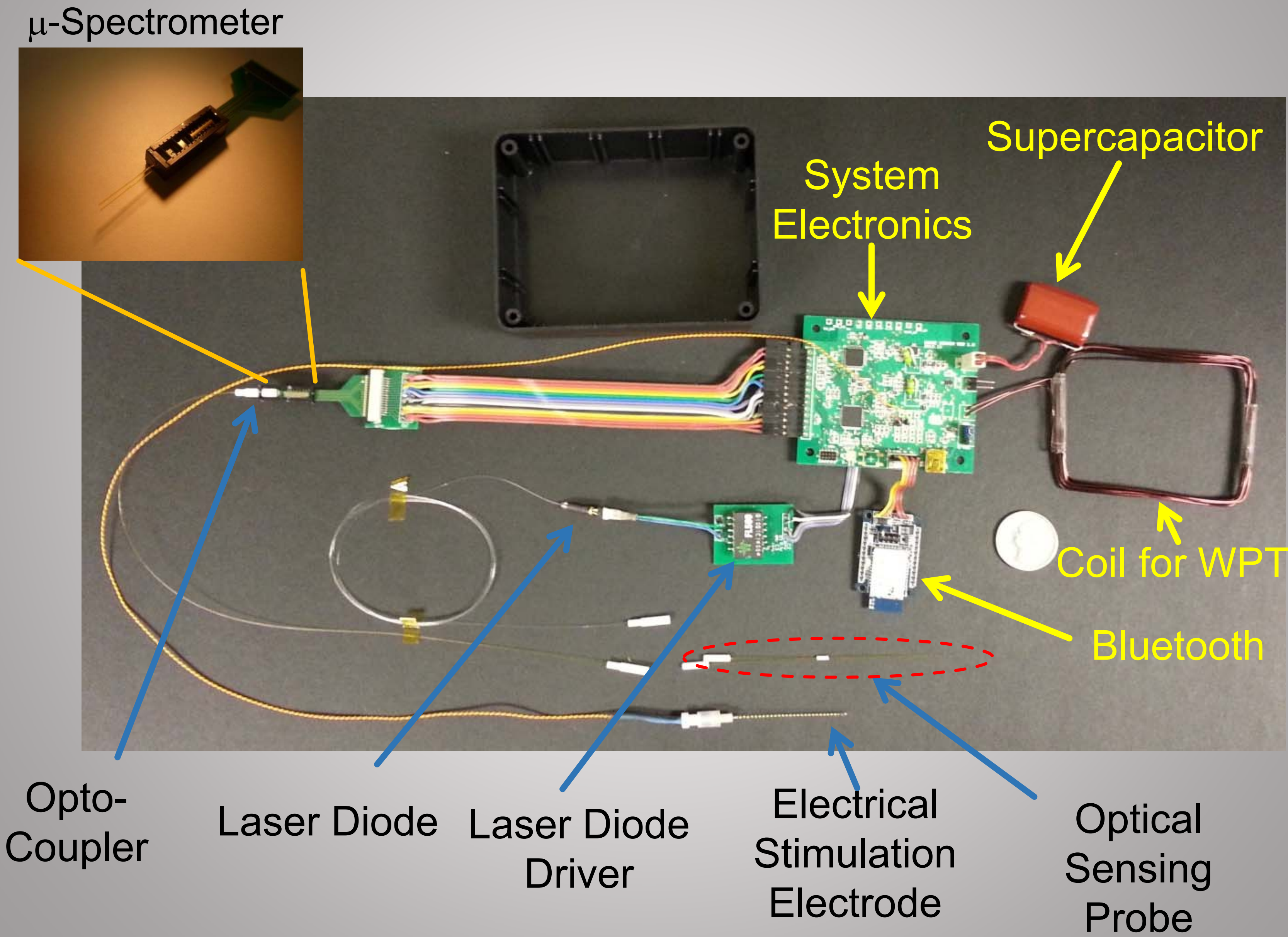
# Optical Performance of the $1^{st}$ Spectrometer Chip



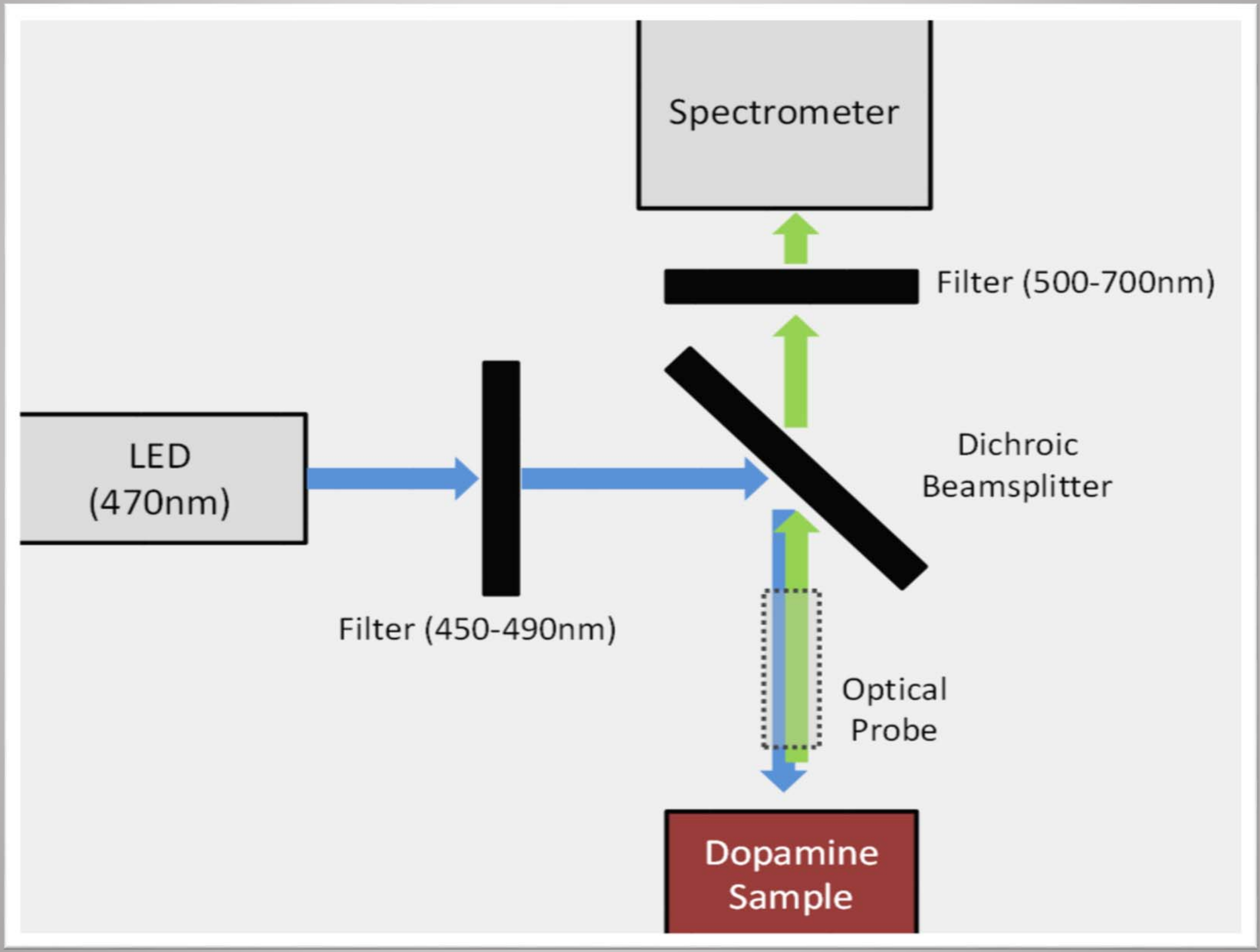
# PPD Logic (internal) with TFRA or MIC



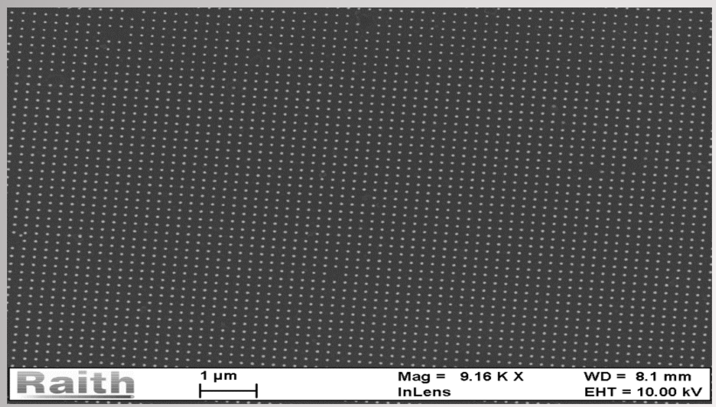
# 1-D Scan Prototype System

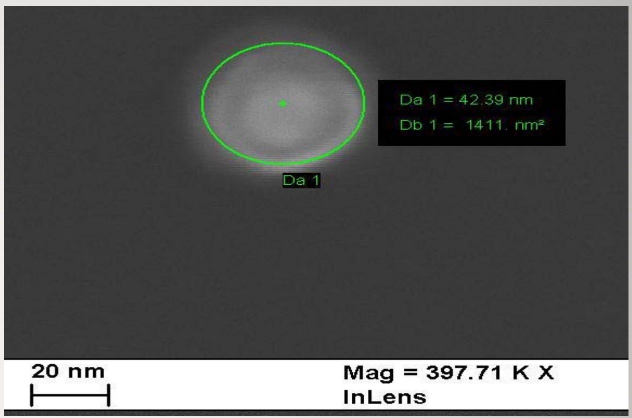


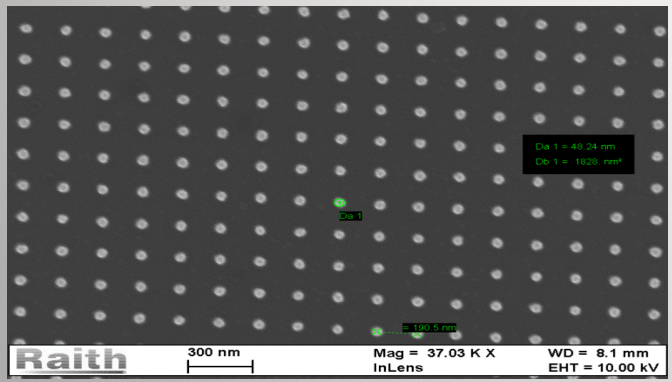
# Optical Sensing Diagram

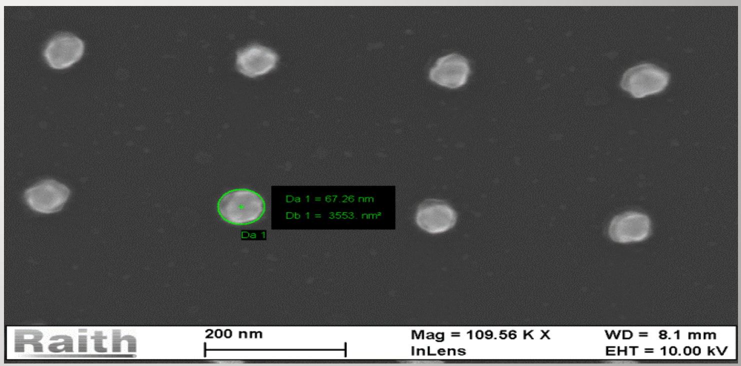


# SERS Substrates

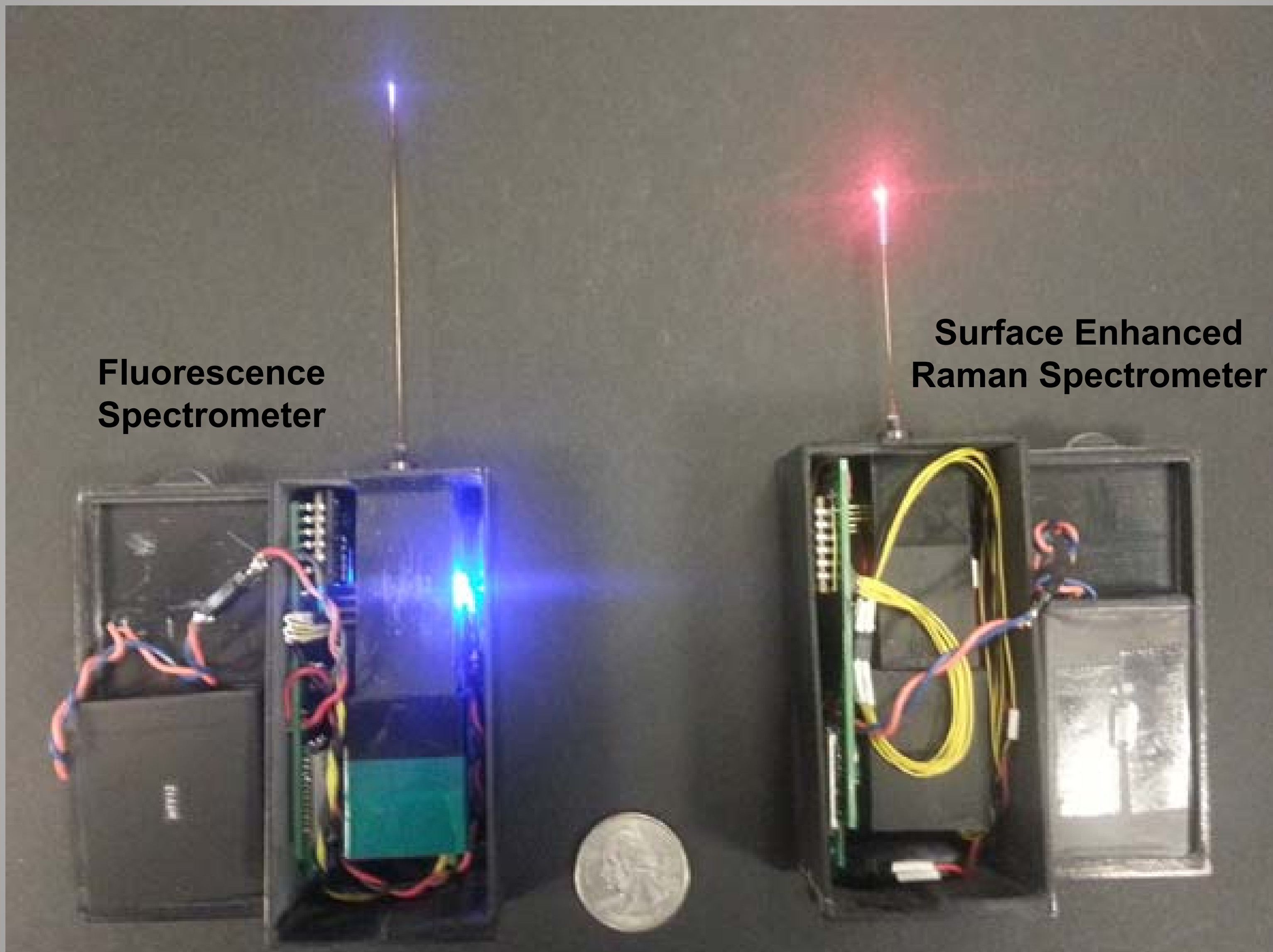


# Dopamine Sensing Modules



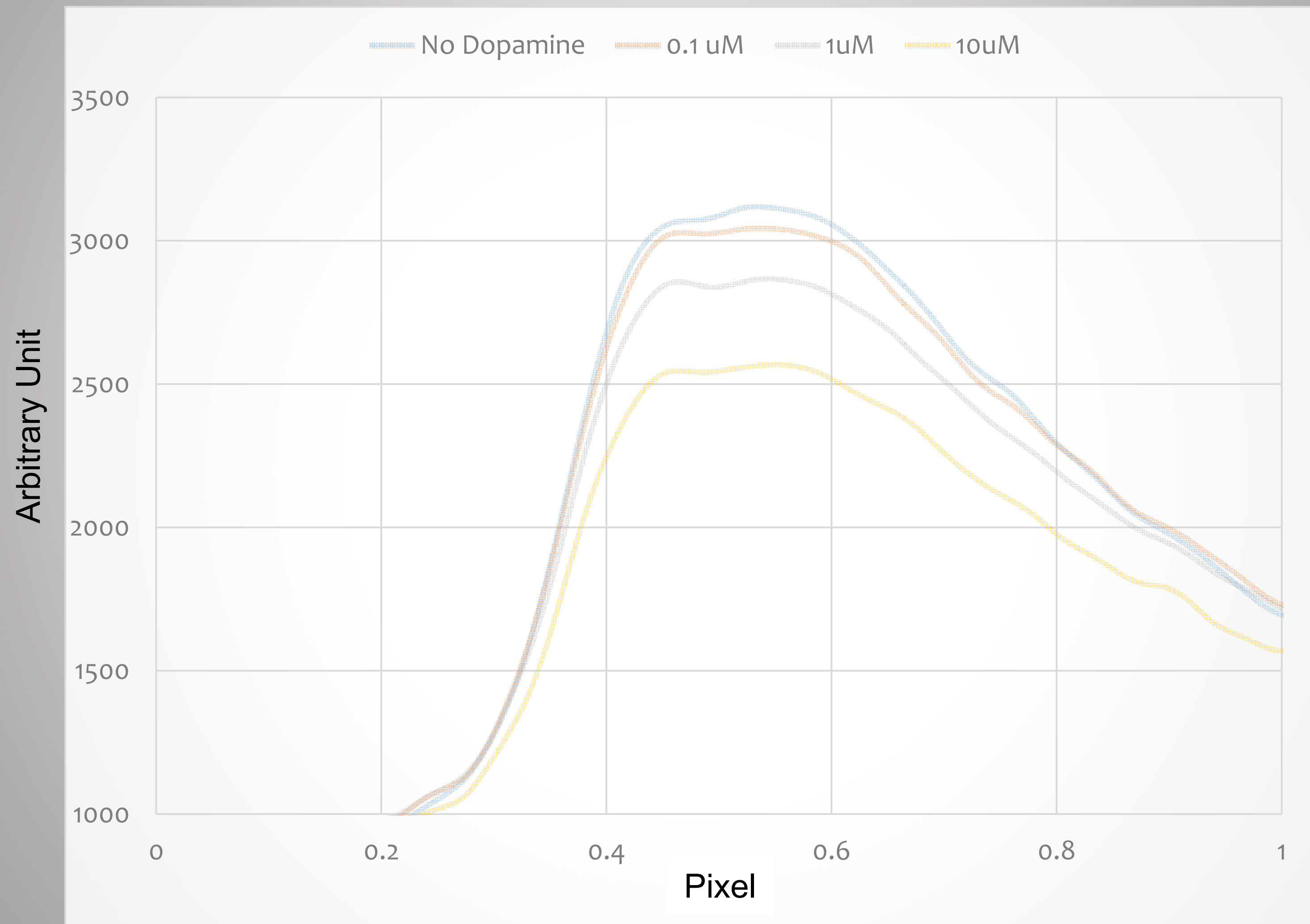
# Comparison Table

| | Current (Activa-PC+S)* | Prototyped (DBS+μ-Spectrometer) |
|---|---|---|
| Height | 65 mm | 54 mm |
| Length | 49 mm | 50 mm |
| Case Thickness | 15 mm | 20 mm |
| Battery Type | Primary cell | No battery<br>Wireless Power Transfer/Supercapacitor |
| Adaptive Sensing | Local Field Potential | Optical Sensing (Neurotransmitter) |
| Sensing Method | **Electrical Sensing** | **Optical Sensing** |
| Sensing Target and Range | Local Field Potentials (< mm) | Neurotransmitters (< mm)<br>O2Hb, HHb Concentration Change (< cm) |
| Longevity | **Depending on Battery Life and Usage ( < 5 years)** | **Wireless Power Transfer (no limit)** |

* Currently evaluated for FDA approval (first implantation: Aug. 7, 2013)

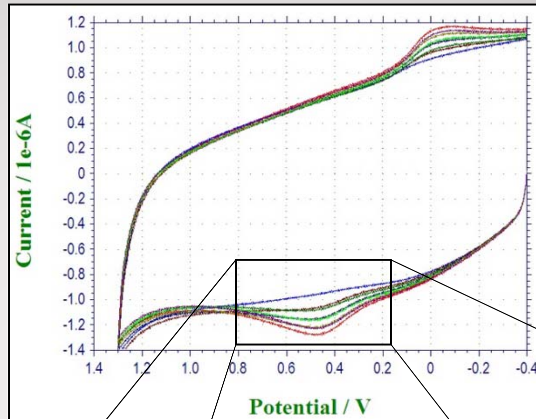
# Wireless Dopamine Sensing Test

# Dopamine Sensing Results

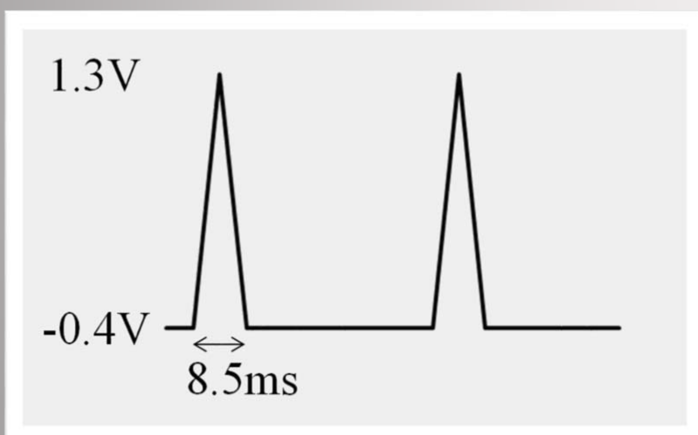


# Electrical Dopamine Sensing

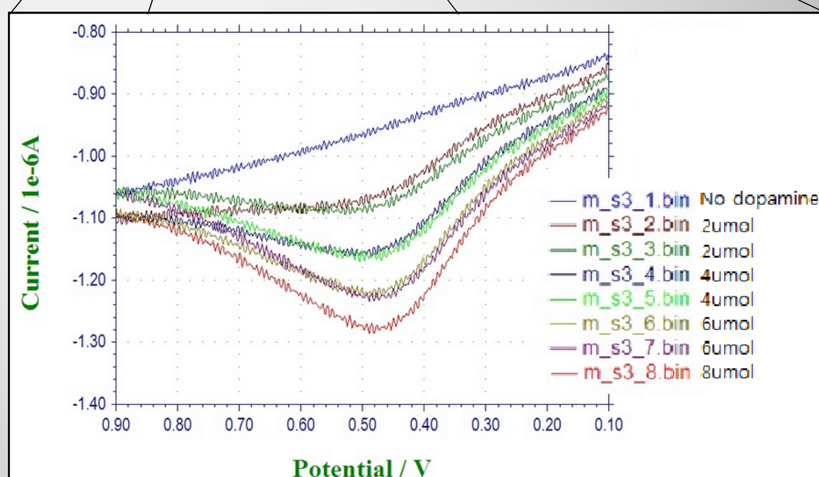
- FSCV, 400V/s
- Carbon fiber vs. Ag/AgCl
- Sensing electrode: Paralyne-C coated carbon fiber




o **Carbon fiber microelectrodes**



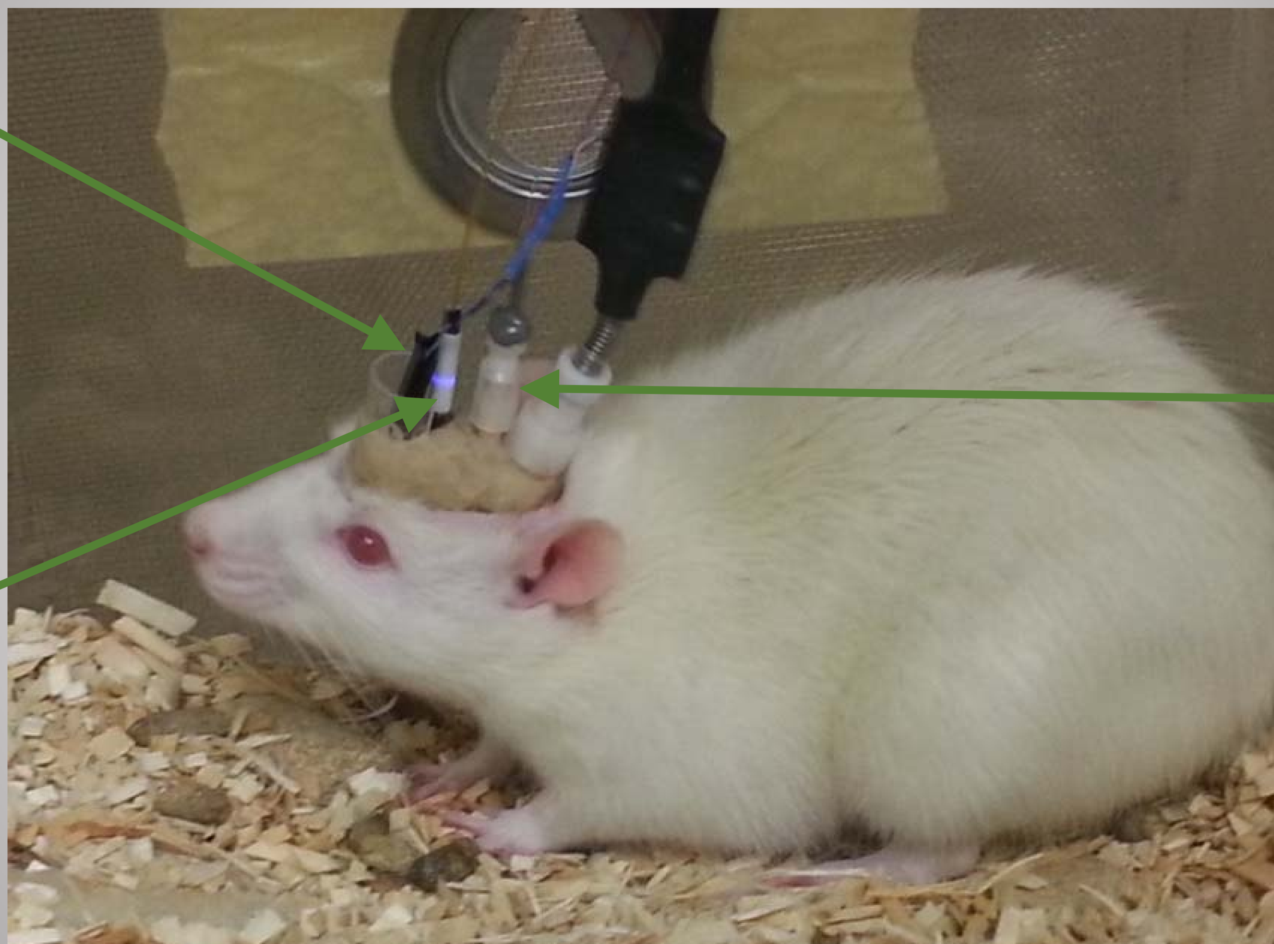

o **Voltammetry waveform**



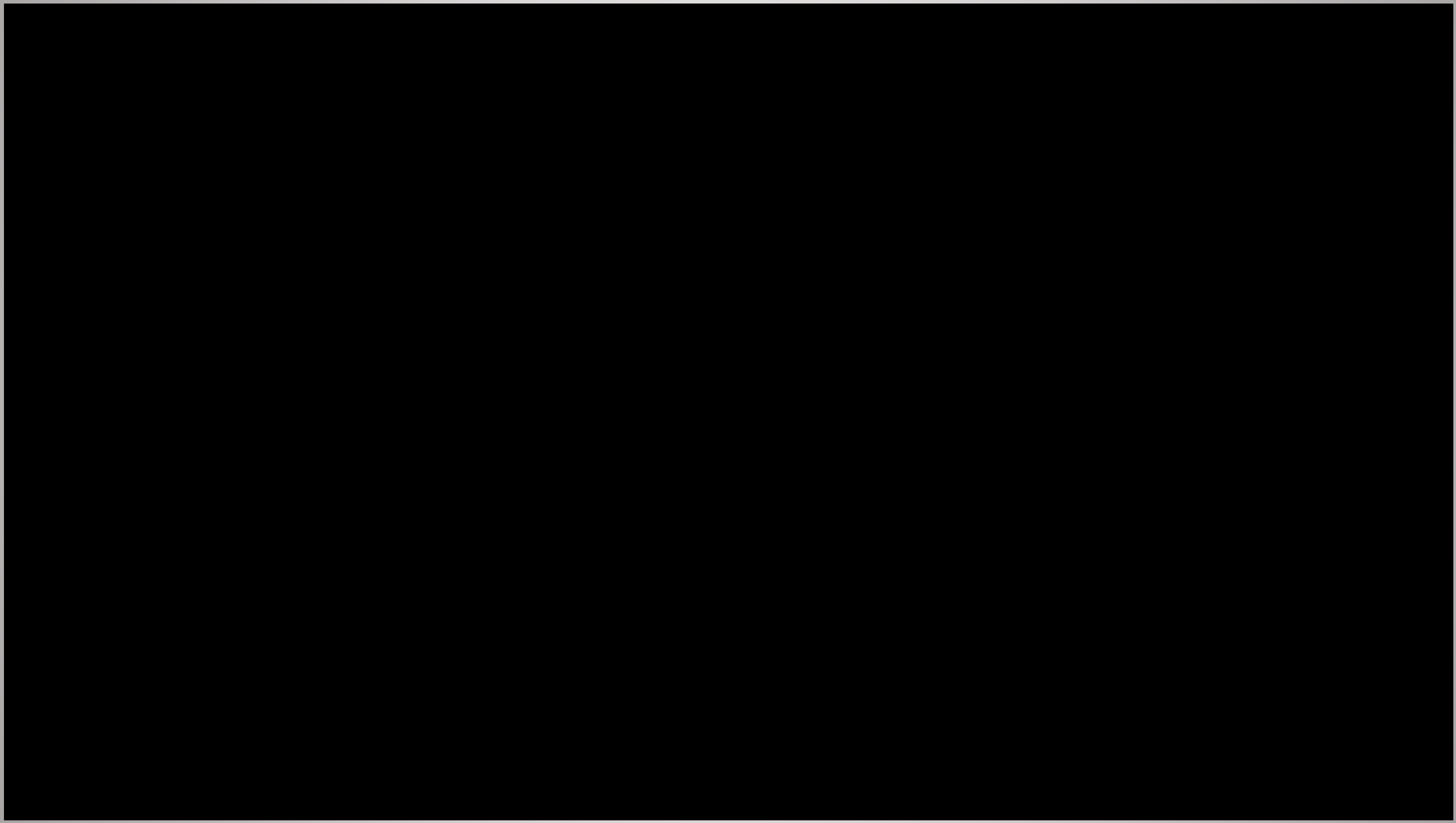

o **Result of cyclic voltammetry of dopamine sensing using carbon fiber electrode**

# Chronic Dopamine Sensing of Evoked Activity in Rat Brain

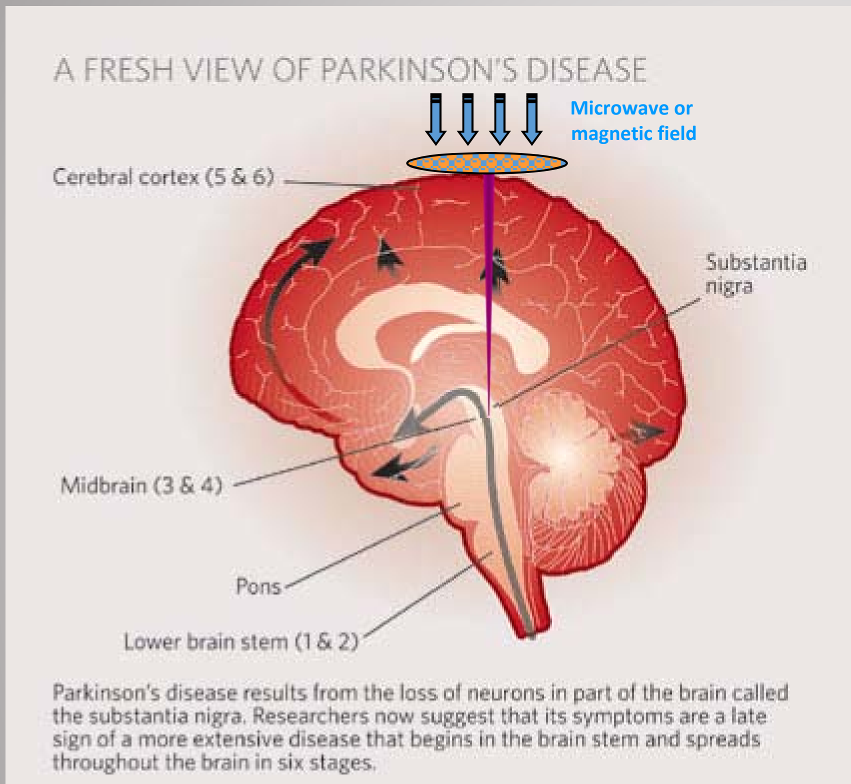
# Chronic Dopamine Sensing of Evoked Activity in Rat Brain



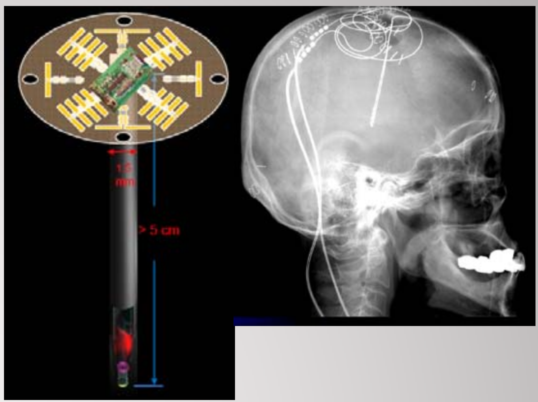
# Chronic Sensing Test



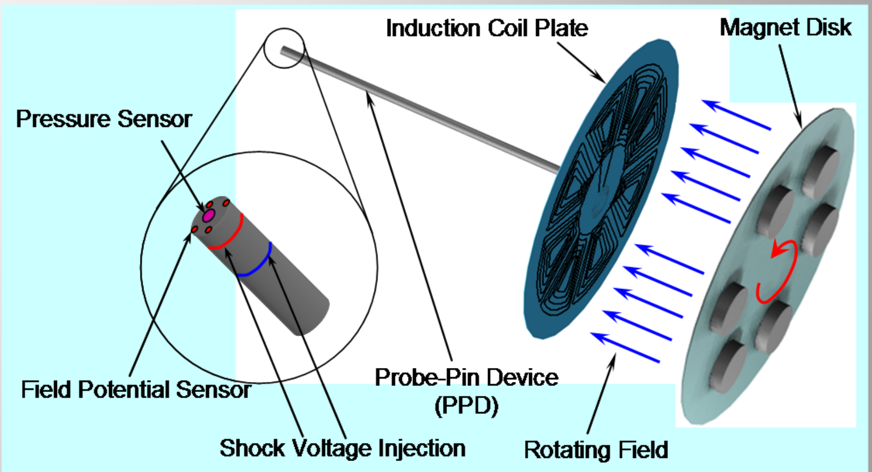
# Medical Applications of WPT




*A wireless power receiver with a probe-pin device (PPD) is implanted for deep brain stimulation (DBS). The wireless power receiver couples with incident microwave or with rotating magnetic field .*



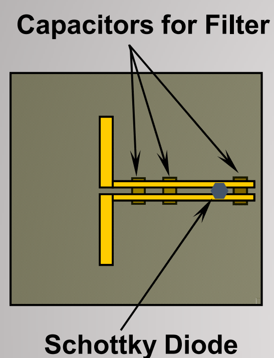
*An array of dipole rectennas with a probe-pin device (PPD) couples with microwave to generate DC power for DBS.*



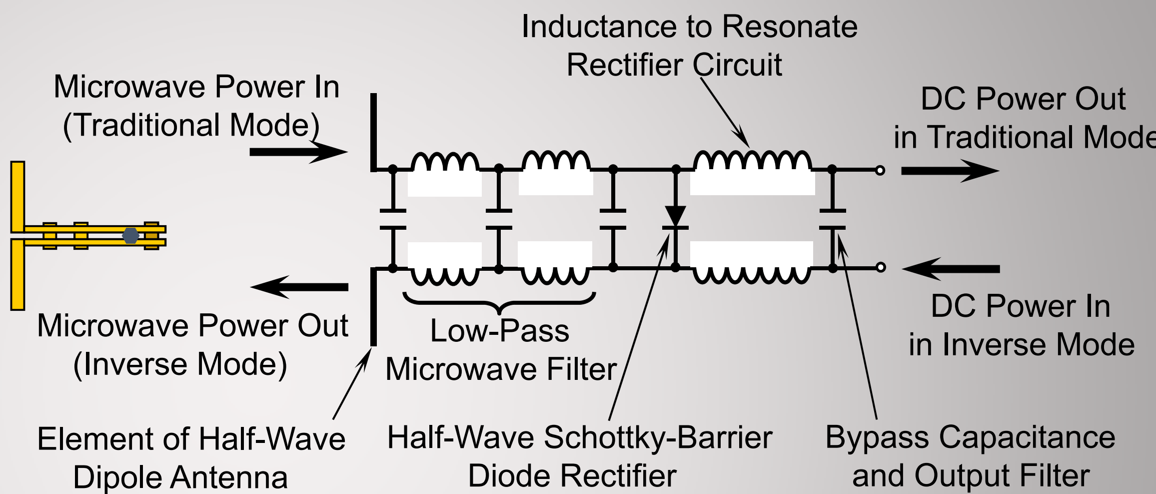

*A magnetic induction coils with a probe-pin device (PPD) couples with a rotating magnetic field for DC power for DBS.*

# Thin-film Dipole Rectenna Array

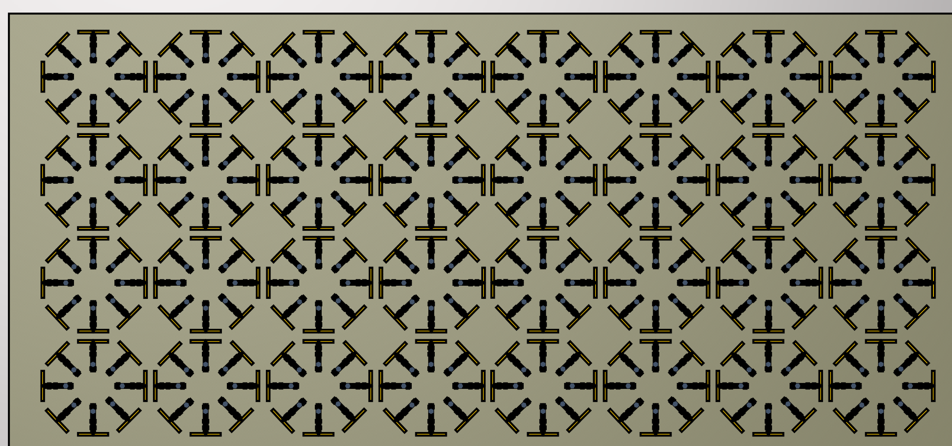
**Thin-Film Rectenna Dipole Element**



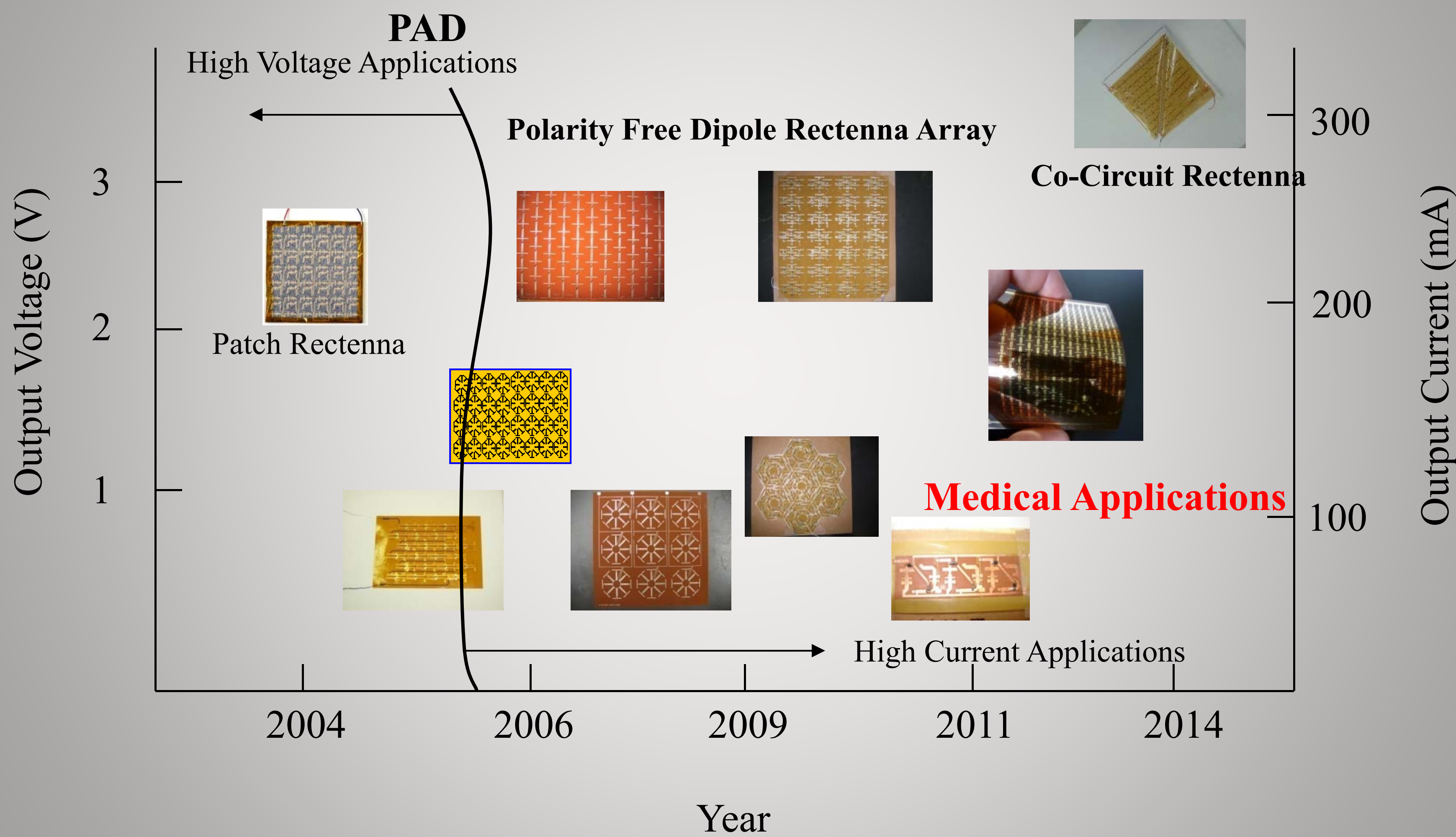

**Circuit of Thin-Film Rectenna Dipole Element**




**Densified Thin-film Membrane Dipole Rectenna Array (Langley Designed)**



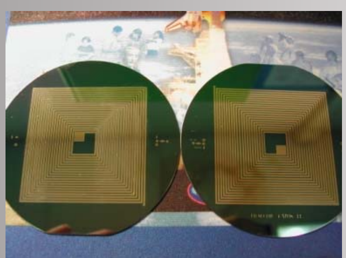
# Development of Dipole Rectenna



# Wireless Power Transfer

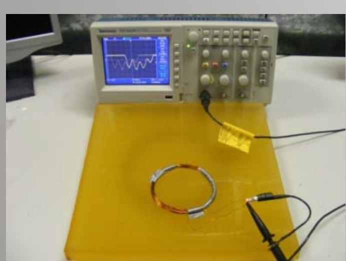
## Inductance Power Transfer

- 0-3 cm,  short range
- Safe for human interaction
- low power applications

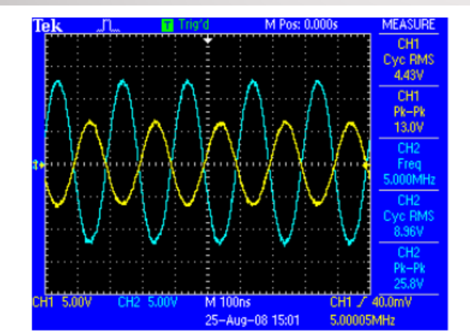


Planar  Coils

Coil powering an LED



Coil Test Setup

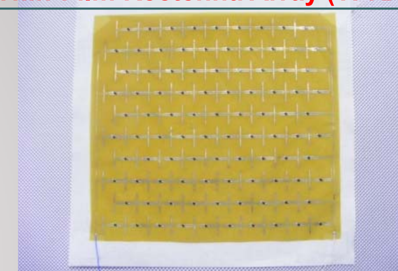


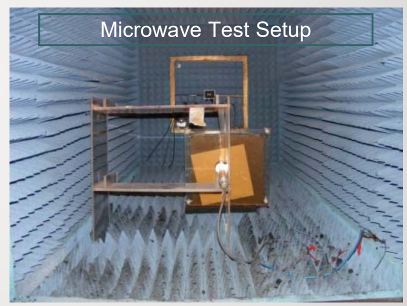

**8 mm** TDS 2022B - 3:01:24 PM   8/25/2008

## Microwave Power Transfer

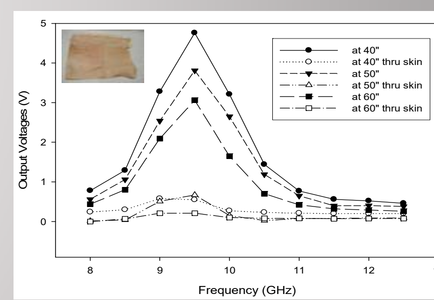
- 1-1000 m,  long range
- Low to high power

Thin-Film Rectenna Array (TFRA)

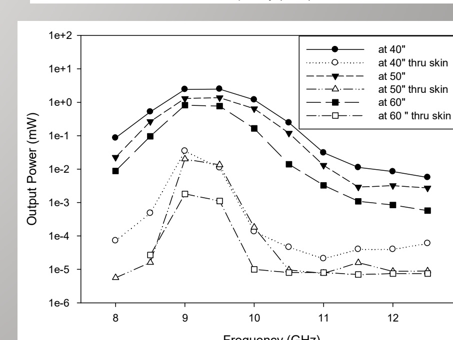




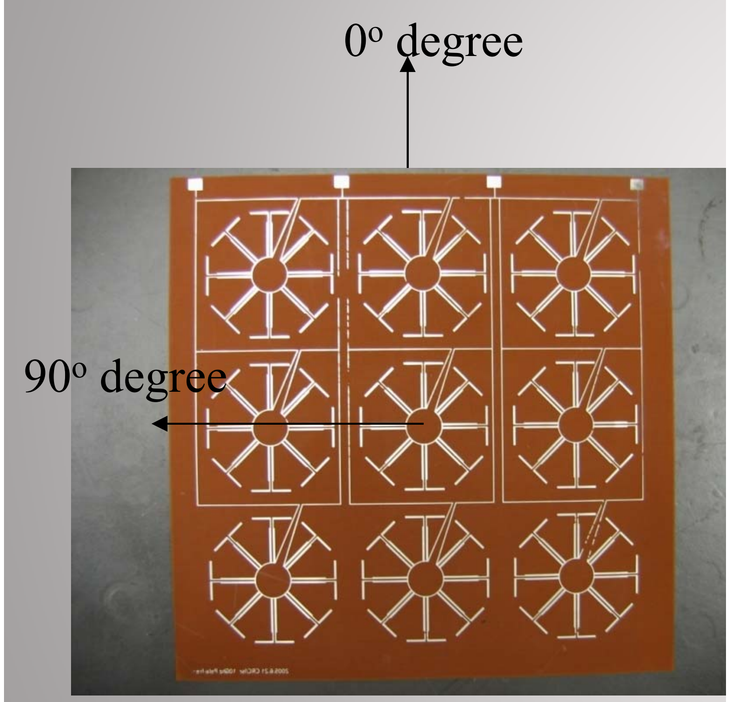

Flexible Rectenna Array



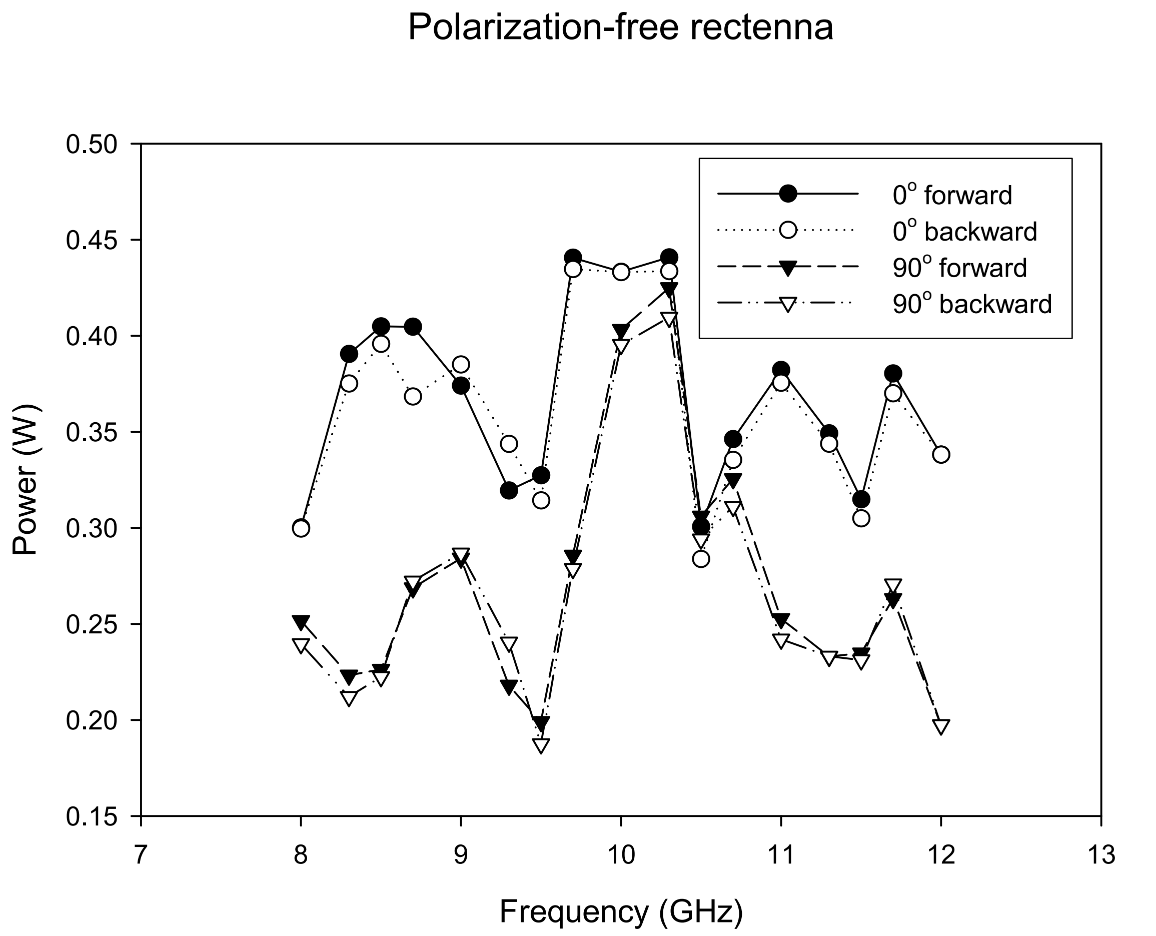

Microwave Generator and Amplifier



# Compact and Polarity-free Enhanced Dipole Rectenna Array

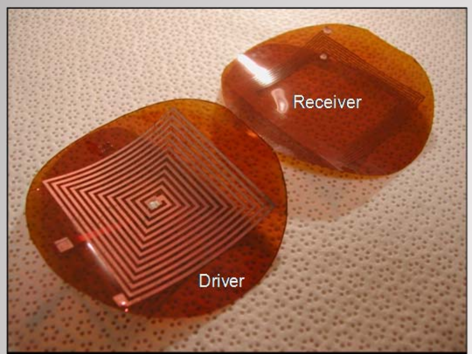



3 x 3 Flexible rectenna

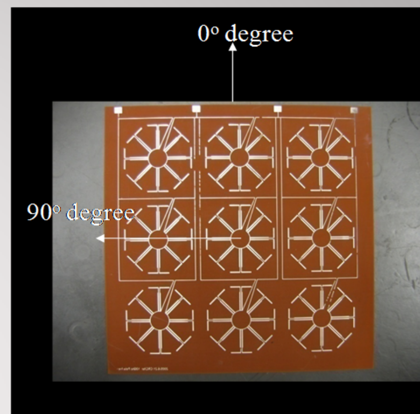


# Mobile Wireless Power Transfer with Micro Coil and Microwave

Micro Induction Coil (MIC)

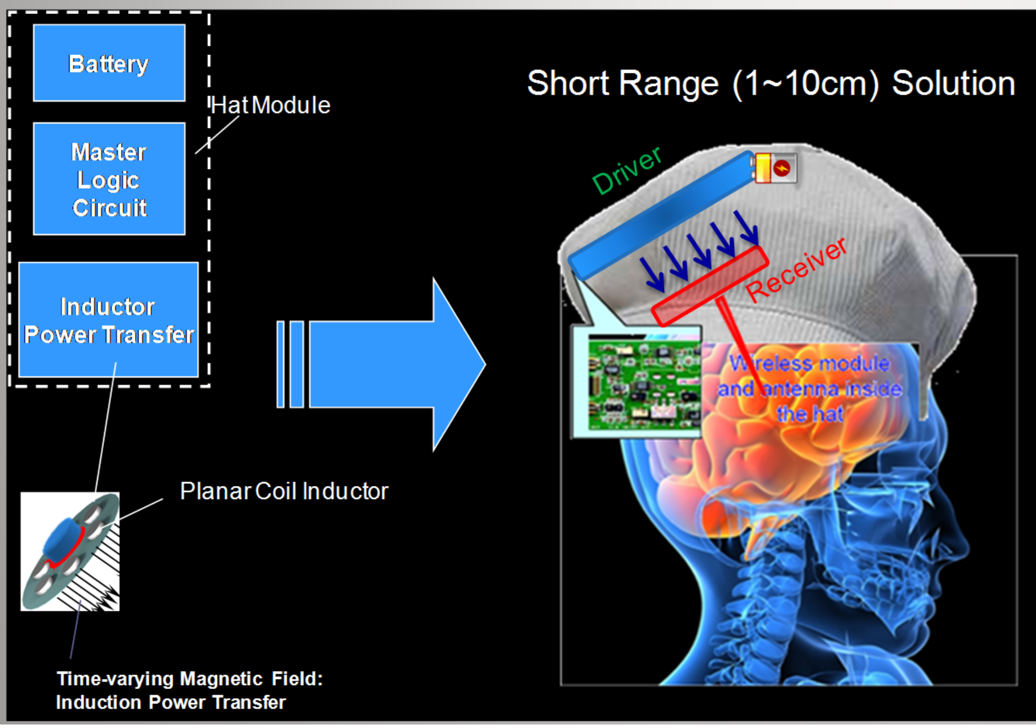


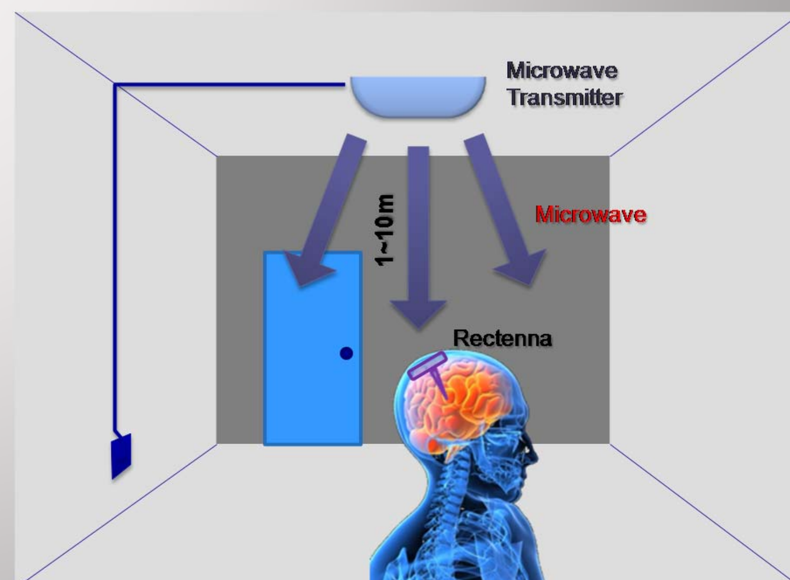
Flexible Membrane Inductor



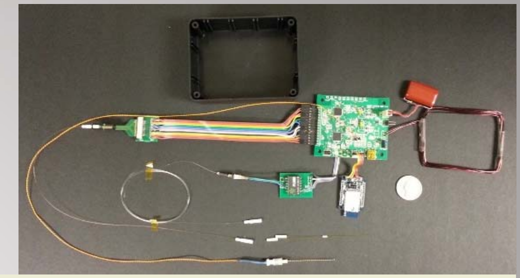
3 x 3 flexible rectenna

Thin-Film Rectenna Array (TFRA)

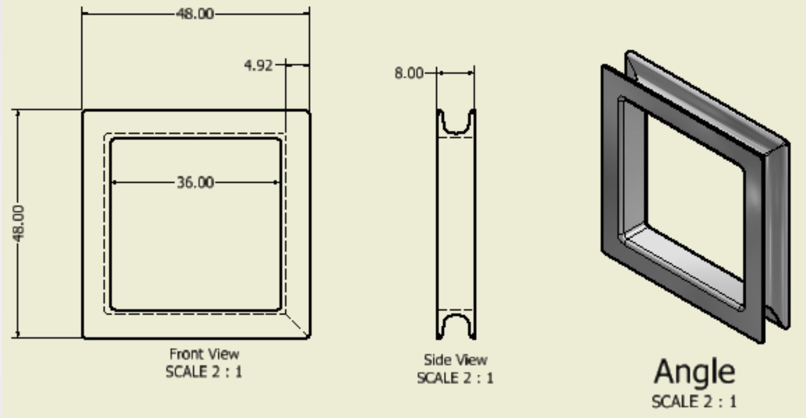


# Wireless Power Transfer: Magnetic Resonance Coupling



| Items | Coil-1 | Coil-2 | Coil-3 | Coil-4 |
|---|---|---|---|---|
| Coil Width | $d_{W1}$=35.5cm | $d_{W2}$=35.5 cm | $d_{W3}$=5.5 cm | $d_{W4}$=5.5 cm |
| Coil Height | $d_{H1}$=17.3cm | $d_{H2}$=17.3cm | $d_{H3}$=5.5cm | $d_{H4}$=5.5cm |
| Number of turns | 1 | 3 | N/A | 2 |
| Radius of coil | 5.6 mm | 5.6 mm | N/A | 0.325 mm |




| Sample | 3rd Gauge | 3rd Turns | Capacitor (pF) | Inductance (µH) | Resonant Frequency (MHz) | | Percentage Error | Output (V) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Calculated | Measured | | |
| A1 | 20 | 9 | 47 | 14.74 | 6.05 | 12.2 | 101.65 | 2.5 |
| A2 | 20 | 12 | 22 | 26.21 | 6.63 | 7.58 | 14.33 | 6 |
| A3 | 20 | 15 | 10 | 40.96 | 7.86 | 7.24 | 7.89 | 5 |
| A4 | 20 | 25 | 5 | 113.77 | 6.67 | 5.9 | 11.54 | 8.5 |
| A5 | 30 | 10 | 10 | 17.8 | 11.93 | 10.85 | 9.05 | 4.2 |
| A6 | 30 | 20 | 10 | 71.4 | 5.96 | 5.73 | 3.86 | 4.52 |

# Concluding Remarks

- Neural probe-pin devices (PPD) based on Fresnel diffraction micro-spectrometer were developed
- Neural PPD was successfully tested with animal brain
- Wireless power transmission through human tissue is a promising technology: microwave and magnetic induction coupling
- Microwave transmission through a thin skin was successfully tested and considered for the integration with neural probe-pin devices