

# Proposal of a New Disk-Repeater System for Contactless Power Transfer

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**SUMMARY** The authors propose “Disk-repeater” as a new structure alternative to the conventional resonator repeater. Disk-repeater has a simple structure comprised of just copper plates and wire, non-resonant structure. First, coupling coefficients are measured as functions of disk diameter and wire length to characterize the basic performance of Disk-repeater. It is explained by several experimental evidences that Disk-repeater and resonator are not magnetically coupled but electrically coupled. It is also shown that the transmission distance extends dramatically longer than that of conventional resonator repeater. Further, two-dimensional arrangement, where multiple disks are connected, shows very high efficiency and uniform transmission characteristic regardless of positions of receiving resonator. Disk-repeater gives possibility of unprecedented versatile application with the simple structure.

**key words:** *Disk-repeater, simple structure, electric coupling, two-dimensional arrangement, contactless power transfer, non-resonant structure*

## 1. Introduction

Wireless power transfer (WPT) systems based on coupling of non-radiation field around a resonator have been studied extensively since the demonstration by Massachusetts Institute of Technology (MIT) in 2007 [1]. This system can transfer power with high-efficiency for the medium distance. The transmission distance, however, depends on the resonator diameter strongly, and thus, non-excited resonator placed between transmitting and receiving resonators, which is called “resonator repeater”, is sometimes used to extend transmission distance [2], [3]. But, this system configuration is cumbersome, because adjustment of each resonator position and resonant frequency is required. Furthermore, the transmission distance is limited due to loss accumulation by the inserted resonators.

The authors reported a study on WPT systems through water, where a phenomenon that coupling coefficient changes greatly depending on the number of plastic bottles of water placed in the coupling space was observed [4]. Generally, coupling is a combination of electric and magnetic components, and the electric field distribution is af-

fectured by the bottled water, resulting in change of electric coupling component [5]. It is considered that the electric field is guided by the water, so that the electric coupling becomes stronger. This novel concept of field guide could easily be extended to different structures.

In this paper, we propose a new structure for contactless power transfer (CPT) system called “Disk-repeater” [6]. It can improve coupling coefficient by appropriate guide of non-radiating field. We will use the term “CPT” instead of “WPT” for our system, since it looks like a wired system though it is still contactless. First, configuration of the transmission system using Disk-repeater is shown. Then, basic investigation of Disk-repeater is carried out to clarify its characteristics. Next, efficiencies versus transmission distance for Disk-repeater and conventional resonator repeater are compared. Finally, two-dimensional arrangement of multiple disks will be shown followed by proposal of various applications.

## 2. Structure and Performance of Disk-Repeater

### 2.1 Structure of Disk-Repeater

The proposed “Disk-repeater” has a very simple structure comprised of just copper plates and wire, on the basis of guide effect of non-radiating electric field. Open spiral coil resonator with open-ends shown in Fig. 1 is mainly used in Disk-repeater system. This resonator self-resonates without a loading capacitor, and couples not only magnetically but also electrically [7].

Coupling coefficient of Disk-repeater is measured as one of its basic characteristics by a VNA (Vector Network Analyzer). The basic structure of a CPT system using Disk-repeater is shown in Fig. 2, where the resonators are coupled to the source and load through a loop exciter, and Disk-repeater is located between the transmitting resonator and receiving resonator. Coupling coefficients are calcu-

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Diameter: 30 cm  
Number of turns: 99  
Resonant frequency: 2.3MHz

Fig. 1 Open spiral coil resonator.

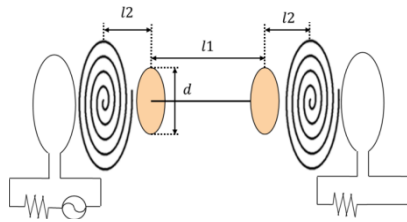


Fig. 2 WPT system using Disk-repeater.

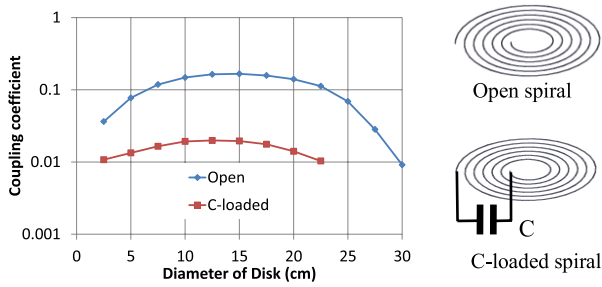


Fig. 3 Coupling coefficient vs. disk diameter  $d$ .

lated from measured S parameter  $S_{21}$ . The loop exciters are loosely coupled to the resonators so that they do not disturb electromagnetic field around the resonators.

### 2.2 Characteristics of Disk-Repeater

We will compare the coupling coefficient for 2 kinds of structure as functions of disk diameter  $d$ . One structure is just the same as Fig. 2, using open spiral resonators, and another uses capacitor loaded spiral resonators as shown in the insert of Fig. 3. The other parameters are kept constant, length of copper wire ( $l_1$ ) 40 cm and distance between resonator and disk ( $l_2$ ) 1 cm. Measured results are shown in Fig. 3. As is seen in Fig. 3, coupling coefficient for capacitor loaded spiral coil resonators is very small compared with open spiral resonators, probably because the electric field is confined in the capacitor [8]. Disk-repeater may use mainly electric field for coupling.

Another point is that, optimum disk diameter for the maximum coupling coefficient is about 15 cm in Fig. 3. Since the resonator diameter is 30 cm, it is just half of the resonator diameter. This is explained by the fact that the direction of electric flux of open spiral coil resonator is changed at nearly half of the diameter, as shown in Fig. 4. When the disk diameter is smaller than the diameter indicated by dotted lines, larger diameter gives stronger coupling. But, if disk diameter is larger than diameter indicated by the dotted lines, coupling becomes weaker according to the diameter, because the electric flux with reverse direction cancels the coupling. Therefore, disk diameter has an optimum value for resonator diameter.

In some cases, capacitor loading might be required to tune the resonant frequency. Thus, the effect of loaded capacitor is inspected. For a spiral coil of 15 turns, capacitance is varied from 0 pF to 30 pF. The result is shown in Fig. 5. As

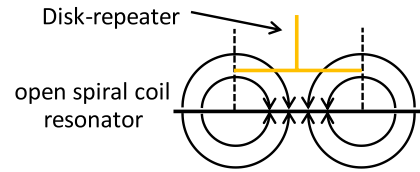


Fig. 4 Electric field distribution of spiral coil and disk.

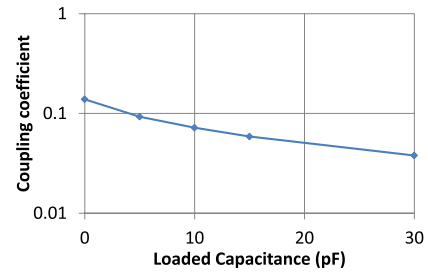


Fig. 5 Relation between loading capacitance and coupling coefficient.

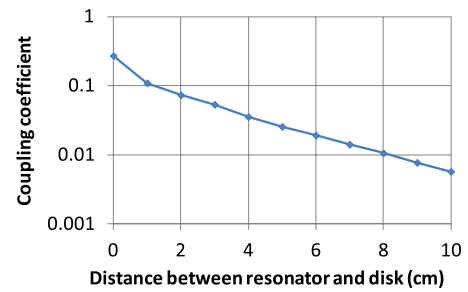


Fig. 6 Coupling coefficient vs. distance  $l_2$  between resonator and disk.

expected, coupling coefficient becomes smaller according to the increase of capacitance.

The performance of Disk-repeater could be understood by considering that a spiral coil and the facing disk make a parallel plate capacitor coupled by the electric field. The capacitance is inversely proportional to distance between the coil and disk ( $l_2$ ). Dependency of coupling coefficient on distance  $l_2$  is shown in Fig. 6. Here,  $l_1$  is set to 40 cm and  $d$  is set to 10 cm. Coupling coefficient becomes larger, if distance  $l_2$  becomes smaller. Also, the resonant frequency goes lower as distance  $l_2$  becomes smaller as shown in Fig. 7 [9].

Referring to the study above, the equivalent circuit of the system is given in Fig. 8, though parasitic resistances are omitted. The encircled area by dotted line exhibits the disk repeater, which is made of T-shaped circuit with 3 capacitors. They embody the coupling with 2 spirals by 2 corresponding series capacitors  $C_m$ , and the shunt path from the connecting wire to the ground by capacitor  $C_g$ . The calculation of response has been given elsewhere already [9].

### 2.3 Transmission Performance of Disk-Repeater

Dependency of coupling coefficient on distance between

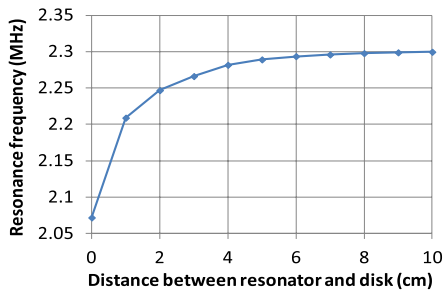


Fig. 7 Frequency shift for distance  $l_2$  between resonator and disk.

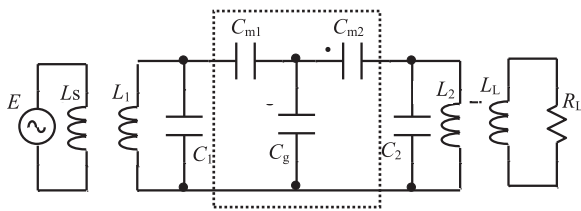


Fig. 8 Equivalent circuit of Disk repeater system.

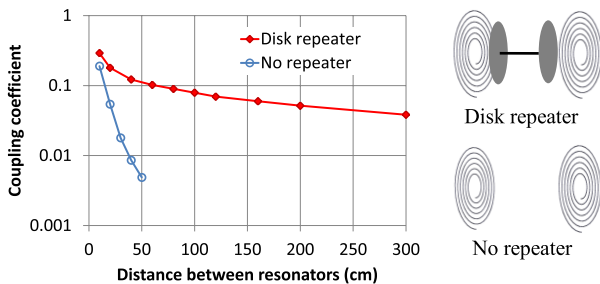


Fig. 9 Coupling coefficient vs. distance between resonators.

resonators is shown in Fig. 9. Lengths of  $l_2$  are set to 1cm at both sides of the system and  $d$  is set to 10 cm. It can be seen that transmission distance is overwhelmingly extended being compared with the case of no Disk-repeater.

Some people blame that it is not a wireless but a wired system. Yes, most part of the system is wired indeed, but the both ends are non-contact (wireless). This fact makes difference from the ordinary wired system. The conventional resonator repeater is, on the contrary, overestimated simply because each resonator couples wirelessly. But the extended distance by the chain of resonators is utilized for very limited purposes. In fact, once the repeater resonators are settled and tuned, one cannot either change the alignment or insert anything. It is more rigid than wired systems.

Our Disk repeater system is quite versatile to change the alignment, distance of resonators or number of receiving resonators. Thus, we can propose variety of applications as will be shown in Sect. 4.

There might be a possibility that transmission performance of Disk-repeater is changed with number of turns. And hence, coupling coefficients in terms of number of turns are measured and shown in Fig. 10. But there is no characteristic change due to number of turns.

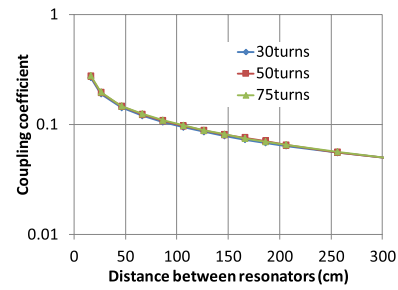


Fig. 10 Coupling coefficient vs. number of turns of spiral coils.

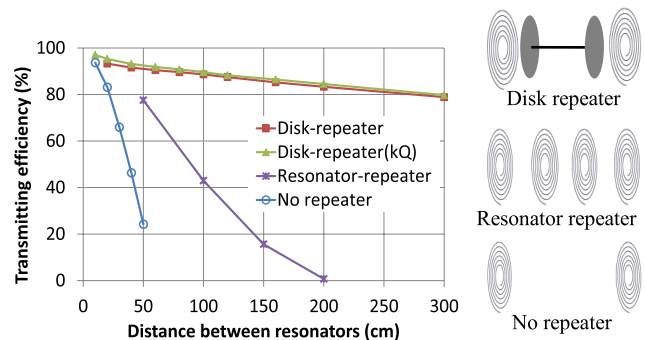


Fig. 11 Comparison of power transfer efficiency.

Transmission performances of Disk-repeater and resonator repeater are compared to make the difference clearer. For resonator repeater, two non-excited resonators are placed between transmitting and receiving resonators in the present example. The performance with no repeater is also shown in Fig. 11 together with those with repeaters. Transmission efficiency of resonator-coupled WPT system is generally calculated by product of coupling coefficient ( $k$ ) and unloaded  $Q$  ( $Qu$ ) [6]. The calculated result by  $kQ$  is added in Fig. 11 for the case of disk-repeater, as well. It is confirmed that measured efficiency and calculated value from  $kQ$ -product show good agreement.

Although transmission distance is certainly extended in the above-mentioned resonator repeater system, efficiency goes down to almost 0% at distance of 200 cm. In contrast, Disk-repeater can keep efficiency of more than 80% at the same distance. Therefore, it can be concluded that Disk-repeater has big advantages over resonator repeater to name the distance. In addition, copper wire can easily be bent. In transmission experiment for Disk-repeater with 80 cm copper wire, the wire was bent at the center and two resonators were arranged perpendicularly. There was no change for coupling coefficient and transmission performance. Thus, it can be said that Disk-repeater is easy to handle and has flexibility for selecting power transfer route [6].

### 3. Two-Dimensional Arrangement

Multiple disks are wired and arranged to construct two-dimensional contactless power transfer system. As Multiple-disk-repeater, two wiring patterns, “mesh connec-

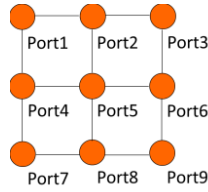


Fig. 12 Configuration of mesh connection.

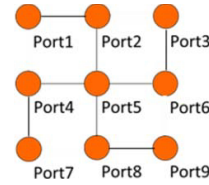


Fig. 14 Configuration of bended cross connection.

1 0.0184	2 0.0192	3 0.0184	1 0.0164	2 0.0195	3 Transfer point
4 0.0194	5 Transfer point	6 0.0192	4 0.0150	5 0.0163	6 0.0206
7 0.0184	8 0.0192	9 0.0181	7 0.0140	8 0.0153	9 0.0164

Fig. 13 Coupling coefficient for mesh connection.

1 0.0246	2 0.0247	3 0.0245	1 75%	2 75%	3 75%
4 0.0243	5 Transfer point	6 0.0247	4 74%	5 Transfer point	6 75%
7 0.0248	8 0.0250	9 0.0249	7 75%	8 76%	9 76%

Fig. 15 Coupling coefficient and power transfer efficiency for bended cross connection.

tion” and “swastika connection”, are considered. Here, nine plates are arranged and transmission performances are investigated.

### 3.1 Mesh Connection

Configuration of mesh connection is shown in Fig. 12. Port number is assigned as shown in the figure, where diameter of disk ( $d$ ) is 10 cm and distance between adjacent disks is 40 cm. Coupling coefficients for the two cases, in which a transmitting resonator is located on port 3 or port 5 disk, are measured. The receiving resonator is placed on one of the other ports than the transmitting port. Measured results are shown in Fig. 13. When the transmitting resonator is located on port 5, then port 2, 4, 6, 8 are the first nearest ports and port 1, 3, 7, 9 are the second nearest ports. As a result, almost the same coupling coefficients were obtained for all receiving ports. When transmitting resonator is located on port 3, coupling coefficients of ports far from the transmitting port naturally become smaller.

### 3.2 Swastika Connection

Configuration of swastika (bended cross) connection is shown in Fig. 14. Measured results are shown in Fig. 15, for the case when the transmitting resonator is located on port 5. Coupling coefficient is almost the same for all receiving ports. Further, the values are slightly larger than those of mesh connection. It may be due to no interference from multiple paths deteriorating the mesh connection in Fig. 12. Transmission efficiency is also shown in Fig. 15. Efficiency more than 70% is obtained at all ports. Comparing with conventional multi-hop system [10], efficiency is independent of receiving positions. And, no ON/OFF control of switching to optimize transmission path is required, which is essential for conventional multi-hop systems.

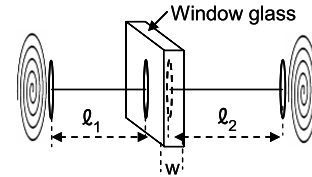


Fig. 16 Basic configuration for through-glass CPT.

## 4. Proposal of Applications

Since Disk-repeater has the advantages of

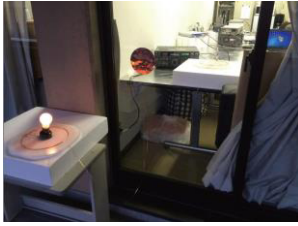
- 1) Non-contact power transfer
  - 2) Quite low loss
  - 3) Simplest, lightest and versatile structure
  - 4) Non-resonant structure
- it is applicable to varieties of purposes.

### 4.1 Through-Glass CPT System [6], [11]

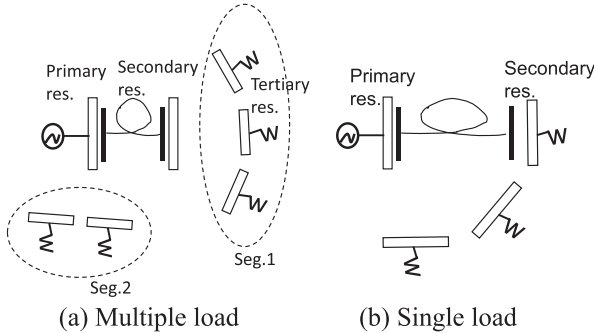
As is shown in Fig. 16, the disk repeater can be divided with spacing without appreciable loss. Therefore, the through-glass CPT system can be constructed very easily by sticking 2 disks to the glass. It could be used to deliver power for garden work or for outdoor events without drilling any holes on the wall. Demonstration of 30 W light bulb is shown in Fig. 17.

### 4.2 Contactless Power Catering [6]

Freedom from definite placement of the 2ndary resonator of Disk-repeater system suggests a new concept of application shown in Fig. 18. If the group of loads only need power time to time, one may place the pair of 2ndary resonator and the 2ndary disk close to them when needed as shown in (a). It can be carried to any places where smaller resonators are waiting. When the power delivery is over at one place, the



**Fig. 17** An example of through-glass CPT (A lamp outside of a room is delivered power from indoor).



**Fig. 18** Contactless power catering system.



**Fig. 19** A X-mas tree on the CPT mat made of 9 disks.

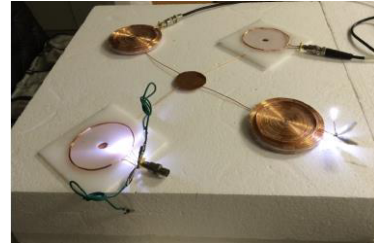
2ndary resonator can be moved to another place with hand. The case (b) shows a little different configuration, where the loads are individual. The secondary disk and resonator are separated and they are faced each other when needed. These 2 CPT systems may be used for charging a sensor system.

4.3 Contactless Power Mat [9]

The 2 dimensional systems shown in Sect. 3 are utilized as the contactless power mat on which multiple loads are delivered power at the same time. Figure 19 explains how it works, where the primary resonator is put on Port 5 and a Xmas tree is put on Port 8 in Fig. 14. Multiple loads are also acceptable.

4.4 Contactless Power Transfer Platform [12]

The disks in the system have their self-resonant frequency at several tens of MHz band, and thus, they are considered non-resonant in the several MHz band in which the systems



**Fig. 20** CPT platform made of 5 disks (2 systems working at the same time).

work. As a result, we can use multiple power sources with different frequency at the same time in a single system. In Fig. 20, 1.8 MHz and 14 MHz source/load pairs coexist in the system and deliver power independently to LEDs. The non-resonant nature of disk repeater system will be useful for multiple power sources with the different frequency. Thus, it will be easy to deliver power without wires to additional equipment as needed.

5. Conclusion

“Disk-repeater”, as a new structure alternative to conventional resonator repeater, is proposed. By using Disk-repeater, very high efficiency in long distance is realized, even though it has a simple structure comprising of copper plates and wire. It is confirmed that Disk-repeater utilizes mainly electrical coupling, something like a wired pair of capacitances.

“Multiple-Disk-repeater”, in which multiple disks are arranged in two dimensions, has also been proposed. It shows uniform transmission property for receiving resonators on a different position. In addition, non-resonant nature of the disks allows coexistence of different frequency source/load pairs in a single system. It will enlarge the application field of the Disk-repeater further.

In the future, a purely electrically-coupled resonator more suitable for Disk-repeater should be developed, because Disk-repeater mainly utilizes electric coupling [13]. Also, a more ingenious equivalent circuit of Disk-repeater will be required for the effective system design.

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