Tech Note TN03

Fast-charging of micro-batteries using directive ultrasound

A collaborative technical note by Ilika and Piezo Energy Technologies

Introduction

Medtech is transforming rapidly by embracing the progress in miniaturization of micro-electronic components and power-pack designs, combined with optimization of communication protocols and charging concepts. The Wireless Body Area Network concept (**WBAN**) is now real, which describes active implanted medical devices (**AIMD**) placed at an increasing number of places in the body: these devices sense biological parameters, provide therapies and transmit physical data wirelessly both in or out of the body. This concept enables in-home patient monitoring, without the requirement of constant hospital visits. Miniaturizing AIMD has several benefits: small devices can be implanted via subcutaneous or intravascular routes, and through other simpler and less risky procedures; smaller devices can be placed closer to the targeted organ for more effective application. For example, miniaturized AIMDs can be placed in close proximity to nerves, in lungs or heart, etc., and their placement is not limited to a few of anatomical pockets (e.g., chest, groin, or buttocks) as used for larger conventional implants. Examples of such AIMD include neurostimulation devices, cardiac sensing, smart orthopedic joints and others. Powering implanted devices has traditionally been achieved using bulky primary (non-rechargeable) batteries. For example, batteries in conventional pacemakers represent 2/3 of the device's volume. In addition, passive devices are powered wirelessly and episodically by an external transmitter: this latter example limits the functionality of the devices to only the time-windows when it is externally powered. Using rechargeable batteries in AIMD is an increasing occurrence whilst United States Food and Drug Administration (**FDA**) has so far allowed this design primarily in non-life-critical devices. By miniaturizing AIMD, product designers place tough requirements on the size of batteries, which will unavoidably carry less energy than larger ones, and will need frequent recharging. Patient compliance with regular charging has also historically been low, hence solutions for charging AIMD rapidly would go some way in improving adoption of small medical implanted devices.

This technical note reports on a collaboration between Ilika Technologies (**Ilika**) and Piezo Energy Technologies (**PET).** It demonstrates the rapid recharging of a miniature solid state battery using ultrasound wireless power transfer **(UWPT)**.

Ultrasound wireless power transfer

Most wireless charging modalities use electro-magnetic (**EM**) fields for charging AIMD and are regulated by Federal Communications Commission standards – kHz to MHz bands used in power transfer; and ~GHz frequencies for Bluetooth and Wi-Fi protocols. In contrast, ultrasound waves propagate via particle motion and require a material medium. Ultrasound beams can easily couple energy through metallic and non-metallic AIMD shell materials. For example, a miniaturized AIMD located several centimeters deep in soft tissue can effectively be charged wirelessly with an ultrasound source, due to the beam's directive nature, and a nominal 0.5 dB/cm/MHz attenuation coefficient. At MHz frequencies, with a short wavelength (order of millimeters) compared to a transmitter's several centimeter dimensions, ultrasound energy can be electronically steered when source – AIMD misalignment is detected.

PET is developing an ultrasound technology that can recharge batteries within an AIMD, and shows potential benefits versus more traditional EM technologies. Ultrasound technology has a several decades-long record of safe-use in diagnostic imaging. For imaging, it works by the propagation of an acoustic wave through human tissues and recording of discrete reflected signals from various tissue interfaces, by the same external transducer ("pulse-echo"). For transfer of power to an implant *in situ*, a piezoelectric transmitter applied onto the skin sends an ultrasound wave through the body to a receiver incorporated within the AIMD ("pitch-catch"). The piezoelectric receiver converts the mechanical (ultrasound) energy into electric energy. For the transmitter and receiver, suitable piezoelectric materials are used, which convert electrical energy into mechanical energy (transmitter) and vice versa (receiver). Incorporated within the AIMD, the receiver interfaces with a very compact, miniaturized, all-in-one chip which powers the AIMD or recharges a SSB for later use. Ultrasound fields do not interfere with other EM signals, making it safer if charging takes place in proximity of other EM signals such as at home or in a healthcare facility. The design is based on the form factor envisioned for current applications: with a ~25 mm diameter transmitter operating at low-MHz frequencies, the acoustic field is directive, like a collimated "flash light." If needed, the transmit beam can be electronically steered using a simple multi-element array. After detecting misalignment through active feedback or passive means, the electronic steerability is one means of improving transferred energy efficiency by correcting for positional transmitter-receiver offset. Electronic beam steering is not possible for EM-based systems used for powering AIMD, due to the large signal wavelength compared to the transmitter dimensions. As opposed to other power transfer modalities, UWPT for miniaturized AIMD is potentially more viable in delivering useful ultrasound charging energy for SSB deeper in the body, as well as accessing metal-clad implants with ultrasound energy. In fact, PET has issued patents for effective ultrasound charging of implants using dry (non-gel) coupling of the transmitter to skin, combined with array-based optimization of energy transfer efficiency using a close-loop system, correcting for transmitter-receiver misalignment.

Miniature solid state batteries

Solid state batteries are rechargeable lithium-ion batteries (**LIB**) where the liquid electrolyte has been replaced by a solid ceramic material. Because SSB do not include a liquid, they do not need to be packaged in a metallic foil or can, which avoids leakage in LIB. Hence, the lack of a bulky packaging enables manufacturing of SSB of smaller dimensions than LIB. SSB technology is also safer than LIB since it does not incorporate a toxic, flammable electrolyte. SSB have a cuboid form factor enabling compact printed circuit board design with other integrated components. SSB cells can be stacked on top of each other and connected in parallel to create packs of cells of higher energy but same footprint as a single cell. Finally, SSB comprise of electrodes and electrolyte layers of micron-level thickness: these thin films enable rapid ionic transfer, high power capability and fast charge. Ilika is developing a range of solid state batteries, branded Stereax, ideally suited for miniaturized AIMD. The experiments described in this technical note used a proof-of-concept, non-commercial prototype of cm-scale (Stereax M250), but Ilika is now developing SSB with higher energy density, 300 µAh capacity and a 3.6 mm x 5.6 mm x 1.1 mm envelop.

Description of the experiment

The aim of this collaboration between Ilika and PET was to demonstrate, using physical prototypes, that ultrasound energy could be used to recharge a miniaturized solid state battery. Hence, this experiment simulates the charging of an SSB-powered AIMD implanted inside the body using power transfer via ultrasound. This experiment also demonstrates that both ultrasound and SSB technologies are aligned with miniaturization trends in the medical device industry: for example, the transmitter was only 25 mm diameter, the (“spot”) receiver was a 0.75 mm x 3 mm “sliver” with sub-millimeter thickness.

Description of the hardware used

A 1 MHz, planar transducer, 25 mm diameter, was aligned with the spot receiver having nominal dimensions of a few wavelengths compared to the source field (wavelength = 1.5 mm). The acoustic propagation medium was 0.9% saline, whereas the transmitter-receiver range was 90 mm. A schematic of the experimental set up and the signal conditioning for SSB charging is shown in Figure 1.

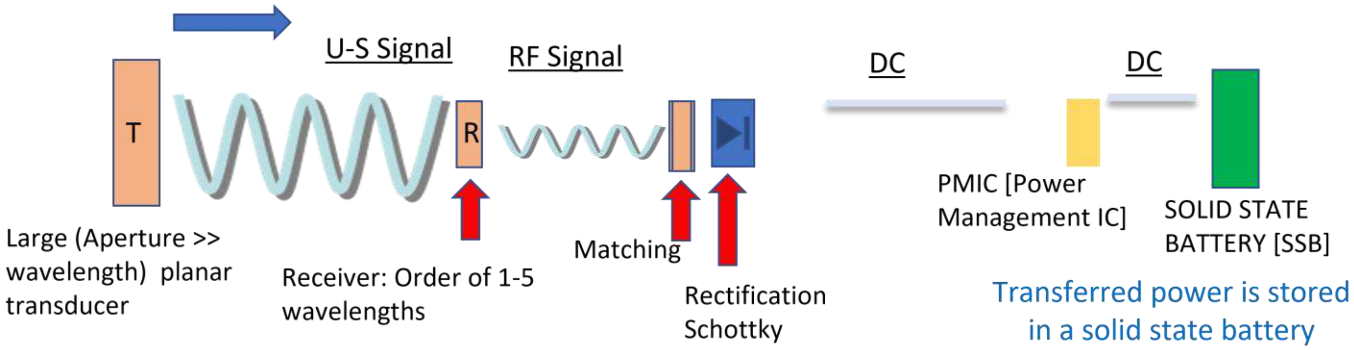

Figure 1: UWPT spot-receiver concept: signal transition schematic

For the present experiment series, the transmitted acoustic power was 0.25 W. The field resulting from these source parameters is much less than the FDA mandated maximum derated spatial maximum intensity of 760 mW/cm^2. Temperature increases calculated at this source power in tissue media are anticipated to be much less than the maximum recommended 2˚C. The maximum acoustic pressures resulting from our source conditions at 1 MHz are well below the acoustic cavitation thresholds in fluid media and FDA requirements, accounting for a safe operational mode. In terms of safe energy delivery, during extensive *in vivo* porcine experiments, as reported in the resources listed with this note, PET has been able to demonstrate delivery of up to 2 W of acoustic power without any histological damage to the intervening porcine tissue following about 2 hours of continuous charging of an implanted 200 mAh lithium battery.

The acoustic energy at the large-acceptance angle spot-receiver 90 mm distant from the 25 mm source is converted to a 1 MHz electrical signal. With appropriate impedance matching a Schottky doubler circuit rectifies the signal, which is input into a Power Management Integrated Circuit (**PMIC**) SPV1050 (ST Microelectronics), enabling charging of an Ilika SSB. Charge current for the SSB and battery voltage was constantly monitored. A block diagram of various components is included in Figure 2 as a schematic.

The battery used in these experiments was a Stereax M250 SSB from Ilika, with 250 µAh capacity, 3.5 V nominal voltage and dimensions 18 mm x 20 mm x 0.7 mm, Figure 3. In these experiments, charging was limited to ~ 3.9 V to avoid damaging the battery whose maximum charging voltage is 4.0 V.

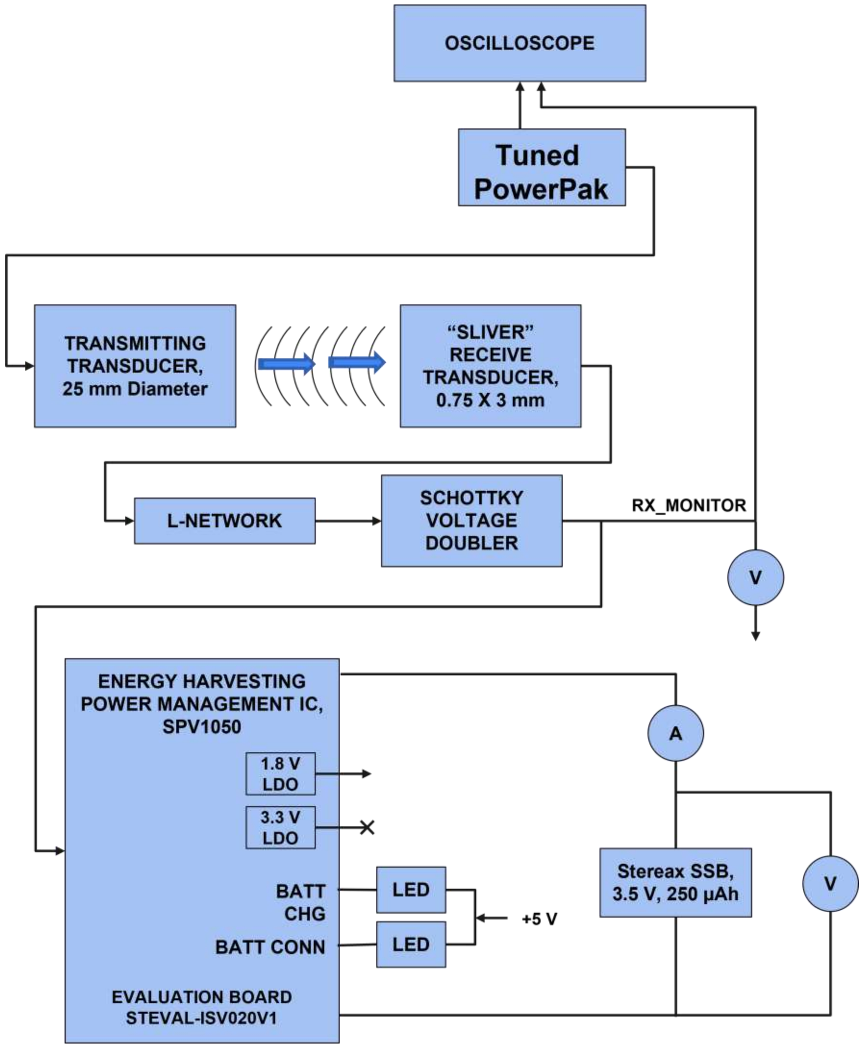

Figure 2: Block Diagram of UWPT Spot-Charging Test Set Up

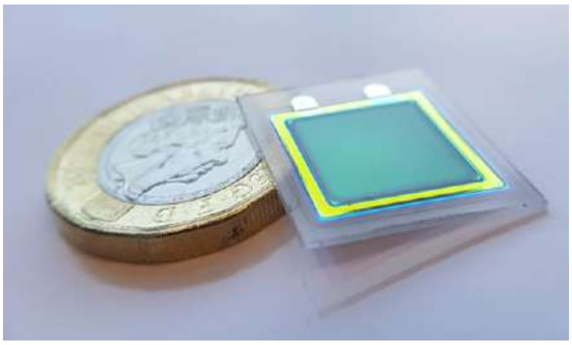

Figure 3: Photograph of Stereax M250

Results

By measuring current input into the battery and battery voltage, charging was observed over time. Characteristic curves for charging a fully depleted Stereax M250 SSB were obtained. A representative plot for charge current and battery voltage is shown in Figure 4: with a nominal charge duration of 20 minutes (3C), the battery voltage reached ~3.9 V, which is near the maximum recommended charging voltage (4.0 V). After 20 minutes, the charging current was left to decay slowly and minimal additional capacity was added in the battery. The battery was then discharged into a load down to 3.0 V is a 750 µAh current (3C): the capacity measured upon discharge was ~ 250 µAh, Figure 5. For propagation through tissue, by increasing the source power, the present set up can easily be scaled up to achieve rapid charging of the Stereax SSB while accounting for tissue attenuation.

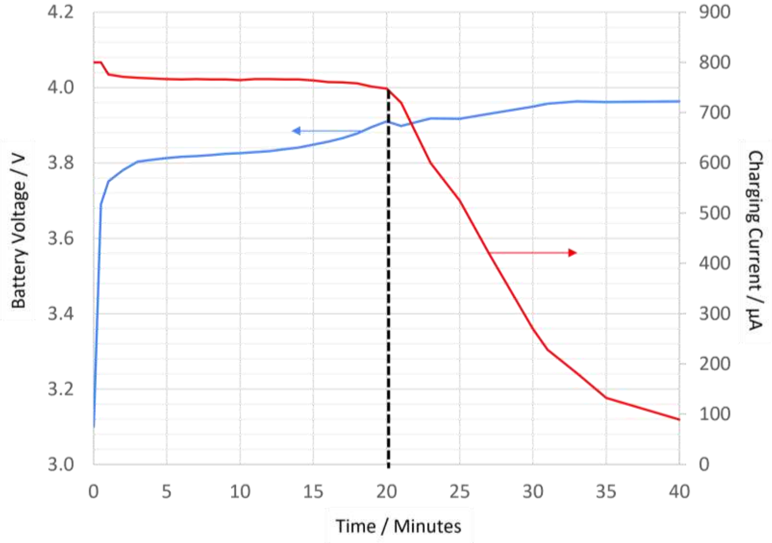

Figure 4: Example of battery charging profile (blue) and corresponding charging current (red). Power was ~ 3.1 mW, corresponding to ~ 3C charge

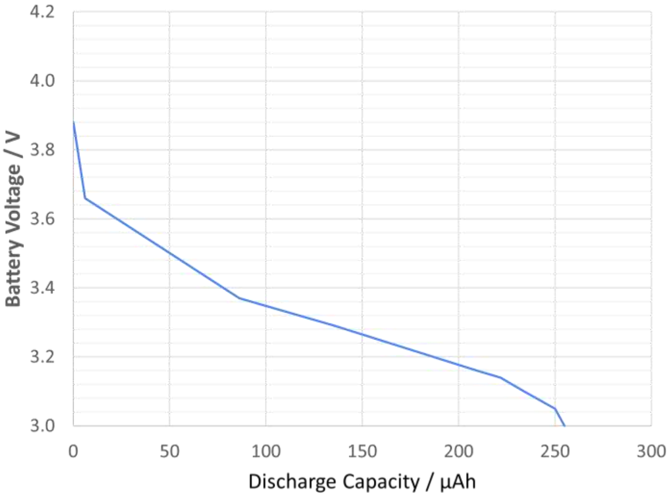

Figure 5: Constant current discharge plot at 750 µAh (3C)

Discussion

Our experiments demonstrate for the first time that a miniature SSB can be recharged in approximately 20 minutes (3C) using a 1 MHz ultrasound source and spot receiver. Using saline as a test environment, these experiments mimic the recharge of a mm-scale battery powering a miniature AIMD, using safe ultrasound technology. The ability of this system to charge the battery rapidly could enable fast charging of next-generation AIMD and improve patient compliance with regular recharging. A PET publication referenced (see Resources) describes a more sophisticated approach of initiating a steerable ultrasound signal using an array transmitter, in combination with a closed loop correction algorithm. This methodology can further achieve more predictable charging of the miniaturized SSB implanted deep in the body.

The current experiments also demonstrate a scalable system that can be adapted depending on the application, e.g., depth in the body and dimensions and energy requirement of implanted devices, by varying battery size and capacity, as well as power density, footprint and the number of spot ultrasound receivers. As described in associated published results, PET has demonstrated charging of a 200 mAh battery in 30-60 min during *in vivo* acute and 4-week survival porcine studies. Although the battery used in the current demonstration was small, only 250 µAh, and part of Ilika's development road map, a sweet spot for next generation miniaturized AIMD would be a slightly higher capacity battery on the order of 1-5 mAh, relevant for many use cases. Modifying source power for UWPT, a larger battery at greater depth of implantation could as easily be recharged rapidly.

In addition to power transfer, ultrasound is capable of bidirectional wireless communication between transmitter and receiver. A representative information from the AIMD in a human implant use case could be to understand the presence of fibrosis after implantation. Device integration in combination with temporal power sequencing can enable effective charge powering and remote communication using one or more ultrasound transmitter and receiver elements.

Based on our experience, charging of miniaturized SSB using ultrasound energy transfer is highly feasible, with integration within an AIMD.

More about the authors

- **Ilika Technologies**

Ilika is a pioneer in a ground-breaking solid state battery technology designed to meet the specific demands of a wide range of applications in MedTech, Industrial IoT, Electric Vehicles and Consumer Electronics. Ilika is headquartered in Southampton, in the UK.

Learn more by visiting www.ilika.com

- **Piezo Energy Technologies, LLC**

This effort was led by Inder Raj Makin, MD, PhD, who is the Chief Technology Officer of PET, LLC. Dr. Makin is a scientist-innovator in the area of medical instrumentation and ultrasound, having published about 35 peer-reviewed publications and book chapters and ~50 issued patents. He is cofounder of Ulthera, Xthetix, and Guided Therapy Systems, LLC, and is currently a Professor at A.T. Still University, AZ, working in the area of medical ultrasound research and teaching. Piezo Energy Technologies was founded by Professor Leon Radziemski in 2004. Together with the parent company UltraPower, Inc., PET provides wireless powering solutions and ultrasound electrical recharging of medical implants, as well as Ultrasound Power^{TM} Transfer (**UPT**) for consumer and industrial applications.

Learn more by visiting www.ultrasound-power.com and www.gopiezo.com

Definition of abbreviated terms

Term	Description
AIMD	Active Implanted Medical Devices
EM	Electro Magnetic
FDA	United States Food and Drug Administration
LIB	Lithium-Ion Battery
PET	Piezo Energy Technologies
PMIC	Power Management Integrated Chip
SSB	Solid State Battery
UPT	Ultrasound Power Transfer
UWPT	Ultrasound Wireless Power Transfer
WBAN	Wide Body Area Network

Resources

Application Note AN01: Using Stereax batteries with a PMIC

Application Note AN02: Using Stereax batteries with additional capacitance

Makin IRS. Charging devices inside the body or outside: Ultrasound Wireless Powering offers several possibilities: 2022 Acoustical Society of America Meeting, Denver, Invited Lay Language Paper

Makin IRS, Jabs H, Mast TD, and Radziemski LJ. Demonstration of Healthcare-Specific Li-ion Battery Charging Using Ultrasound Power Delivery. 2021 IEEE Wireless Power Transfer Conference (WPTC). *2021: 1-4,* doi: 10.1109/WPTC51349.2021.9458228

Radziemski LJ, Makin IRS, *In vivo* demonstration of ultrasound power delivery to charge implanted medical devices via acute and survival porcine studies, Ultrasonics, Volume 64, Pages 1–9, 2016, doi: 10.1016/j.ultras.2015.07.012

Work with Ilika!

We are battery experts. We can recommend how best to use these batteries in your next disruptive product so that you can optimise its energy budget. For more information and to discuss how Stereax solid state batteries can help your project, contact us on info@ilika.com or visit www.ilika.com.

Revision history

Revision	**Date**	**Comments**
1.0	July 23	First version

Important

Whilst Ilika has used reasonable efforts to ensure that the information contained in this Application Note is accurate, Ilika accepts no liability for any errors or omissions contained herein, nor for any reliance that any party may make on this Application Note. Ilika Stereax products are not approved for use in life critical applications. Users are solely responsible for confirming the suitability of the Ilika Stereax product in any products or applications in which the Ilika Stereax product is used, and are solely responsible for all legal, regulatory and safety-related requirements applicable to such products and applications, and for all liability arising from the use of such products and applications. References to third party products and/or manufacturers are used as examples and for identification purposes only and do not imply any endorsement by such manufacturer.