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Three-Phase Time-Multiplexed Planar Power Transmission to Distributed Implants

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Abstract

A platform has been presented for wireless powering of receivers (Rx's) that are arbitrarily distributed over a large area. A potential application could be powering of small Rx implants, distributed over large areas of the brain. The transmitter (Tx) consists of three overlapping layers of hexagonal planar spiral coils (hex-PSC) that are horizontally shifted to provide the strongest and most homogeneous electromagnetic flux coverage. The three-layer hex-PSC array is driven by a three-phase time-division-multiplexed power Tx that takes the advantage of the carrier phase shift, coil geometries, and Rx time constant to homogeneously power the arbitrarily distributed Rx's regardless of their misalignments. The functionality of the proposed three-phase power transmission concept has been verified in a detailed scaled-up high-frequency structure simulator Advanced Design System simulation model and measurement setup, and compared with a conventional Tx. The new Tx delivers 5.4 mW to each Rx and achieves, on average, 5.8% power transfer efficiency to the Rx at the worst case 90° angular misalignment, compared with 1.4% by the conventional Tx.

Index Terms

Distributed neural interface; implantable medical devices; planar spiral coils; three-phase excitation; wireless power transmission (WPT)

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I. Introduction

BRAIN-COMPUTER interfaces (BCIs) are promising to restore motor ability in those with severe paralysis. Control of a robotic arm by neural signals obtained from a 96-channel microelectrode array (MEA) placed in a small, local population of motor cortex neurons has already been demonstrated [1], [2]. Now, neuroscientists are asking for advanced tools capable of recording the activities of individual neurons from all over the brain because most brain functions are also distributed [3]–[5]. In addition to area coverage, it is important to maintain a high spatial resolution in recording brain activity. The highest spatial resolution is provided by small electrodes inserted in the brain to record extra cellular activities of nearby neurons, leading to single-unit activity (SUA) recording. Good area coverage with lower spatial resolution is offered by electrocorticography (ECoG) and electroencephalography (EEG), as shown in Fig. 1, with planar electrodes that are implanted on the surface of the brain or under the scalp, respectively [3]. The lack of proper tools for obtaining high spatial resolution signals over large areas in the brain over extended periods is considered one of today's key challenges in neuroscience research.

While many have attempted to record multichannel SUA from a large neural populations, previous recording schemes were limited to a very small area of the brain [1], [7]–[10]. This is because traditionally these architectures have relied on a single or a small number of high-density MEAs, tethered to large implanted electronics. These architectures are not suited for recording from a large brain area covered by a network of small arbitrarily placed implants distributed over the complex, nonuniform, and folded (gyri and sulci) surface of the brain.

Instead of the single, large, and centralized implant, a large number of tiny implants, distributed over a large brain area has been proposed as an alternative for recording from the brain [11], [12]. In the distributed system architecture, implants are small, wireless, and central rigid, and form a large network [13]. Therefore, the main constraints for these distributed implants are size, power, and functionality. Neither batteries nor other large storage elements, such as supercaps, are feasible in a distributed architecture. Energy harvesting from glucose fuel cell [14], thermoelectric [15], or piezo transducers [16] has been proposed, but it is unlikely to provide sufficient power for the desired functionality [17]. Ultrasonic power transfer might be an option. However, since ultrasound cannot penetrate through the skull, it can only be used either for short distance of a few millimeters across the cortical membranes, e.g., dura, or for deeper targets through soft tissue, e.g., in peripheral nerve interfacing [12]. Electromagnetic wireless power transmission (WPT), on the other hand, can penetrate through hard and soft tissue while providing high power density [10], [18]–[21]. Even though several focused WPT methods for a single miniature implant have been proposed [21]–[24], to the best of our knowledge, there has been few external power transmitters (Tx's) designed for numerous floating implants with arbitrary angular and spatial misalignments, distributed all over a large brain area, as shown in Fig. 1.

In this paper, we present a new architecture for a three-phase time-multiplexed scalable power Tx, which has the ability to wirelessly power a large number of distributed receivers (Rx's) with arbitrary angular and spatial misalignments across a large plane. The Tx includes three layers of hexagonal planar spiral coils (hex-PSCs) for homogeneous distribution of the

power transfer efficiency (PTE) and an array of three-phase time-multiplexed RF drivers to generate both vertical and lateral magnetic flux over the entire powered 3-D volume. The proposed architecture cannot only be applicable to small implants distributed over large areas of the brain but also any wirelessly powered mobile unit, with random angular or spatial misalignments, such as multiple socially interacting animal subjects in an EnerCage system [25]. In Section II, the three-phase Tx for driving the hex-PSC array is introduced in comparison with the conventional in-phase or out-of-phase Tx arrays. The time-multiplexing technique for the three-phase Tx array is presented in Section III, followed by the experiment results in Section IV and conclusion.

II. Three-Phase Transmitter for hex-PSC Array

The origin of the proposed Tx architecture is a proven technology, called EnerCage [25]–[27], which was developed to continuously power and communicate with an electronic device attached to or implanted in a freely behaving animal in a smart cage. In the EnerCage system, three layers of overlapping hex-PSCs are used to provide homogeneous PTE over an extended area. However, only one or two hex-PSCs are activated at any time to power one Rx in the cage. Here, the goal is to simultaneously power numerous Rx's distributed over an extended target area with arbitrary position and angular misalignments. Fig. 2(a) shows three examples of angular alignment in a spherical coordinate system, used in this paper and represented by (θ, ϕ) .

If all hex-PSCs in each layer are activated in-phase, as shown in Fig. 2(b), current flows in opposite directions in the adjacent coils and the resulting magnetic fields cancel out, leaving only the edges of the hex-PSCs on the outer perimeter of the array, and reducing the overall PTE. Moreover, since the resulting magnetic field is primarily vertical to the hex-PSC plane, this method of excitation does not address the Rx angular misalignment, resulting from the fact that the coupling coefficient, k , drops roughly proportional to $\cos(\theta)$ [28].

The solution offered in [27] for the angular misalignment was driving the adjacent coils closest to the Rx with a pair of out-of-phase carrier signals to reinforce the horizontal component of the magnetic field at the Rx location, as shown in Fig. 2(c). This out-of-phase excitation can power an Rx coil that is close to the hex-PSC array when it is tilted by $\theta = 90^\circ$ (worst case condition). However, it is not extendable to a large number of arbitrarily located/aligned Rx coils over an extended area. Because the vertical magnetic field generated by the adjacent out-of-phase hex-PSCs weaken one another at the position of a horizontal Rx that is further away from the PSC array, resulting in significant reduction in the PTE. The 180° phase shift cannot be extend over the coverage area either because each hex-PSC is surrounded by six adjacent PSCs, as shown in Fig. 2(d). Although 180° out-of-phase array satisfies extension via square-shaped PSCs in four layers [29], the vertical magnetic field attenuation at the Rx position would still occur.

Here, we present a new solution for driving a scalable array of hex-PSCs in a way that it can power not only vertically oriented Rx's but also those with angular misalignments. Fig. 3(a) shows the geometry and relative positioning of the hex-PSCs with 120° excitation phase shift between adjacent coils. This arrangement significantly improves both the vertical and

angular magnetic fields over the extended 3-D space. In this excitation scheme, every three adjacent hex-PSCs are driven by $\beta = 0^\circ, 120^\circ$, or 240° carrier signals, similar to three-phase electric power grids. Fig. 3(b) shows that the inductive coupling between any two adjacent coils is constructive at the Rx position, thanks to the 120° phase difference. If we consider a simple case of an Rx coil positioned symmetrical with respect to the nearest hex-PSC segments, and superimpose the magnetic field generated from those segments of the 120° and 240° phase shifted hex-PSCs (carrying I_{120} and I_{240}) with those from the 0° hex-PSC (carrying I_0) and consider their associated coupling coefficient, k , then the resultant magnetic field of the 0° coil with respect to Rx, B_0 , is increased from its original value according to

$$\begin{cases} I_{0,1} = I_{0,2} = \alpha \sin(\beta) \\ I_{120} = \alpha \sin(\beta - 120^\circ) \\ I_{240} = \alpha \sin(\beta - 240^\circ) \end{cases} \quad (1)$$

$$\begin{aligned} B_0 &\propto (I_{0,1} - k \cdot I_{120} + I_{0,2} - k \cdot I_{240}) \\ &= 2 \cdot \alpha \sin(\beta) - k \cdot \alpha \sin(\beta - 120^\circ) - k \cdot \alpha \sin(\beta - 240^\circ) \\ &= 2 \cdot \alpha \sin(\beta) + k \cdot \alpha \cdot [2 \cdot \sin(-\beta + 180^\circ) \cdot \cos(120^\circ)] \\ &= 2 \cdot \alpha \sin(\beta) - k \cdot \alpha \sin(\beta - 180^\circ) \\ &= \alpha(2 + k) \sin(\beta) \end{aligned} \quad (2)$$

where α is the amplitude of the current and β is the phase of the current. In contrast, in the in-phase excitation in Fig. 3(c), the coupling between any two adjacent hex-PSCs is destructive, resulting in weakening of the induced current in the Rx coil

$$B_0 \propto (I_{0,1} - k \cdot I_{0,3} + I_{0,2} - k \cdot I_{0,4}) = 2 \cdot \alpha \sin(\beta) - 2k \cdot \alpha \sin(\beta) = \alpha(2 - 2k) \sin(\beta). \quad (3)$$

Therefore, the proposed three-phase excited hex-PSC array is able to extend the WPT coverage without suffering from the magnetic field attenuation effect, and can also accommodate Rx coils with angular misalignments.

III. Three-Phase Time-Multiplexed Transmitter

Although the hex-PSC array with three-phase excitation can simultaneously power the horizontally and even vertically oriented Rx coils, our simulations showed that there still exist dead zones for these extreme Rx orientations at the boundaries of every two adjacent hex-PSCs and at the center of each hex-PSC, respectively. Fig. 4(a) shows a few Rx coils distributed over one layer of hex-PSC array with various positions and orientations. The horizontally oriented Rx coils 1, 5, and 10 are located near the center of hex-PSCs and can be powered, as shown in Fig. 4(b), while Rx coil 3 cannot be powered because the lateral magnetic field is weak in the center of a hex-PSC, as shown in Fig. 4(c). In contrast, at the boundaries of hex-PSCs, lateral magnetic fields are stronger, and vertical magnetic fields are weaker, resulting in vertically oriented Rx coils 2 and 6 in Fig. 4(a) receive more power than horizontally oriented coils 4 and 9, as shown in Fig. 4(b) and (c), respectively. The directionality (ϕ) of the vertically oriented Rx coils is also important, as shown in the case of

Rx coils 7 and 8 in Fig. 4(c), which do not receive enough power despite being located near the boundaries of the hex-PSCs.

A. Three-Layer Overlapping hex-PSC Array

To eliminate the aforementioned dead zones and create a homogeneous PTE over an extended volume around the Tx plane, we have combined three layers of hex-PSC arrays by offsetting the centers of every three adjacent hex-PSCs on three different layers to be on the corners of an equilateral triangle [27]. This is shown from the top and side views in Fig. 5(a), in which three conductive hex-PSC layers in blue, green, and red are stacked to create an overlapping hex-PSC array. These three layers cannot be driven with the aforementioned three-phase signal at the same time because the magnetic fields from each layer will be destructive to the fields generated by the other two layers. Hence, each layer is time-division multiplexed (TDM), as shown in Fig. 5(b), to avoid any electromagnetic interference between layers. The appropriate TDM period, T , is decided by the carrier frequency, time constant of the capacitance following the Rx coil and rectifier, Rx loading, and the acceptable level of ripple on the regulated supply voltage of the electronics that are powered by the Rx coil.

B. Safe Tx Coil Deactivation Using Resonant Inverter

One of the important design considerations for the power amplifiers (PAs) used to drive the overlapping hex-PSC array in the three-phase TDM scheme is the ability to rapidly charge and discharge the LC -tank in each Tx coil. Because each hex-PSC array should be repeatedly turned ON and OFF by the control signals, shown in Fig. 5(b), and a delayed charge or discharge time in one layer can affect the wireless link PTE by degrading the magnetic field generated by another layer. Normally when the PA is turned OFF, the residual energy stored in the LC -tank is dissipated by the parasitic resistance in the LC -tank and the matching circuit in the PA.

Fig. 6(a) shows the simplified schematic of a three-phase TDM current mode class-D (CMCD) PA, as part of the distributed Tx. The control block provides three-phase clock signals at 13.56 MHz in the industrial, scientific, and medical band, which are 0° , 120° , and 240° phase shifted, as well as three TDM control pulses for each CMCD PA board. The CMCD PAs in [30] is a suitable choice for rapidly deactivating the LC -tank because the LC -tank terminals can be grounded and shorted by activating both M_1 and M_2 together. This will provide a free-wheeling path for the inductor current, avoiding a high voltage spike across M_1 and M_2 , which could result in device failure.

A pair of nonoverlapping clock pulses are generated in each PA from the three-phase clock signal associated to each layer to drive M_1 and M_2 , while being masked with the layer ON/OFF signal from the TDM control block. When the TDM signal is high, supply provides current to the corresponding CMCD PA board, and when the TDM signal is low, the PA is disabled and both gate drivers for M_1 and M_2 are raised to short the LC -tank to ground. The two ends of each parallel LC -tank in the Tx array are shorted to ground by switches M_1 and M_2 to quickly reduce the resonant current in the LC -tank down to zero during the OFF phase, and facilitate a sharp TDM using CMCD PAs. There is some undesired mutual

coupling between the overlapping coils in different layers, which is small because the shorted parallel LC -tank does not resonate at 13.56 MHz. As a result, the induced current and corresponding power loss in the shorted Tx coil is not high. More specifically, the current in the shorted Tx coil depends on not only the mutual coupling but also its resonant frequency. Since the shorted Tx coil is no longer a resonator, the current is small. The ON/OFF timing of the PA is critical because it should not be turned OFF when there is high voltage across the LC -tank. Simultaneous high voltages and currents across the MOSFET switches may destroy them when they are turned ON by the TDM signal. Therefore, the PA should be turned off at a moment that the voltage across the LC -tank is the lowest. At this moment, the current in L_0 is the maximum based on the basic CMCD operation [31]. Back-to-back MOSFET switches, M_3 and M_4 , are used to completely isolate the power source from the inductor, L_0 , when the TDM signal goes low. The free-wheeling current in L_0 passes through the free-wheeling diode between L_0 center tap and ground, and the residual energy dissipates in the parasitic resistance of M_1 and M_2 during the M_1 and M_2 on time.

Fig. 6(b) shows the desired nonoverlapping clock for M_1 and M_2 gates and the layer ON/OFF TDM signals. The timing between TDM and gate drive signals should be synchronized at t_2 to achieve the zero-voltage switching condition. Switching the PA OFF at any other time, such as t_1 , should be avoided. Positive edge-triggered D-type flip-flop (74AHC74) is used in the sync block of Fig. 6(a) for this purpose. The TDM signal in Fig. 5(b) is implemented by a decade counter with a master reset pin to count up to three. The 120°-shifted gate driver signals are generated by a DS1100Z fixed delay element. Each tap of DS1100Z has 25 ns delay, which is almost the equivalent of 120° phase shift in a 13.56 MHz clock. Fig. 7 shows the measured TDM signal and the corresponding voltage across the LC -tank in a hex-PSC. The TDM frequency in this prototype is 10 KHz with a 33% duty cycle. These waveforms show that TDM signal turns OFF the PA when the voltage across the LC -tank becomes low and the energy stored in the LC -tank dissipates in ~ 100 ns, without causing any voltage spike. The small oscillation across M_1 in Fig. 7 when the layer is OFF is partly because of this induced current and partly because of the induced voltage in the probing instrument, which also results in a noisy GND terminal, visible in the digital layer-ON/OFF control signal in Fig. 7.

IV. Simulation and Measurement Results

Scaled-up prototypes of the hex-PSC array and Rx coil were designed and fabricated as a proof-of-concept for the proposed three-phase TDM WPT to randomly distributed Rx's. Unlike the earlier EnerCage design, which focuses the delivered power on a handful of moving targets, the new scheme is meant to homogeneously power an entire volume, where numerous Rx's are distributed.

Dimensions of the hex-PS C array and wire-wound coil on the Tx and Rx sides were adopted from the optimization procedure in [27], and summarized in Table I. Each coil in the three-layered hex-PSC array has 12.7-cm outer diameter with two turns. A fourth layer on the printed circuit board (PCB) was used for interconnects between the PA and hex-PSCs. The Rx coil diameter was limited to 1 cm in the coil optimization procedure [32], and the nominal distance between the Rx coil and the Tx array was set to 7 cm in this proof-of-

concept scaled-up prototype with a factor of ~ 7 . The optimization procedure for small implants with shorter Tx–Rx separation has been presented elsewhere [22]. The nominal dc load, $R_L = 5 \text{ k}\Omega$, corresponds to $\sim 5\text{-mW}$ power consumption in the Rx, in which the selected number of turns, $n_3 = 3$, offers maximum PTE [32].

A. HFSS and ADS Simulations

Operation of the three-layer overlapping hex-PSC array, driven by a three-phase TDM sinusoidal carrier signal at 13.56 MHz was simulated using a combination of the high-frequency structure simulator (HFSS, ANSYS) and Advanced Design System (ADS, Agilent) environments. To consider the cross-coupling among all coils, the S-parameters were extracted from the HFSS model, shown in Fig. 8(a), in the form of a 13×13 matrix, consisting of 12 overlapping hex-PSCs on the Tx array and one Rx coil, which was swept within the orange-shaded area in three different scenarios of $\theta = 0^\circ$, $\phi = 0^\circ$ (case-A), $\theta = 90^\circ$, $\phi = 90^\circ$ (case-B), and $\theta = 90^\circ$, $\phi = 45^\circ$ (case-C). The S-parameter matrix was then used in an ADS circuit model, in which 12 hex-PSCs were driven by three-phase signals at 13.56 MHz that were TDM at 10 KHz to power the Rx coil, being loaded by a 5-k Ω resistor. In the HFSS simulation environment, a lumped port was defined between the two ends of each coil and the boundary property was selected as radiation. The Tx array was placed in FR4_epoxy, which has a relative permittivity of 4.4, considering the actual PCB material.

Fig. 8(b)–(d) shows the simulated PTE distributions of the in-phase (left) versus three-phase/TDM (right) excitation of the overlapping hex-PSC array in case-A, case-B, and case-C, respectively. Although the power consumption in each Tx layer is time multiplexed, i.e., varies with time, the excitation cycle is periodic with a 33.3% duty cycle. Therefore, the power consumption can be averaged over T to calculate the overall system efficiency, which can be calculated by the ratio of the received power in the Rx and the average power consumed by one PA according to

$$\text{Efficiency}(\%) = \frac{P_{R_L}}{P_{\text{Supply}}/n_{\text{PA}}} \times 100 \quad (4)$$

where P_{R_L} is the power consumption in the load, P_{Supply} is the overall system power consumption, and n_{PA} is the number of PAs used in the Tx.

With no angular misalignment in case-A, the average PTE with three-phase excitation has been reduced from 12.8% to 9.1%, because of the 120° phase shift to increase the lateral magnetic flux between adjacent hex-PSCs. Since Rx coils that are in parallel with the hex-PSC plane are already in the best orientation to receive power, this nominal PTE reduction (28.9%) does not affect the system performance.

The key impact of the three-phase excitation can, however, be observed in the significant increase in the average PTE in cases B and C, which are among the worst case scenarios for arbitrary Rx distribution. In Fig. 8(c), the maximum and minimum PTEs in case-B are 4% and 0.02% for in-phase excitation versus 8.66% and 4.1% for the three-phase excitation, respectively. Moreover, the average PTE across the powered area has been increased from

1.4% to 5.8%, a 392.8% increase. Similarly, in Fig. 8(d), max/min and average PTE have changed from 4%/0.02% and 1.5% for the in-phase to 8.4%/3.9% and 6.1% for the three-phase excitation, respectively, which represent a 306.6% improvement on average.

These simulation results clearly show that the proposed three-phase method for TDM excitation of overlapping three-layer hex-PSCs can significantly increase the PTE in the worst case scenarios, in which the power Rx's are at the risk of malfunction due to insufficient power, at a cost of a modest PTE degradation in the best positions.

Alternatively, these results indicate that to ensure fully functional Rx's (e.g., implants) that are arbitrarily distributed within the powered 3-D space, including those that are in the worst case positions or orientations, the transmitted power can be much less than the traditional in-phase method, using the same type of Tx coils. This is the result of a more homogeneous PTE distribution across the powered space for any angular and spatial misalignments. The PTE for the angular misalignment tends to drop along the edges of the simulated area because this simulation was limited to only 12 overlapping hex-PSCs due to extended simulation time with a larger number of coils. The uniform simulated area in Fig. 8(a) has a triangular shape inside (0, 0), (8, 0), and (4, 7) coordinates. This inhomogeneity is expected to be reduced when the overlapping hex-PSC array is further extended to a larger array.

B. Experimental Measurements

Fig. 9 shows the measurement setup, with the hex-PSC array implemented on a pair of two-layer 1 oz FR4 PCB, which are described in [25]. Each CMCD PA driver board, shown in the lower right inset was vertically mounted on the bottom of hex-PSC array, and connected to the main control board, shown in the lower right inset. The Rx board, shown in the upper right inset, includes the Rx coil specified in Table I, a passive rectifier (BAS4002) followed by a 2- μ F capacitor, and a 5-k Ω load. In this experiment, 7 coils were used to verify the operation of three-phase TDM excitation of a hex-PSC array, as shown in Fig. 10(a). The measurement procedure was similar to the simulations described in Section IV-A, comparing the PTE of the in-phase and three-phase excitations for the three cases in Fig. 8(a), while the Rx board was moved over the orange area in Fig. 10(a) at $d_{23} = 7$ cm.

Despite a smaller number of active hex-PSCs, the measured PTE distributions in Fig. 10 are in close agreement with the simulation results in Fig. 8. Although the average PTE for the parallel Rx coils, i.e., with no angular misalignment (case-A), was reduced from 12.8% with in-phase excitation to 9.1% with three-phase excitation, strengthened lateral magnetic field in three-phase excitation improved the average PTE from 0.86% to 4.9% in case-B and from 0.87% to 5% in case-C, where the average power delivered to the load (PDL) was 5.4 mW. Similar to simulation results, a drop in the PTE was observed at the boundaries of the area covered by the active hex-PSCs, which is expected to be flattened once the hex-PSC array and powered area is extended beyond seven coils. Multiple Tx coils that are in one layer and have the same phase can be driven by only one PA because they are all turned ON/OFF at the same time and with the same phase. Therefore, theoretically, we only need three driver boards in each layer as long as the PA has the capability to drive all Tx coils. In practice, if some Tx coils are far from the PA, the long routing may cause additional losses. Therefore, determining the right number of PAs depends on each specific design.

Fig. 11 compares the measured and calculated PTE at 7-cm Tx-Rx separation and perfect alignment versus load variations. The measured results indicate $R_L = 6 \text{ k}\Omega$ as the optimal loading, which is very close to the designed target of $R_l = 5 \text{ k}\Omega$. Fig. 12 shows the measured power flow from the dc source, V_{dd_Tx} , to one of the distributed loads with $\theta = 90^\circ$ and $\phi = 90^\circ$ angular misalignment [case-B in Fig. 10(c)], using three-phase excitation. In this case, for PDL = 5.4 mW at $d_{23} = 7 \text{ cm}$, the power source supplies 2.24 W to seven CMCD PAs with 49% efficiency to drive seven overlapping hex-PSCs. The calculated power loss in each PA during LC-tank deactivation/discharge for TDM is $\sim 12 \text{ mW}$, which is negligible with respect to the PA output power. Finally, the received power before and after the Rx rectifier was 7.6 and 5.4 mW, respectively.

V. Conclusion

A novel WPT platform has been presented that is suitable for a large number of Rx's, distributed over an extended area. The proposed three-phase TDM Tx takes advantage both timing of the excitation carrier signals and geometrical arrangement of a three-layer overlapping hex-PSC array to create a homogeneously powered 3-D volume that would be robust against arbitrary angular or spatial misalignments of the Rx. The Tx includes time-multiplexed CMCD PAs and a three-phase sinusoidal carrier signal to generate both vertical and lateral magnetic flux to compensate for the angular misalignment of the Rx coils. The functionality of three-phase TDM Tx was demonstrated in both simulation and measurements in comparison with a simple in-phase Tx by delivering 5.4 mW to the Rx in the worst case scenario with 90° angular misalignment. The proposed WPT architecture is applicable to distributed implants and other wireless powering applications, in which a large number of Rx's with arbitrary angular and spatial misalignments need to be continuously powered.

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Fig. 1.

Rendered view of a distributed BCI. Three different categories of recording devices, i.e., EEG, ECoG, and SUA, powered and communicated by an external hex-PSC array.

Fig. 2.

(a) Three examples of angular alignment in the spherical coordinate system used in this paper and represented by (θ, ϕ) . (b) Conventional in-phase excitation of the hex-PSC array. Current flows in opposite directions in adjacent segments of the neighboring hex-PSCs. (c) Out-of-phase excitation of the hex-PSC array, which helps with $(90^\circ, 90^\circ)$ case. However, the vertical field is weakened for horizontal Rx coils $(90^\circ, \text{any})$ when the hex-PSC array is extended over the 2-D plane, as shown in (d).

Fig. 3.

(a) Phase distribution among the hex-PSCs in one conductive layer. The phase difference between any two adjacent hex-PSCs is either 120° or 240°. (b) Current vector diagram in the proposed 120° offset excitation. Part of the magnetic field generated from I_{240} and I_{120} is coupled with coupling coefficient k to the magnetic field generated from $I_{0,2}$ and $I_{0,1}$. The resulting current induced by the 0° coil is increased from its original value $I_{0,1} + I_{0,2}$ because of the constructive nature of the adjacent fields. (c) Current vector diagram in in-phase excitation. The direction of magnetic field coupling is destructive, and the resulting current in the Rx coil is reduced.

Fig. 4.

(a) Top view of distributed Rx coils in various orientations and positions over one layer of three-phase driven hex-PSC array. (b) Distributed Rx coils which can receive enough power from this layer of the hex-PSC arrays. (c) Distributed Rx coils which cannot receive enough power from this layer and need to be powered by the other two overlapping layers.

Fig. 5.

(a) Schematic of the three-layer hex-PSC array for the Tx plane from top (left) and side (right) views. (b) Active periods of each layer in Fig. 5(a) for 33% of the overall period, T , as each hex-PSC in each layer is driven by the three-phase carrier signal in Fig. 3.

Fig. 6. (a) Schematic of the three-phase TDM CMCD PA for driving three-layer overlapping hex-PSCs. (b) Control signals for the gate drivers of M_1 and M_2 , and layer/PA ON/OFF. The control signals should be synchronized at t_2 while switching at other times should be avoided.

Fig. 7.
Measured waveforms of layer ON/OFF signal for controlling each hex-PSC layer and the corresponding LC-tank voltage at the drain of M_1 .

Fig. 8.

Simulation results for three-phase TDM excitation of a three-layer hex-PSC array that constitutes the Tx plane with Rx at 7 cm above the surface. (a) HFSS model of the hex-PSC array with three cases of the Rx coil orientation. Orange-shaded area is where the Rx coil was swept to simulate the PTE distribution in the ADS for in-phase (left) and three-phase (right) excitations in (b) case-A, (c) case-B, and (d) case-C.

Fig. 9.

Experimental setup for the three-phase TDM overlapping hex-PSC array. The control board on the lower left coordinates the activation of each CMCD PA board that is vertically mounted at the bottom of the PSC array to drive each hex-PSC. The Rx coil wound around the Rx board with 1 cm^2 area on the upper right has a rectifier circuit and $5\text{-k}\Omega$ load.

Fig. 10.

Measured results for three-phase TDM excitation of a three-layer hex-PSC array that constitutes the Tx plane with an Rx at 7 cm above the surface. (a) Top view of measurement setup with three cases of the Rx coil orientation. Orange-shaded area is where the Rx coil was swept to measure the PTE distributions for the in-phase (left) and three-phase (right) excitations in (b) case-A, (c) case-B, and (d) case-C.

Fig. 11.
Measured and calculated PTE versus load variation at nominal distance $d_{23} = 7$ cm with no misalignment.

Fig. 12. Measured power flow for PDL = 5.4 mW at $d_{23} = 7$ cm and 90° misalignment of the Rx coil (case-B).

Table I
Coil Specifications for the Prototype Three-Phase WPT System

Parameters	Value
Hex-PSC implemented on two double-layer 1 oz FR4 PCBs as the substrate on the Tx side (L_2)	Inductance = 680 nH Outer diameter = 12.7 cm Number of turns = 2 Line width/spacing = 10/7 mm Conductor thickness = 35 μ m $Q_2 = \sim 160$ for PSCs on layer 1 $Q_2 = \sim 136$ for PSCs on layer 2 $Q_2 = \sim 154$ for PSCs on layer 3
Wire-wound coil with 44 strand Litz wire on the Rx side (L_3)	Inductance = 224 nH Diameter = 1 cm Number of turns = 3 Wire diameter = 0.25 mm Quality factor = 125
L_2 - L_3 nominal distance (d_{23})	7 cm
Nominal DC load (R_L)	5 k Ω (~ 5 mW)
Operating frequency (f_p)	13.56 MHz
TDM frequency ($1/T$)	10kHz