HIGH SCHOOL EDITION
Journal of Student Research
Volume 11 Issue 1 (2022)

Brain Computer Interfaces: Wireless Recording of Brain Signals with Electro-Plasmonic Nanoantenna

Alexa Lowe[1], Safaa Hussain[1], Grace Xia[1], Ahsan Habib[#], and Ali Yanik[#]

[1]The Harker School, San Jose, CA, USA
[#]Advisor

ABSTRACT

Brain-computer interfaces (BCIs) recording brain signals via implantable sensors aims to substitute, restore, improve, add, or enhance human functions. However, wiring requirements for power transfer and signal transmission, acute immune response to implanted electrodes, and the limited scalability of the ever-popular microelectrode arrays prevent wide adaptation of BCIs. Here, we show that electro-plasmonic nanoparticles, plasmonic nanoparticles loaded with an electrochromic polymer, can overcome the limitations of the conventional implantable microelectrode arrays as BCI probes. Much like radio frequency identification (RFIDs) tags that use backscattering for remote readout, electro-plasmonic nanoparticles report the spiking activity of neurons by modulating the input light and the re-radiated light spectrum. Our electro-plasmonic nanoantennas are non-invasive, wire-free, highly sensitive (field sensitivity up to 15.5%) and require no surgical implantation. We believe that electro-plasmonic neural probes can help usher in a new era of BCIs.

Introduction

A major challenge for the advancement of brain-computer interfaces (BCIs) is the absence of non-invasive, ultra-sensitive and high-bandwidth electric field sensors that record and report activity of neurons. Microelectrode arrays (MEAs), which consist of a grid of closely spaced microscopic electrodes, are the leading candidate for BCIs. Typical MEAs, also known as passive MEAs, comprise of a few hundred electrodes embedded in a glass substrate with off-chip signal amplification and actuation [1]. The number of electrodes is limited due to the wiring requirement, contributing to the system's total noise level and crosstalk. To overcome this issue, electrophysiologists employ active MEAs (a.k.a., CMOS MEAs) [2], which include integrated electronic components such as filters and amplifiers located directly beneath the electrodes' surface. As a result, active MEAs can provide superior electrode density, resulting in excellent sensing and actuation capability [1]. However, active MEAs must make a trade-off between electrode density (i.e., electrode size) and signal-to-noise ratio (SNR) [3]. The use of larger electrodes has the combined benefit of (i) increased signal due to lower electrode impedance and (ii) allows for a larger area for the signal processing elements, resulting in a better SNR. Even so, this method lacks spatial resolution, making single-cell detection difficult. Subcellular-sized electrodes, on the other hand, allow for greater electrode density and, ideally, single-cell recording. However, this detection method does not have a high SNR.

Furthermore, implantable MEAs consists of materials with elastic modulus far exceeding those of neural tissues, resulting in the formation of glial scars around the electrodes, which eventually encapsulate (insulate) the electrodes [4]. Because of the decrease in SNR, this type of immune response limits the long-term applications of MEAs. Recently, Elon Musk and Neuralink have demonstrated a high-bandwidth brain-machine interface system using flexible MEAs [5]. Although this method improves biocompatibility, it has the disadvantage of restricting the number of electrodes to a few thousand due to the inherent scaling limitations of MEAs. Furthermore, the devices consume a lot of

power due to the onboard amplification and digitization. Moreover, the electrode must be inserted into the brain via invasive surgery. As a result, widespread adoption of the MEA BCI remains an elusive, far-off goal.

In a 2019 *Science Advances* paper, Habib et al. introduced an ultrasensitive and extremely bright nanoscale electric-field probe that harnesses electrochromic response of conducting polymers to an external electric field [6]. They demonstrated that electrochromic polymers can be used as an electric field–controlled load, allowing active and reversible tuning of optical resonances through electrogenic cell activity. Unlike MEAs, this type of probe is not restricted by the electrode dimensions, physical wiring, or electronic bandwidth limitations as electro-plasmonic signal conversion eliminates front-end signal processing and allows remote readout. Furthermore, because of its nanoscale dimensions, it can be delivered to various brain regions without surgery [7]. Here, a conceptual utilization of this scalable, non-invasive, and long-lasting probe for the BCIs is shown in **Figure 1**. Our probe consists of (i) an ultrathin electrochromic polymer load and (ii) a plasmonic nanoantenna (nanoparticle). As shown below, a single nanoprobe can perform ultrasensitive wireless recording in vivo with a field sensitivity of up to 15.5% at visible wavelengths.

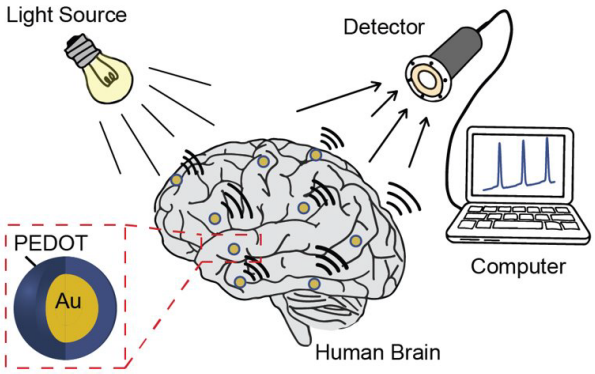

Figure 1. The envisioned function of the electro-plasmonic nanoantennas. Light shines on nanoparticles in the brain, resulting in scattering detected externally.

Methods

We used Finite Difference Time Domain (FDTD) simulations, a rigorous electromagnetic modeling tool, to understand light scattering from a spherical gold nanoparticle with an electrochromic load (**Figure 2A**). Our nanoparticle has a 60 nm diameter gold (Au) core, and a 20 nm thick Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) shell, which is small enough to cross the blood-brain barrier. We obtain light scattering spectrum of a plane-wave source within a wavelength range of 300–800 nm. For each simulation run, we adjusted the complex dielectric constant of the PEDOT material for different electric field values using Drude-Lorentz model to calculate the varying refractive index of the electrochromic material. Assuming a voltage difference of 100 mV in between a neuron's resting and firing states, we calculated the extracellular transient electric field using a capacitive model [7].

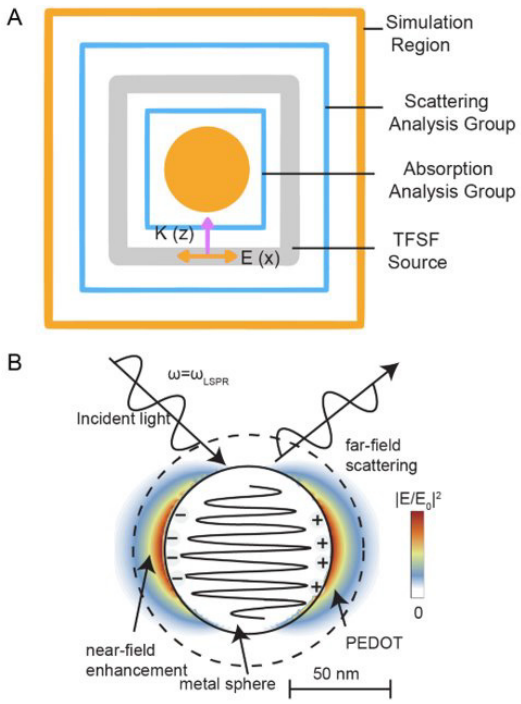

Figure 2. FDTD simulation setup and near-field enhancement: **(A)** FDTD allows us to realistically obtain data on the light scattering in different electric fields by adding objects such as a light source, and monitors. **(B)** FDTD allowed us to investigate near-field intensity enhancement distributions at resonance wavelength.

Results and Discussion

For external electric fields ranging from 0 mV/nm and 10 mV/nm, we compared plasmonic (gold) nanoparticles and electro-plasmonic nanoantenna response to external field. Because gold's dielectric constant is difficult to modulate due to its high electron density, changes in the scattering spectrum of pristine gold nanoparticles (plasmonic nanoparticles) were barely detectable. The PEDOT loaded electro-plasmonic nanoantenna, on the other hand, exhibits superior field sensitivity to external field [6]. Large differential scattering was enabled by the strong light-matter interactions at hotspots near the metal nanoparticle surface (**Figure 2B**), causing a significant red shift in the scattering spectrum as well as an increase in the scattering intensity at resonance (**Figure 3**). An intensity modulation of 15.5% at 600 nm for an external field of 10 mV/nm is observed, opening door to high SNR measurement capability. Although maximum differential signal is observed at 600 nm, electro-plasmonic response was strong enough at longer wavelength where light absorption within a biological tissue is significantly weaker, a critical requirement for *in vivo* measurements.

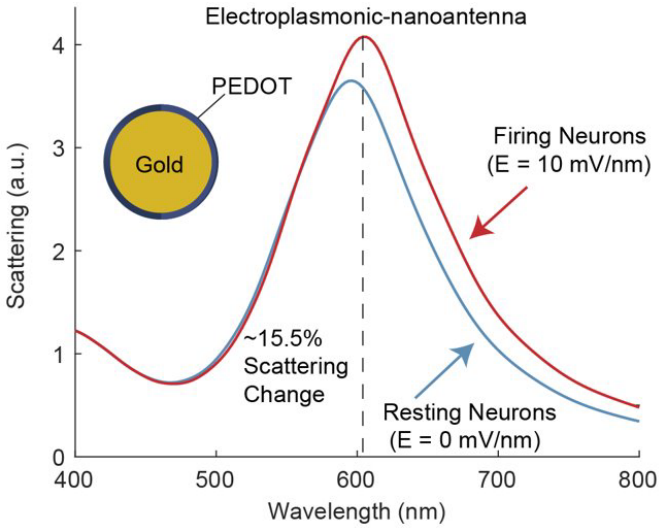

Figure 3. Scattering with electro-plasmonic nanoantenna: The scattering spectrums for a resting neuron (0 V/m) and firing neuron (10 mV/nm).

Conclusion

By capturing extracellular signals of the neurons using electro-plasmonic nanoantenna, we can translate brain activity into processible information for output devices, forming the essence of BCIs. Bridging the gap between neurons and computers have many important medical implications including high precision control of prosthetics with brain signals and neurorehabilitation. Our simulations prove that sensing neural activity with electro-plasmonic nanoantenna is a promising, effective, and sensitive method for BCIs.

Acknowledgements

We would like to thank the Science Internship Program at the University of California, Santa Cruz (UCSC), along with the UCSC Nanoengineering Group, for giving us the opportunity to conduct this research.

References

1. Miccoli, B., et al., High-density electrical recording and impedance imaging with a multi-modal CMOS multi-electrode array chip. Frontiers in neuroscience, 2019. **13**: p. 641. https://doi.org/10.3389/fnins.2019.00641

2. Müller, J., et al., High-resolution CMOS MEA platform to study neurons at subcellular, cellular, and network levels. Lab on a Chip, 2015. **15**(13): p. 2767-2780. https://doi.org/10.1039/c5lc00133a

3. Huys, R., et al., Single-cell recording and stimulation with a 16k micro-nail electrode array integrated on a 0.18 μm CMOS chip. Lab on a Chip, 2012. **12**(7): p. 1274-1280. https://doi.org/10.1039/c2lc21037a

4. Canales, A., et al., Multifunctional fibers for simultaneous optical, electrical and chemical interrogation of neural circuits in vivo. Nature biotechnology, 2015. **33**(3): p. 277-284. https://doi.org/10.1038/nbt.3093

5. Musk, E., An integrated brain-machine interface platform with thousands of channels. Journal of medical Internet research, 2019. **21**(10): p. e16194. https://doi.org/10.2196/16194

6. Habib, A., et al., Electro-plasmonic nanoantenna: A nonfluorescent optical probe for ultrasensitive label-free detection of electrophysiological signals. Science advances, 2019. **5**(10): p. eaav9786. https://doi.org/10.1126/sciadv.aav9786

7. Hardy, N., et al., Neuro-SWARM³: System-on-a-Nanoparticle for Wireless Recording of Brain Activity. IEEE Photonics Technology Letters, 2021. **33**(16): p. 900-903. https://doi.org/10.1109/LPT.2021.3092780