A Hybrid Active/Passive Domino Architecture with MIMO Power Flow Control and Mixed Frequency Operation for Extended Range and Multi-Medium Wireless Power Transfer

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***Abstract*—Wireless power transfer (WPT) systems with Domino repeater arrays can be used to transfer power through complicated structures and extend the effective transfer range. This paper explored a hybrid active/passive Domino architecture with multi-input multi-output (MIMO) power flow control and mixed-frequency operation. By designing and optimizing the circuits and the control methods, the hybrid active/passive Domino architecture can achieve higher efficiency and higher power transfer capability than a passive domino architecture. The hybrid Domino architecture significantly expands the control degree-of-freedom by enabling multi-way power combining and multi-frequency wireless power transfer. The hybrid Domino architecture also enables the high performance multi-layer multi-medium wireless power transfer by combining different control strategies. A prototype hybrid Domino WPT system with ten resonators is built and tested to verify the effectiveness of the approach. The prototype delivered 12 W of power from the source and buffer to the load (56% from the source, and 44% from the buffer) with 40% end-to-end efficiency. The end-to-end power transfer distance (22 cm) is more than 4 times of the resonator diameter (5 cm). Another experimental setup is built with two transfer mediums (i.e., chicken breast and salt water) to validate the multi-layer multi-medium power transfer capability of the hybrid Domino architecture, where one active resonator is placed at the interface of the two mediums. The hybrid Domino WPT system can delivery 30% more power than a passive Domino system in the multi-medium WPT experiments.**

***Index Terms*—hybrid Domino wireless power transfer, active/passive resonator, multi-layer multi-medium power transfer, extended transfer range, time-division multiplexing, frequency-division multiplexing, phase-shift multiplexing.**

I. Introduction

Wireless power transfer (WPT) is an enabling technology for a wide range of applications including consumer electronics and biomedical applications [1], [2]. Significant efforts were made to improve the performance of WPT systems, including coil design, compensation circuits, repeating resonators, and inverter topologies [3]–[5]. Placing passive repeater arrays between the transmitting coil and receiving coil is an effective way to extend the range for wireless power transfer. Fig. 1 (a) shows the principles of a Domino WPT architectures. A passive Domino WPT system usually comprises a transmitting resonator with a source, a receiving resonator with a load, and multiple passive repeaters in between. Previous research on passive Domino architectures usually focus on the optimal load and efficiency, optimal position, frequency selection, and the impedance matching techniques [6]–[9]. Domino architecture has been proved effective for multi-load WPT application (Fig. 1 (b)) [10]–[12]. [10] investigated the optimal petitioning of the repeaters in the multi-load Domino architecture. A multi-load Domino architecture with load independent characteristics is presented by using a dual-coil configuration - one coil as a receiver and the other as a transmitter [11], [12].

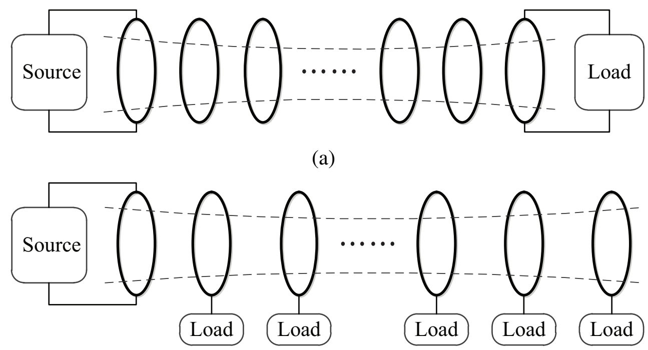


Fig. 1. Domino WPT architecture: (a) Domino WPT architecture with multiple passive repeaters; (b) Domino WPT architecture with multiple loads.

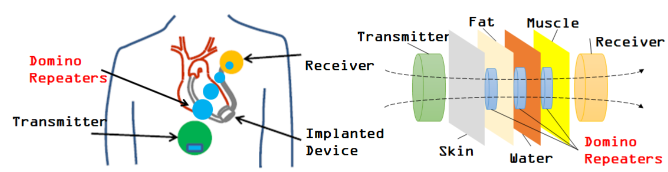


Fig. 2. Application scenarios for Domino wireless power transfer.

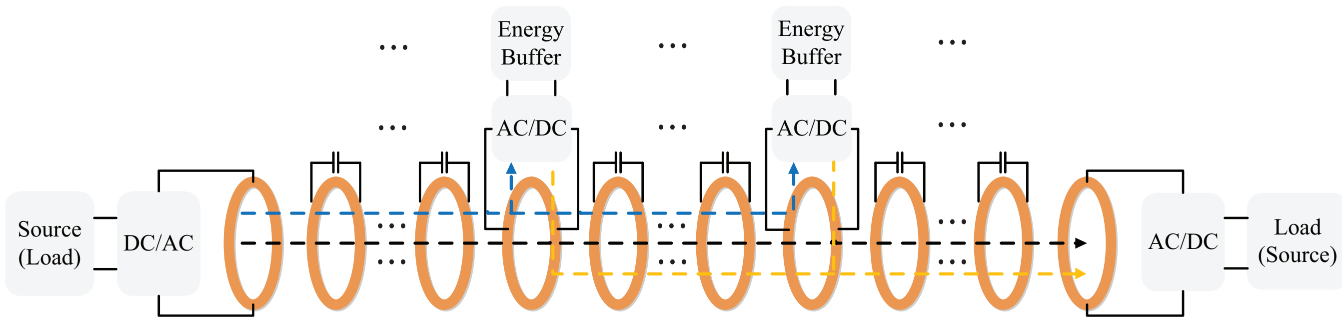


Fig. 3. Block diagram of the hybrid active/passive Domino wireless power transfer system.

As illustrated in Fig. 2, WPT systems with Domino repeater arrays can be used to transfer power through complicated structures and extend the transfer range. It is known that the optimal frequency to transfer wireless power through different materials are different. In a traditional Domino architecture, all resonators have to work at the same frequency to deliver power, the power transfer capability will be highly affected when delivering power through multiple layers of different materials. For instance, a lower operating frequency is usually desired to transfer power through salt water (or human tissue) with high efficiency, and a higher frequency can be used to extend the wireless power transfer range in distilled water. It is beneficial to be able to transfer power through different materials at different frequencies through a few wireless power repeaters placed in the power transfer path.

This paper presents a hybrid active/passive Domino architecture with multi-input multi-output (MIMO) power flow control and mixed frequency operation. By adding a limited number of active repeaters with energy buffers into the array, the Domino architecture can achieve higher efficiency and higher power transfer capability than a passive Domino architecture. The hybrid Domino architecture creates additional control degrees-of-freedom to manage the power flow in the Domino array and improve the power transfer capability. The hybrid Domino architecture also enables the high performance multi-layer multi-medium wireless power transfer by combining different control strategies, i.e., time-division multiplexing (TDM), frequency-division multiplexing (FDM), and phase-shift multiplexing (PSM). A prototype hybrid Domino WPT system with ten resonators is built and tested to verify the effectiveness of the approach. The prototype delivered 12 W of power from the source and buffer to the load (56% from the source, and 44% from the buffer) with 40% end-to-end efficiency. The end-to-end power transfer distance (22 cm) is more than 4 times of the resonator diameter (5 cm). Another experimental setup is built with two transfer mediums (i.e., chicken breast and salt water) and 5 cm transfer distance to validate the multi-layer multi-medium power transfer capability of the hybrid Domino architecture, where one active resonator is placed at the interface of the two materials. The hybrid Domino WPT system can delivery 33% more power than a passive Domino system in the multi-material WPT setup.

II. Hybrid Domino WPT Architecture

Fig. 3 shows a block diagram of the hybrid active/passive Domino architecture, comprising a transmitting resonator and a source (or load) with a dc-ac inverter, multiple passive repeating resonators, multiple active repeating resonators, a receiving resonator and a load (or source) with one ac-dc rectifier. Each active repeater is connected to an energy buffer (e.g., battery or super-capacitor) through a bi-directional ac-dc converter. The energy buffer in the active repeater can be configured as a source or load, depending on the control strategy and the working conditions. The power flow between two arbitrary active ports (including the energy buffers, the source and load) can be controlled by modulating the phase-shift between the ac-dc converters (inverters and rectifiers). If a repeater is configured as a load, power is transferred from the source to the repeater and the end-load. If a repeater is configured as a source, power is transferred from the source and the repeater to the end-load. If multiple repeaters are activated, the power flow in the WPT system is multi-input multi-output (MIMO). The transmitting resonator and active repeaters in the hybrid Domino architecture can operate at different frequencies (one after the other) to match the optimal frequency for different medium and improve the power transfer capability. This approach can also effectively extend the range of multi-layer multi-medium wireless power transfer.

The advantages of the hybrid active/passive Domino architecture include: 1) Improved efficiency and power transfer capability by allowing a better impedance matching between the load and the source across a wide operation range; 2) The additional control freedom of the repeaters enables time-division multiplexing (TDM), frequency-division multiplexing (FDM), and phase-shift multiplexing (PSM) among the source, the repeaters, and the loads across different loading conditions, transfer distance and transfer medium; By mixing these control strategy, a maximum wireless power transfer performance can be achieved. 3) This architecture enables high performance multi-layer multi-medium wireless power transfer. The active repeaters are placed at the interface between two materials and the power can be converted from one frequency to another frequency to optimize the power delivery through different materials and complicated multi-layer structures (e.g., living organism, plastics, robotics, or in vivo).

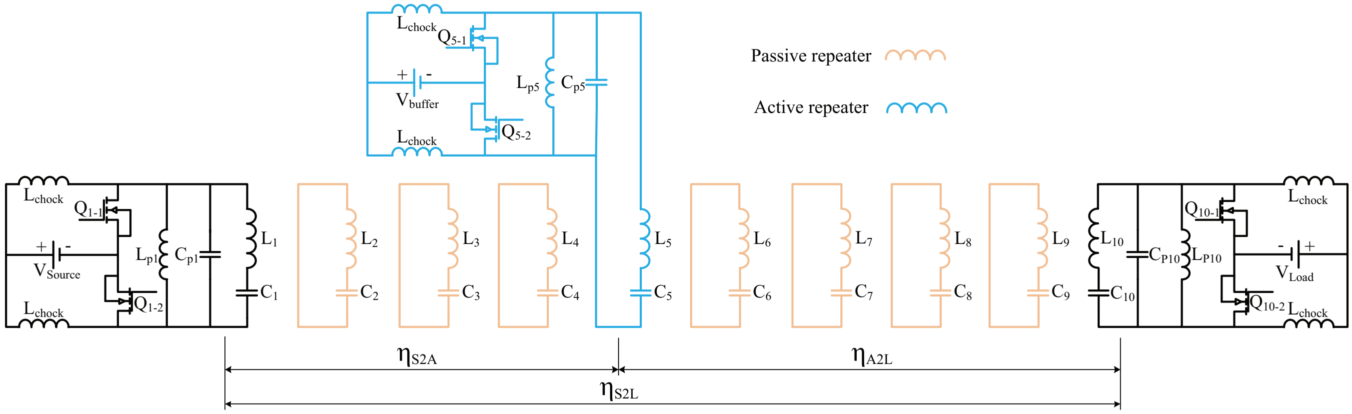


Fig. 4. An example implementation of the hybrid active/passive Domino WPT system with one active repeater and seven passive repeaters. The transmitter, active repeater and receiver are all implemented as current-mode Class-D inverters / rectifiers, operating at around 13.56 MHz.

III. Operation Principles of the Architecture

Fig. 4 shows an example implementation of the hybrid active/passive Domino WPT architecture with a source, a load, seven passive repeating resonators, and one active repeating resonator as the fifth repeater from the left. L_1 and L_{10} are the inductors of the source and load resonators, and C_1 and C_{10} are their compensation capacitors, respectively. L_2-L_4 and L_6-L_9 are the inductors of the passive resonators, and C_2-C_4 and C_6-C_9 are the compensation capacitors. L_5 and C_5 are the inductor and compensation capacitor of the active resonator. The ten resonators are loosely coupled with each other, one after the other. Current-mode (CM) Class-D inverters are adopted to implement the dc-ac converters due to its ground-referenced switches, current-source behavior and high performance at MHz. Other high frequency inverter topologies, such as Class-E, Class-EF, Class-Φ, are also applicable. The resonant tanks of all repeaters are optimized to match the impedance and minimize the loss.

To simplify the analysis, assume energy laterally propagates through the Domino structure from left to right (i.e., assuming 1D Poynting Vector propagation), the source-to-load efficiency of the hybrid Domino resonators is determined by the efficiency of the transmitter (η_{T1}), the passive repeater $\eta_{P2} - \eta_{P9}$, the round-trip efficiency of the active repeater η_{A5}, and the efficiency of the load receiver η_{R10}. Note the round-trip efficiency of the energy buffer is included in η_{A5}. Assume the power flow from the source to the load is P_{S2L}, the power flow from the active repeater to the load is P_{A2L}, based on the rule of superposition, the full system loss of this specific 10-coil Domino system, P_{loss} equals:

$$\begin{aligned}&(1-\eta_{T1}\eta_{P2}\eta_{P3}\eta_{P4}\eta_{P5}\eta_{P6}\eta_{P7}\eta_{P8}\eta_{P9}\eta_{R10})\times P_{S2L}\\+&(1-\eta^*_{T1}\eta^*_{P2}\eta^*_{P3}\eta^*_{P4}\eta_{A5}\eta_{P6}\eta_{P7}\eta_{P8}\eta_{P9}\eta_{R10})\times P_{A2L}. \quad (1)\end{aligned}$$

Note the energy loss during the charging process of the energy buffer should also be included ($\eta^*_{T1}\eta^*_{P2}\eta^*_{P3}\eta^*_{P4}$). η^*_i is different from η_i. The efficiency of the full system is approximately:

$$\eta_{system} = 1 - \frac{P_{loss}}{P_{S2L} + P_{A2L}}. \quad (2)$$

A common clock signal is needed to synchronize the transmitter, the repeaters, and the rectifier. The hybrid active/passive Domino architecture effectively functions as a power combiner which merges the energy from the source and the energy buffer and pushes the power to the load. It can achieve a higher efficiency and transfer distance than a traditional passive system by optimally and dynamically combining P_{S2L}, P_{A2L}, η, and η^*. For instance, the active repeater can be slowly charged by the source at a lower frequency with lower power rating, and can be rapidly discharged when transferring power to the load at a higher frequency which can better propagate through channel material. Fundamentally, the active repeater decouples the power transfer channels in the Domino system, separates the design constraints, and create a wide range of design and control flexibility for different application scenarios.

IV. MIMO Power Flow Control

Due to the topological complexity of the hybrid Domino WPT system, the full-order cantilever model [13] is not suitable to modeling and control the MIMO power flow. An alternative way to model the n-resonator hybrid Domino WPT architecture is to simplify the cantilever model into a wave propagation model [14]. Fig. 5 shows the lumped circuit model and a simplified wave propagation model of the hybrid Domino WPT architecture. For illustration purpose, the active repeaters and the passive repeaters are placed in alternative. The active repeaters are driven by external sinusoidal current sources i_1, i_3, ..., i_n and the passive repeaters are driven by the induced resonant current, i.e., i^*_2, i^*_4, ..., i^*_{n-1}. Here L_i is the self-inductance of the ith resonator and $L_{i,j}$ is the mutual inductance between the i^{th} and j^{th} resonators.

Assume all repeater coils are perfectly tuned, the impedance matrix of the Domino WPT system is:

$$\begin{bmatrix} v_1 \\ v^*_2 \\ \cdot \\ v_n \end{bmatrix} = \begin{bmatrix} 0 & \omega L_{1,2} & \cdots & \omega L_{1,n} \\ \omega L_{2,1} & 0 & \cdots & \omega L_{2,n} \\ \cdot & \cdot & \cdots & \cdot \\ \omega L_{n,1} & \omega L_{n,2} & \cdots & 0 \end{bmatrix} \begin{bmatrix} i_1 \\ i^*_2 \\ \cdot \\ i_n \end{bmatrix}. \quad (3)$$

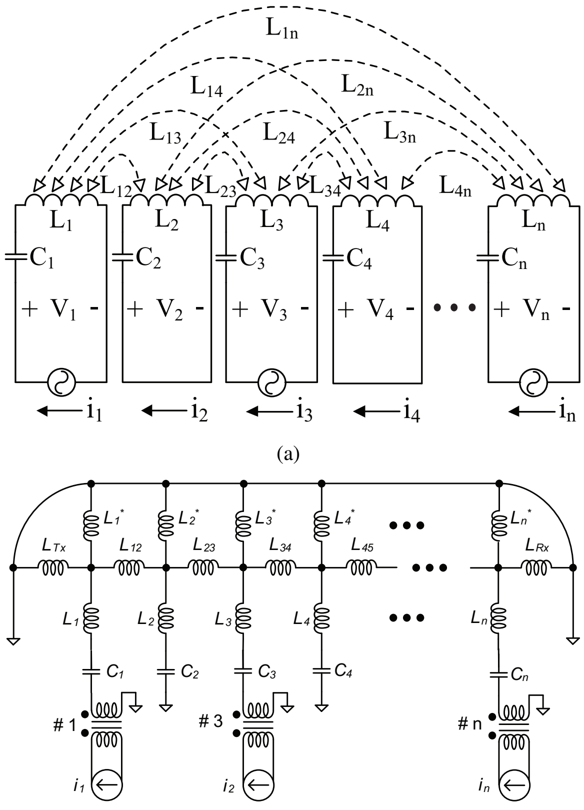


Fig. 5. (a) Lumped circuit model for a Domino WPT system; (b) simplified Wave propagation model for the analysis of Domino WPT.

Note $L_{i,j}$ equals to $L_{j,i}$ in the matrix and the L and C of each coil is self resonant. The active power feeding into the active resonator k is the summation of the power picked up from all resonators:

$$P_k = V_k \times i_k^* = \frac{1}{2} \sum_{q=1, q \neq k}^{n} \omega L_{k,q} I_k I_q sin\theta_{qk}. \tag{4}$$

Here i_k^* is the conjugate current of i_k. I_k and I_q are the magnitudes of the current at port k and q. ϕ_{qk} is the phase difference between the currents of port k and q. Eq. (4) indicates that the MIMO power flow control among the active repeaters (including the source and load) can be achieved by modulating the magnitudes, phases, and frequency of all the active ports in the hybrid Domino WPT architecture. The wave propagation model in Fig. 5 (b) contains a portion of the information in the impedance matrix, but allows full SPICE, time-domain, mixed-frequency simulation of the hybrid Domino system capturing the dynamics of the inverters and rectifiers.

V. Multi-Layer Multi-Medium Power Transfer with Mixed Frequency Operation

The hybrid Domino wireless power transfer architecture can be used for the multi-layer multi-medium wireless power transfer applications to improve the power transfer capability. In a hybrid Domino system, the active repeaters can be placed at the interface between two materials (Fig. 2) and the power can be converted from one frequency to another frequency to optimize the power delivery through different medium, i.e., the frequency-division multiplexing (FDM).

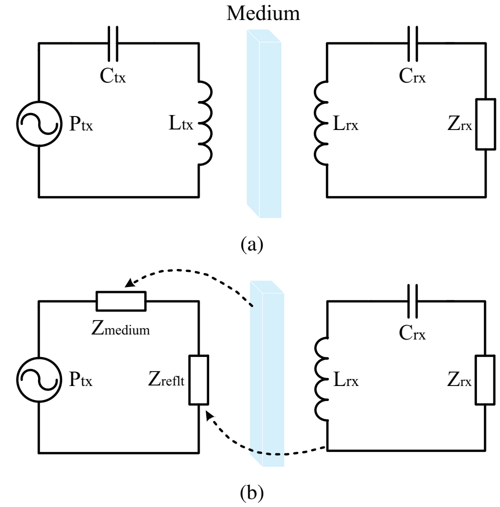


Fig. 6. A simplified lumped circuit model for two adjacent active resonators in a hybrid Domino WPT system: (a) circuit model of the two adjacent active resonators; (b) circuit model with the reflected impedances.

Fig. 6 (a) shows the simplified circuit model of two adjacent active resonators in the hybrid Domino WPT system. Here the power is transferred from left side to right side through a specific material (which can be modeled as a repeater). The self inductance of the active resonator sending the power is L_{tx} and its compensation capacitor is C_{tx}. Similarly, L_{rx} and C_{rx} are the self inductance and compensation capacitor of the active resonator receiving the power. Z_{rx} is the equivalent load impedance of the resonator receiving the power and P_{tx} is the input power of the resonator sending the power. The circuit model given in Fig. 6 (a) can be further simplified by using the reflected impedance, as shown in Fig. 6 (b). Here Z_{reflt} (= R_{reflt} + jX_{reflt}) is the impedance reflected from the receiving side to the transmitting side and Z_{medium} (= R_{medium} + jX_{medium}) is the impedance reflected from the medium to the transmitting side. They are effectively connected in series. Based on the circuit model, the power transfer efficiency between two adjacent active resonators in the hybrid Domino WPT system can be expressed as:

$$\eta_{resonator} = \frac{R_{reflt}}{R_{reflt} + R_{medium}}. \tag{5}$$

Here R_{reflt} and R_{medium} are the real parts of the reflected impedance Z_{reflt} and Z_{medium}. Assuming the reflected resistance at both transmitting and receiving sides, R_{reflt}, is:

$$R_{reflt} = \frac{\omega^2 k^2 L_{tx} L_{rx}}{R_{rx}}. \tag{6}$$

Here ω and k are the angular operating frequency and the coupling coefficient of the resonators, and R_{rx} is the real part of the load impedance Z_{rx}.

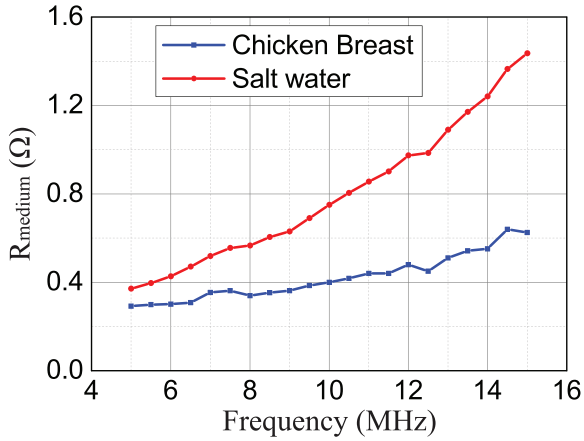
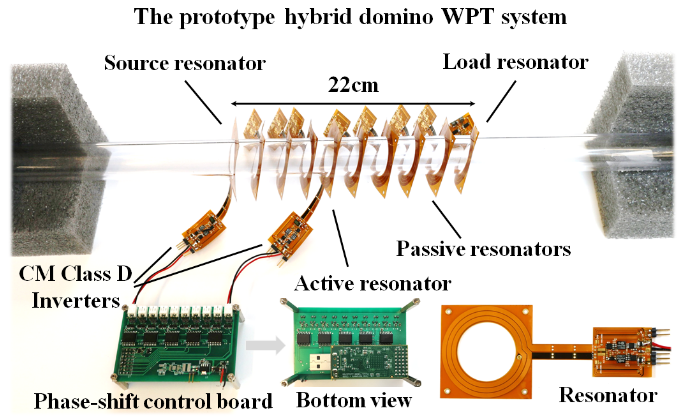


Fig. 7. Measured R_{medium} when sweeping the frequency for two different materials (one is Cheaken Breast, the other is 5.7g/100g salt water).

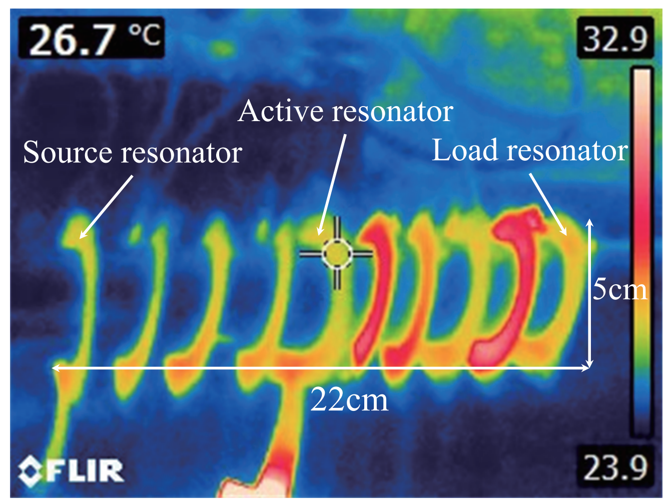
Fig. 7 shows the measured results of the real part of Z_{medium}, i.e., R_{medium}, when sweeping the frequency for two materials. It can be seen that a higher operating frequency leads to a higher R_{medium}, which will cause a higher power loss on the medium and reduce the power transfer capability of the WPT system. Note the imaginary part of Z_{medium} also affects the power transfer capability of the WPT system because it detunes resonators from the resonance at the targeted frequency. According to Eq. (6), a higher frequency can provide a higher R_{reflt} which helps to improve the efficiency and power transfer capability of the resonators (Eq. (5). Therefore, there is an optimal operating frequency to transfer power through a specific material. Here the optimal frequency is jointly determined by the material property, the parameters of the resonators (self-inductance and ESR), the transfer distance (coupling coefficient), and the power level (the load impedance). The hybrid Domino WPT architecture can help to improve the power transfer capability by creating better tradeoff options for many of these design parameters. By using time-domain multiplexing and phase-shift multiplexing, one can effectively tune the load impedance to achieve high performance for wireless power transfer.

VI. Experimental Results

Fig. 8 (a) shows a prototype hybrid Domino WPT system comprising a source resonator, a load resonator, an active resonator, and seven-passive resonators. The circuit model of the prototype is the same as the one in Fig. 4. The source and active resonators are driven by two current-mode Class-D inverters and a Class-D rectifier is connected to the load resonator. The natural frequency of all resonant tank is 13.56 MHz. The self-inductance of the resonator is about 600 nH and the coupling coefficient between two adjacent resonators is measured as 0.18. The end-to-end power transfer distance is 22 cm and the resonator diameter is about 5 cm. The inductance and capacitance of the parallel resonant tank in the Class D inverters are 82 nH and 1650 pF, respectively. GaN transistors, GS61004B, are used as the switches in the



(a)



(b)

Fig. 8. (a) A 13.56 MHz hybrid Domino WPT system with ten resonators; (b) Thermal image of the Domino WPT system with 10 W output power. 52% of the power came from the source, and 48% of the power came from the buffer (active repeater).

inverters and rectifiers. A 10-port controller board is designed to modulate the power flow with TDM, FDM and PSM. It can support ten channels phase delay control and frequency modulation up to 20 MHz. Fig. 8 (b) shows the thermal image of the system when 10 W is delivered to the load (52% from the source, and 48% from the buffer). More power is concentrated in #6–#9 than #2–#4, as expected.

Fig. 9 (a) and (b) show the measured end-to-end efficiency and the output power of the hybrid and passive Domino WPT systems across an input voltage range from 5 V to 10 V. Here the voltage of the energy buffer is 5 V and the phase difference between the active repeater and the source resonator is fixed at 20°. The phase difference is the gate driving phase difference between the Class-D inverters. The hybrid Domino system achieves higher efficiency and higher output power compared to a passive system. The end-to-end efficiency of the system is about 40% when transferring 12 W output power to the load (56% from the source, and 44% from the buffer). Fig. 10a

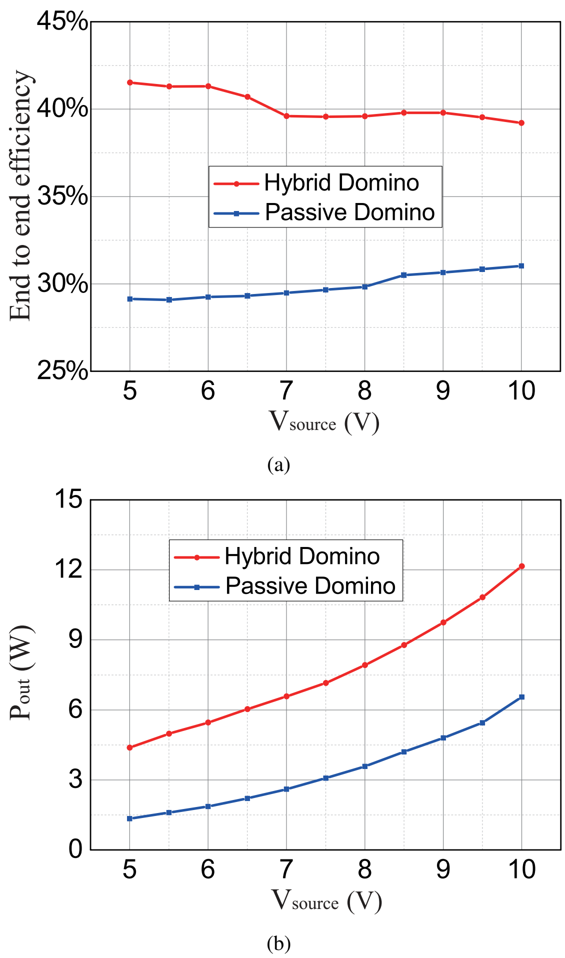


Fig. 9. Comparing hybrid Domino architecture against passive Domino architecture: (a) End-to-end efficiency across a range of input voltage; (b) Output power across a range of input voltage.

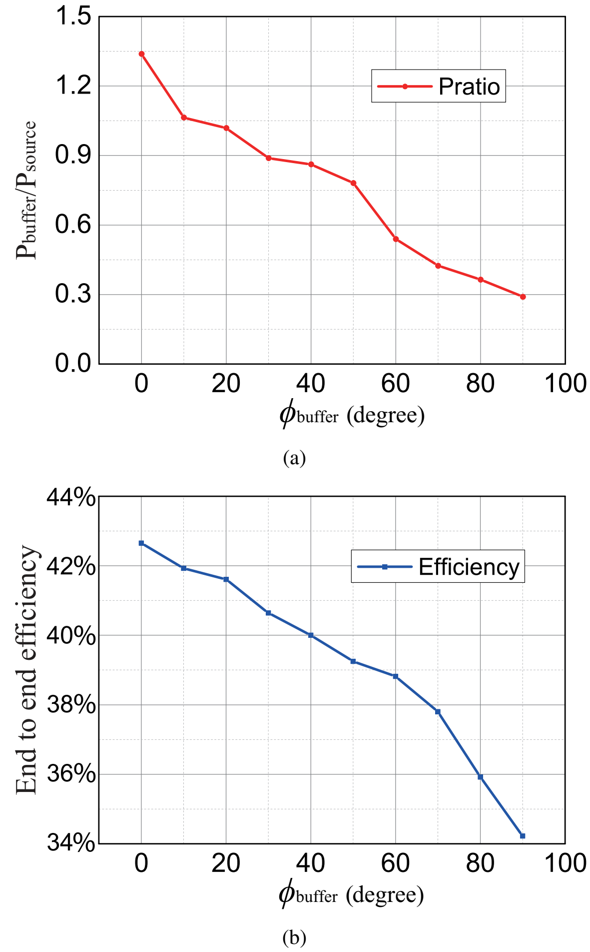
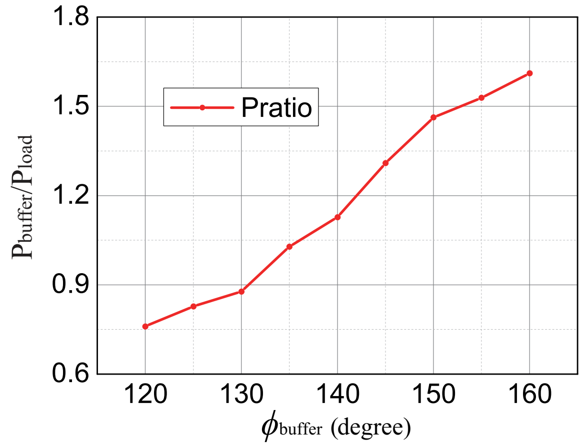


Fig. 10. Modulating the power between the source and the active repeater with active phase-shift control: (a) Power-splitting ratio; (b) End-to-end efficiency. Many control methods can be merged together for optimal performance.

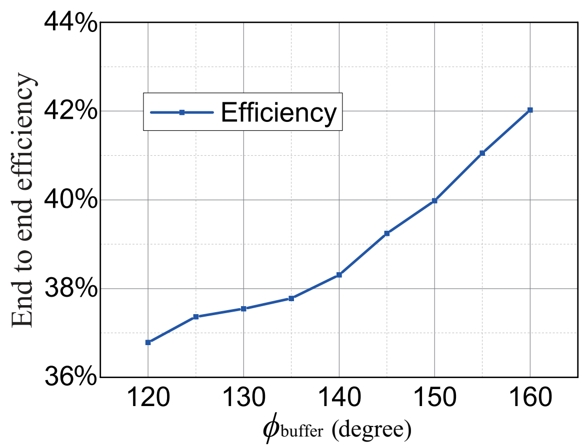
shows the measured output power dividing ratio between the buffer and power source when the buffer (active repeater) is configured as a source. It shows that the power ratio can be modulated by tuning the phase-shift of the active repeater (the buffer), which validates one way to control the MIMO power flow in the hybrid Domino WPT architecture. The end to end efficiency is shown in Fig. 10b. The higher power ratio (higher buffer output power) helps to achieve a higher end to end efficiency. The power splitting ratio between the buffer and load and the end to end efficiency when the buffer is configured as a load are shown in Fig. 11. These experimental results well validate the phase-shift multiplexing operation of the hybrid Domino architecture and opens new opportunity to improve the system performance across different working conditions by integrating multiple control methods.

To validate the multi-layer multi-medium power transfer capability of the hybrid Domino WPT architecture, another experimental setup is built with two different layers of materials, i.e., chicken breast and salt water, as shown in Fig. 12. The whole system consists of three CM Class D converters, three active resonators, and two mediums in the plastic containers. Here the passive resonators are not used in this experiment for simplification purpose. Note the passive resonators can be inserted in the middle of one medium to extend transfer distance of the hybrid Domino system when the active resonators are placed in the interface of two mediums for mixed frequency operation. The power is firstly delivered from the resonator (source) at the bottom layer through the salt water to the active resonator (energy buffer) in the middle. And then the power is sending from the energy buffer through the chicken breast to the resonator (load) at the top layer. The thickness of each material layer is 30 mm.

Fig. 13 shows the experimental results when power is transferred through the chicken breast. The operating frequency and the phase-shift of the hybrid Domino system are tuned as 13.9 MHz and 40° to achieve the maximum output power. Note only one transmitting active resonator and one receiving active resonator are used. The experimental results of the WPT system with a fixed operating frequency 13.56 MHz, are also shown. For this specific experimental setup, a hybrid Domino WPT system can achieve higher output power and higher end-to-end efficiency by operating at 13.9 MHz instead of



(a)



(b)

Fig. 11. Modulating the power between the active repeater and the load with phase-shift control: (a) Power ratio; (b) End-to-end efficiency.

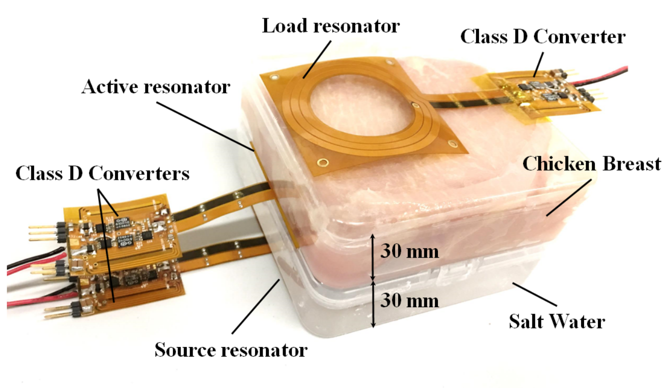
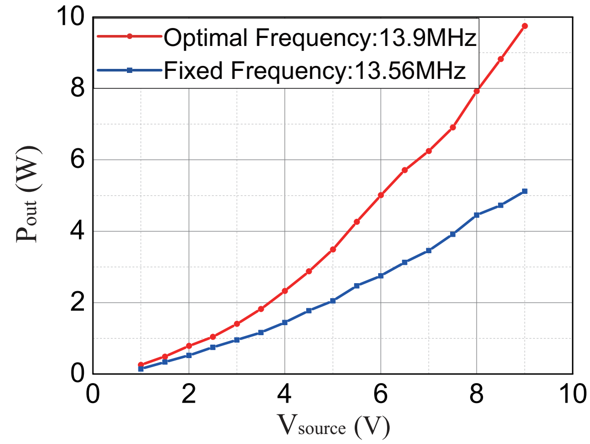
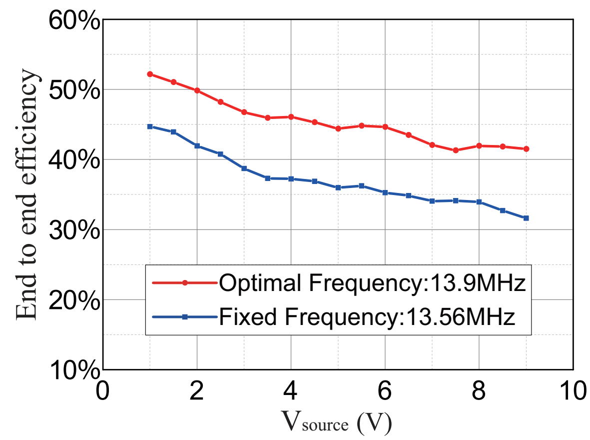


Fig. 12. Experimental setup to test the performance of hybrid Domino wireless power transfer with frequency modulation.



(a)

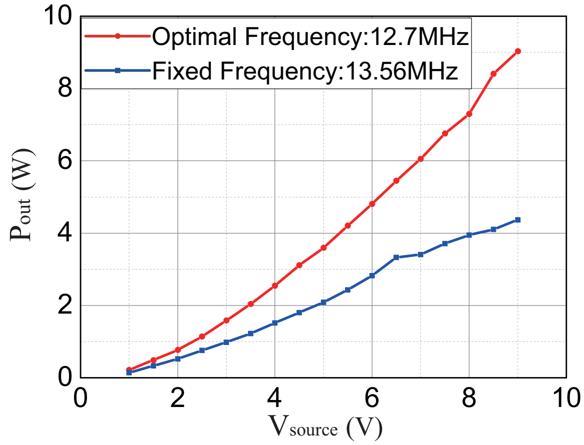


(b)

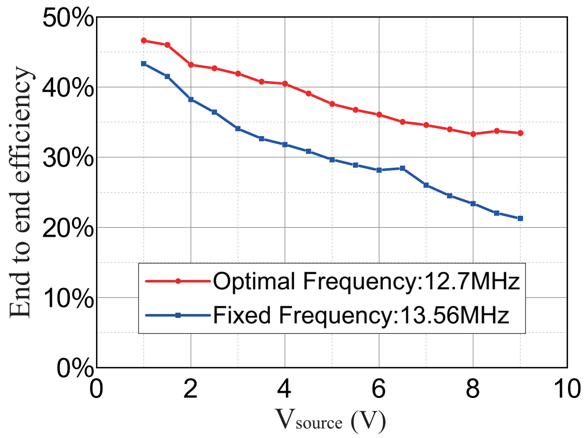
Fig. 13. Experimental results when transferring power through the chicken breast (30 mm thickness): (a) Received power; (b) End-to-end efficiency.

13.56 MHz. Fig. 14 shows the experimental results when the power is transferred through the salt water. Similar results were observed when the operating frequency and the phase-shift are tuned as 12.7 MHz and 15°, respectively. With the same repeater design, different channel material will have an impact on the optimal wireless power transfer frequency. A hybrid repeater design creates opportunity to modulate the frequency.

Fig. 15 shows the experimental results when power is transferred through the entire 60 mm distance with two different materials. Here the input voltage of the hybrid Domino system changed from 1 V to 9 V. The operating frequencies and phase-shift for the power transfer through the chicken breast and the slat water are same with the experiments in Fig. 13 and Fig. 14, respectively. The experimental result of the passive Domino WPT system and a conventional WPT system (without repeater) are compared. A tuned passive repeater is also placed at the interface of two mediums in the experiment for comparison. The operating frequency of the passive Domino WPT system is 13.56 MHz. By combining the power from the source and from the buffer, the hybrid Domino WPT system can deliver about 30% more power to the load than a passive Domino WPT system. The conventional WPT system without repeaters can only deliver very low power because of the very low coupling coefficient (k=0.025 at 60 mm). In the hybrid Domino WPT system, the power is transferred to the active repeating resonator first, and then transferred to load resonator with a different frequency and different phase shift. The entire



(a)



(b)

Fig. 14. Experimental results when transferring power through the salt water (5.7g/100g; 30 mm thickness): (a) Received power; (b) End-to-end efficiency.

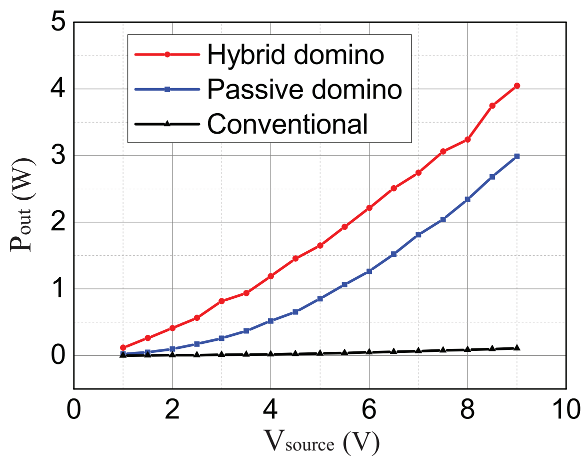


Fig. 15. Experimental results when transferring power through both the chicken breast and the salt water (60 mm thickness in total).

power transfer process of the hybrid Domino WPT system combines phase-shift multiplexing, frequency-division multiplexing, and time-division multiplexing to achieve improved power delivery capability.

VII. Conclusions

This paper presents a hybrid active/passive Domino architecture with MIMO power flow control and mixed frequency operation for extended range WPT. This architecture enables higher efficiency and higher power transfer capability, and creates additional control degrees-of-freedom to manage the multi-way power flow. It enables high performance multi-layer multi-medium WPT by combining different control strategies together. Two experimental setups, i.e., a Domino WPT system with 10-resonator and a Domino WPT system with multiple stack material layers, are built and tested to verify the effectiveness of the approach.

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