Wirelessly Powered Micro-Spectrometer for Neural Probe-Pin Device

Dr. Sang H. Choi
NASA Langley Research Center
Hampton, VA

Dr. Uhn Lee
Gacheon Medical School
Incheon, Korea

Dr. Hargsoon Yoon and Dr. Kyo D. Song
Norfolk State University
Norfolk, VA

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Implanted Probes & Batteries

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

- Optical situation when light passes a spot, $S(\eta, \xi, 0)$ at a coordinate $(\eta, \xi, 0)$ 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.

$$u(P) = \frac{ia}{\lambda} \int S(\xi, \eta, 0) \frac{e^{-i\sigma}}{r} d\xi d\eta$$

Where $\lambda$ = wavelength, $k$ = wavenumber of light.

- According to Fraunhofer Terms

$$u(P) = \int S(\xi, \eta, 0) \exp[ik(l\xi + m\eta)] d\xi d\eta$$

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

- According to Fresnel Terms

$$u(P) = \frac{i}{m} \exp[-ikz] \int S(\xi, \eta, 0) \frac{\exp[-ik\left(x - \xi\right)^2 + (y - \eta)^2]}{2\pi r^3} d\xi d\eta$$

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.
Linear Fresnel Spectrometer

(a) Full circular
(b) Conventional Fraunhofer Spectrometer
(c) Linear Fresnel Spectrometer

(b) Conventional Fraunhofer Spectrometer

(c) Linear Fresnel Spectrometer

Fraunhofer Grating
Periodic Regular Lines

Fresnel Grating Gradient Lines

Focusing Axis
Focusing Plane
Focusing Axis
Focusing Plane
Optical distance $Z = \text{gap distance between Fresnel grating and the edge of the 0th pixel} + \text{pixel pitch/2} + (\text{pixel number} \times \text{pixel pitch})$.

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

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

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

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

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

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** ($\lambda = \frac{hc}{E}$).

**Fresnel Spectrometer (New)**

Fresnel spectrometer’s sampling is linear to the **energy scale** ($E = \frac{hc}{\lambda}$).
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

(a) Light
(b) Fresnel grating with gradient lines
(c) Imaging Sensor
(d) Offset between the edge and center
   Pixel pitch
   0th Pixel
   n-th Pixel
   Optical distance Z

500µm
Optical Performance of the 1st Spectrometer Chip

(a) Direct Beam (0th order)

1st order Fresnel diffraction peak (633nm, 1.96 eV, He-Ne Laser)

Tail of 0th order direct beam

(b) Red Laser (1.96eV, 633nm)  Green Laser (2.3eV, 543nm)

(c)
PPD Logic (internal) with TFRA or MIC

Power Modulator

Power Receiver

Telemetry

Sync Sample/Hold (SSH) Module

Sensor Trigger/Sequence Unit

Wireless Power and Logic Control Unit

Probe-Pin Device (PPD)

Electrodes

Sensor E

Sensor C

Sensor T

Sensor P

XOR

XOR

XOR

XOR

XOR
Optical Sensing Diagram

LED (470nm)

Filter (450-490nm)

Dichroic Beamsplitter

Filter (500-700nm)

Spectrometer

Optical Probe

Dopamine Sample
SERS Substrates
## Comparison Table

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

* Currently evaluated for FDA approval (first implantation: Aug. 7, 2013)
Wireless Dopamine Sensing Test
Dopamine Sensing Results

Arbitrary Unit

Pixel

No Dopamine  0.1 uM  1uM  10uM
**Electrical Dopamine Sensing**

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

![Voltammetry waveform](image)

![Result of cyclic voltammetry of dopamine sensing using carbon fiber electrode](image)
Chronic Dopamine Sensing of Evoked Activity in Rat Brain
Chronic Dopamine Sensing of Evoked Activity in Rat Brain
Chronic Sensing Test
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.

A magnetic induction coils with a probe-pin device (PPD) couples with a rotating magnetic field for DC power for DBS.
Thin-Film Rectenna Dipole Element

Capacitors for Filter

Schottky Diode

Microwave Power In
(Traditional Mode)

Microwave Power Out
(Inverse Mode)

Element of Half-Wave
Dipole Antenna

Circuit of Thin-Film Rectenna Dipole Element

Inductance to Resonate
Rectifier Circuit

Low-Pass
Microwave Filter

Half-Wave Schottky-Barrier
Diode Rectifier

Bypass Capacitance
and Output Filter

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

**Inductance Power Transfer**
- 0-3 cm, short range
- Safe for human interaction
- Low power applications

**Microwave Power Transfer**
- 1-1000 m, long range
- Low to high power

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**Planar Coils**

**Coil Test Setup**

**Coil powering an LED**

**Flexible Rectenna Array**

**Microwave Test Setup**

**Microwave Generator and Amplifier**

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**Thin-Film Rectenna Array (TFRA)**

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**Output Voltage (V)**

- at 40"
- at 50"
- at 60"
- at 40" thru skin
- at 50" thru skin
- at 60" thru skin

**Output Power (mW)**

- 1e-6
- 1e-5
- 1e-4
- 1e-3
- 1e-2
- 1e-1
- 1e+0
- 1e+1
- 1e+2

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**Frequency (GHz)**

- 8 9 10 11 12 13
Compact and Polarity-free Enhanced Dipole Rectenna Array

0° degree

90° degree

3 x 3 Flexible rectenna

Polarization-free rectenna

Power (W)

Frequency (GHz)

0° forward
0° backward
90° forward
90° backward
Mobile Wireless Power Transfer with Micro Coil and Microwave

Micro Induction Coil (MIC)

Flexible Membrane Inductor

Thin-Film Rectenna Array (TFRA)
## Wireless Power Transfer: Magnetic Resonance Coupling

<table>
<thead>
<tr>
<th>Items</th>
<th>Coil-1</th>
<th>Coil-2</th>
<th>Coil-3</th>
<th>Coil-4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coi Width</td>
<td>$d_{W1}=35.5\text{cm}$</td>
<td>$d_{W2}=35.5\text{cm}$</td>
<td>$d_{W3}=5.5\text{cm}$</td>
<td>$d_{W4}=5.5\text{cm}$</td>
</tr>
<tr>
<td>Coi Height</td>
<td>$d_{H1}=17.3\text{cm}$</td>
<td>$d_{H2}=17.3\text{cm}$</td>
<td>$d_{H3}=5.5\text{cm}$</td>
<td>$d_{H4}=5.5\text{cm}$</td>
</tr>
<tr>
<td>Number of turns</td>
<td>1</td>
<td>3</td>
<td>N/A</td>
<td>2</td>
</tr>
<tr>
<td>Radius of coil</td>
<td>5.6 mm</td>
<td>5.6 mm</td>
<td>N/A</td>
<td>0.325 mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>3rd Gauge</th>
<th>3rd Turns</th>
<th>Capacitor (pF)</th>
<th>Inductance (μH)</th>
<th>Resonant Frequency (MHz)</th>
<th>Percentage Error</th>
<th>Output (V)</th>
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</thead>
<tbody>
<tr>
<td>A1</td>
<td>20</td>
<td>9</td>
<td>47</td>
<td>14.74</td>
<td>Calculated 6.05  Measured 12.2</td>
<td>101.65</td>
<td>2.5</td>
</tr>
<tr>
<td>A2</td>
<td>20</td>
<td>12</td>
<td>22</td>
<td>26.21</td>
<td>Calculated 6.63  Measured 7.58</td>
<td>14.33</td>
<td>6</td>
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<tr>
<td>A3</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>40.96</td>
<td>Calculated 7.86  Measured 7.24</td>
<td>7.89</td>
<td>5</td>
</tr>
<tr>
<td>A4</td>
<td>20</td>
<td>25</td>
<td>5</td>
<td>113.77</td>
<td>Calculated 6.67  Measured 5.9</td>
<td>11.54</td>
<td>8.5</td>
</tr>
<tr>
<td>A5</td>
<td>30</td>
<td>10</td>
<td>10</td>
<td>17.8</td>
<td>Calculated 11.93  Measured 10.85</td>
<td>9.05</td>
<td>4.2</td>
</tr>
<tr>
<td>A6</td>
<td>30</td>
<td>20</td>
<td>10</td>
<td>71.4</td>
<td>Calculated 5.96  Measured 5.73</td>
<td>3.86</td>
<td>4.52</td>
</tr>
</tbody>
</table>
Neural probe-pin devices (PPD) based on Fresnel diffraction microspectrometer 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.