HIGH-EFFICIENCY WIRELESS ENERGY TRANSMISSION USING MAGNETIC RESONANCE BASED ON METAMATERIAL WITH RELATIVE PERMEABILITY EQUAL TO −1

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Abstract—In this paper, a high-efficiency wireless energy transmission via magnetic resonance is implemented by using negative permeability metamaterial structures. The metamaterial structure is consisted of a three-dimensional (3D) periodic array of the unit cell that the capacitively loaded split ring resonators (CLSRRs) are periodically arranged in the cubic dielectric surfaces. This metamaterial structure has the negative permeability property that matches free space, which is used as a magnetic flux guide in order to enhance the efficiency of energy transmission between a source and distant receiving coil. The efficiency of energy transmission is improved as reducing the radiation loss by focusing the magnetic field to a distant receiving coil. The distance able to transport the energy with maintaining the same efficiency has been increased by the same mechanism. The efficiency of energy transmission is approximately 80% at a transmission distance of 1.5 m.

1. INTRODUCTION

In recent years, there has been increasing interest in the research and development of wireless energy transmission technology to eliminate the "last cable". The large number of battery operated consumer electronics, such as laptops, cell phones, PDAs, etc., and the associated tangle of wall-wart chargers has generated interest in designing a

single, convenient charging system. The wireless energy transmission systems would permit charging many different devices equipped with the receiving coils and cut the last wire of portable wireless devices. The approaches to wireless energy transmission can be categorized as near-field and far-field. To date, the latter is still impractical for consumer applications due to the high power and large antenna requirement necessary to achieve the levels of power comparable to a wall supply. The analysis of the feasibility of the method using resonant objects coupled through the tails of their non-radiative fields for the wireless energy transmission has been presented in a recent paper. Two resonant objects having the same resonant frequency tend to exchange the energy efficiently, while dissipating relatively little energy in the extraneous off-resonant objects. On the other hand, near-field magnetic resonance has more promise as a wireless energy transmission technology. The magnetic resonances are particularly suitable for daily applications because the interactions with environmental objects are reduced even further [1–4].

The metamaterials are an artificial composite that the electromagnetic properties can be engineered to achieve the extraordinary phenomena not observed in the natural materials as, for instance, negative effective permittivity and permeability. The effective permittivity and permeability of the metamaterials arise from their structure rather than from the nature of their components, which are usually conventional conductors and dielectrics. The metamaterials are fabricated by means of the repetition of a resonant element to constitute a periodic structure. An essential characteristic of the metamaterials is that both the size of this element and periodicity are smaller than the wavelength of the electromagnetic fields that propagate through the structure. One of the most noticeable properties of the metamaterials is the ability of a metamaterial structure with relative permittivity and permeability, both equal to −1, to behave as a "magnetic flux guide" with sub-wavelength resolution, that is, with a resolution smaller than the free-space wavelength of the impinging radiation. Therefore, if we place the metamaterial structures with relative permeability equal to −1 between a RF magnetic field source and a receiving device, the structure will focus the magnetic field from the source towards the receiver. This mechanism can be applied to improve the efficiency of energy transmission due to the fact that the radiation loss is reduced by focusing the magnetic field radiated outside the space between the source and the receiver in the wireless energy transmission system [5–12].

Basically, two types of metamaterials which correspond to two different resonant elements can be used for the wireless

energy transmission applications. The first type is the swiss roll metamaterials. A swiss roll is consisted of a conductive layer which is wound on a spiral path around a cylinder with an insulator separating consecutive turns. The magnetic flux guiding behavior is due to the high effective permeability of the metamaterial. In all these applications, the swiss roll metamaterials mimic a medium with very high magnetic permeability at the proper frequency. The second type is the split ring resonator (SRR) metamaterials. The SRR is consisted of two similar split rings coupled by means of a strong distributed capacitance in the region between the outer and inner rings. Each split ring is a small open ring of copper which is loaded in the gap with a capacitor. Of course, this capacitor has to be non-magnetic for the wireless energy transmission applications. The split rings have the key advantage over the swiss rolls of providing a three-dimensional (3D) isotropy when they form a cubic lattice, which is an essential property if the device has to transport the 3D sources. The SRRs are used as the constituent elements of the 3D negative permeability metamaterial structures in the wireless energy transmission system [4, 13].

In this paper, a high-efficiency wireless energy transmission via magnetic resonance is implemented by using the negative permeability metamaterial structures as the magnetic flux guide.

2. DESIGN PRINCIPLES

One of the most promising applications of the left-handed metamaterials (LHMs) is the Veselago-Pendry lens made of a single slab of a thickness d showing relative electric permittivity and magnetic permeability both equal to -1. The media characterized by simultaneously negative permittivity and permeability are allowed by Maxwell's equations, and that the plane waves propagating in them would have their electric field, $\bar{E}$, magnetic field, $\bar{H}$, and propagation constant, $\bar{k}$ form a left-handed triplet. Also, one has to choose the negative branch of the square root to properly define the corresponding refractive index, i.e., $n = -\sqrt{\mu\epsilon}$. Thus, such LHMs support negative refraction of the electromagnetic waves. Consequently, when such media are interfaced with the conventional dielectrics, Snell's law is extended to negative angles, thus leading to the negative refraction of an incident electromagnetic plane wave. In principle, this device will be able to reproduce with any desired resolution including sub-diffraction resolution of the electromagnetic field between a source device located in front of the source metamaterial structure and a receiving device located behind the receiving metamaterial structure separated on a specific distance from the source device. However, this effect is strongly limited by the

losses, which in practice reduces it to a near field effect. In fact, it can be shown that the minimum resolution attainable from a lossy slab, having the real parts of the relative permeability and permittivity both equal to −1, is given by

$$\triangle \geq \frac{2\pi d}{\ln(2/\delta)} \tag{1}$$

where δ is the loss tangent of the slab, and d is the thickness of the metamaterial structure. It is clear from Eq. (1) that $\triangle > d$ for any realistic metamaterial. This means that in order to obtain sub-diffraction resolution ($\triangle < \lambda$) the slab thickness must be substantially smaller than the wavelength. Therefore, only slabs with relative permeability or permittivity equal to −1 are necessary in order to obtain sub-diffraction resolution in the near field [14].

Figure 1 shows the mechanism of the wireless energy transmission using the negative permeability metamaterial structures. As shown in Fig. 1, in the source device, when the magnetic field radiated by the coupling loop of the source device is contact to the negative permeability metamaterial structure of the source device, the magnetic field is refracted inside the space between the negative permeability metamaterial structures of the source and receiving devices. If this is the conventional positive permeability structure, the magnetic field is refracted outside the space between the conventional positive permeability structures of the source and receiving devices. In the receiving device, when the magnetic field refracted to the negative permeability metamaterial structure of the receiving device is contact
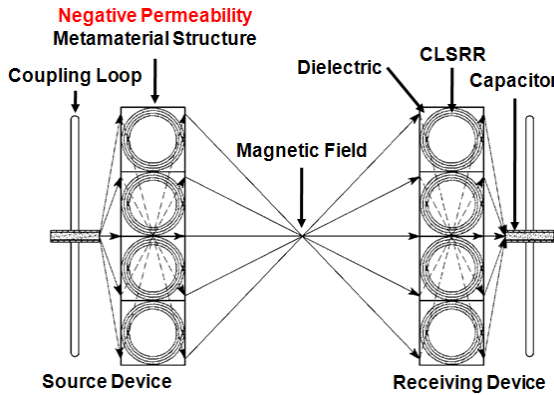

Figure 1. Mechanism of wireless energy transmission using negative permeability metamaterial structures.

to the negative permeability metamaterial structure of the receiving device, the magnetic field is refracted inside the space between the negative permeability metamaterial structure and coupling loop of the receiving device. If this is the conventional positive permeability structure, the magnetic field is refracted outside the space between the conventional positive permeability structure and coupling loop of the receiving device. It is because of the reversed refraction property of the negative permeability metamaterial structure. Through this mechanism, the magnetic field radiated by the coupling loop of the source device is focused to the coupling loop of the receiving device. Namely, because the radiation loss in the wireless energy transmission reduces by focusing the magnetic field through the negative permeability metamaterial structures, the efficiency of energy transmission can be further improved at the same transmission distance [15–19].

In Fig. 1 showing the metamaterial structures with an ideal relative permeability equal to −1 for the wireless energy transmission applications, in general, a SRR structure exhibits both magnetic response induced by the solenoidal currents flowing around the SRR, and electric response by the dipole-like charge distribution along the incident electric field. Since the losses in the metamaterials are essentially given by the losses in its constitutive elements, it is desirable from this point of view to use electrically big capacitively loaded SRRs (CLSRRs) for the design. On the other hand, since according to Eq. (1) the minimum resolution cannot be made smaller than the slab thickness, there is no reason to use more than two or three periods along the slab width. From these considerations, a practical implementation of this structure using the CLSRRs has only one period along the slab thickness as shown in Fig. 1 [14, 19].

The negative permeability metamaterial structure is designed by using the 3D periodic array of the unit cell that the CLSRRs are periodically arranged in the cubic dielectric surfaces. The CLSRR consisting of the unit cell of a 3D negative permeability metamaterial structure with relative permeability equal to −1 is shown in Fig. 2. As shown in Fig. 2, the CLSRR used to design the unit cell of a 3D negative permeability metamaterial structure is consisted of the concentric inner and outer metallic rings (dark gray) with the open gap etched on a nonmagnetic dielectric board and the lumped capacitors (black) loaded at the open gap of the concentric inner and outer metallic rings. In general, a CLSRR structure exhibits both magnetic response induced by the solenoidal currents flowing around the CLSRR, and electric response by the dipole-like charge distribution along the incident electric field. The magnetic response of the CLSRR structure exhibits

a resonance in the transmission spectrum. This resonance behavior is observed as a rise in the transmission spectrum of a single CLSRR structure. When the CLSRRs are arranged in a periodic medium, due to the interaction between the CLSRRs the resulting medium exhibits a band pass in the transmission spectrum. The frequency selective behavior of the CLSRR can be also explained by the induced current loops in the rings at the resonance. These current loops are closed through the distributed capacitance in the region between the concentric rings. The CLSRR can be modeled as LC resonant tanks that can be externally driven by a magnetic field. They are able to reinforce the signal propagation in a certain narrow band if they are properly oriented. Since the equivalent capacitance C is given by the edge capacitance between the concentric rings, the resonant frequency can be made very low by decreasing the ring separation s. It is obvious that any coupling generated by using these coupling structures is the proximity coupling through the fringing fields. The nature and intensity of the fringing fields decide the nature and strength of the coupling [13, 14, 19, 20].

3. SIMULATION RESULTS

Figure 3 shows the dimensions of the wireless energy transmission structure using the 3D negative permeability metamaterial structures consisted of the periodic array of the unit cell that the CLSRRs with relative permeability equal to -1 are periodically arranged in the cubic dielectric surfaces. The outside diameter (d) and thickness (a) of the coupling loop are 400 mm and 80 mm, respectively. The unit cell is consisted of the cubic dielectric with a dielectric constant of 10.2
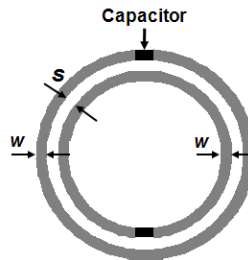

Figure 2. CLSRR consisting of unit cell of 3D negative permeability metamaterial structure with relative permeability equal to -1.
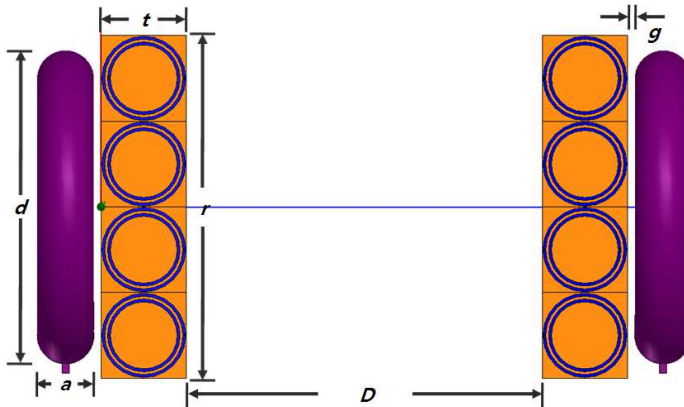
Figure 3. Dimensions of wireless energy transmission structure using 3D negative permeability metamaterial structures with relative permeability equal to −1.

and size (t) of 120 mm on a side. Because the negative permeability metamaterial structure is designed by periodically arranging the unit cell as 4×4 array, the dimension of the negative permeability metamaterial structure is 480 (r) $\times 480 \times 120$ mm. The width (w) of the inner and outer rings and the separation (s) between the inner and outer rings are all 4 mm in the CLSRRs etched on all surfaces of the cubic dielectric. The gap (g) between the coupling loop and the negative permeability metamaterial structure is 10 mm.

If the metamaterial structure is treated as a homogeneous dielectric slab, the effective permeability can be extracted from two-port scattering parameters. One unit cell of this structure was simulated inside an ideal parallel-plate waveguide by using Ansofts High Frequency Structure Simulator (HFSS) finite-element-method software package. Also, the ohmic dissipation in the metals and dielectric losses in the metamaterial structure were considered to exactly simulate the performances of the wireless energy transmission such as the efficiency of energy transmission, effective permeability, and magnetic field flows, etc in the simulation model. The effective permeability is plotted versus the frequency in Fig. 4. As shown in Fig. 4, the effective permeability is approximately −1 at the design frequency of 23.20 MHz.

Figure 5 shows the simulation results of the transmission (S_{21}) and reflection (S_{11}) properties of the wireless energy transmission without and with the negative permeability metamaterial structures. As shown in Fig. 5, the transmission gain of the wireless energy
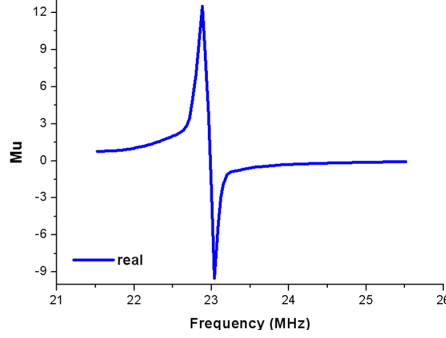
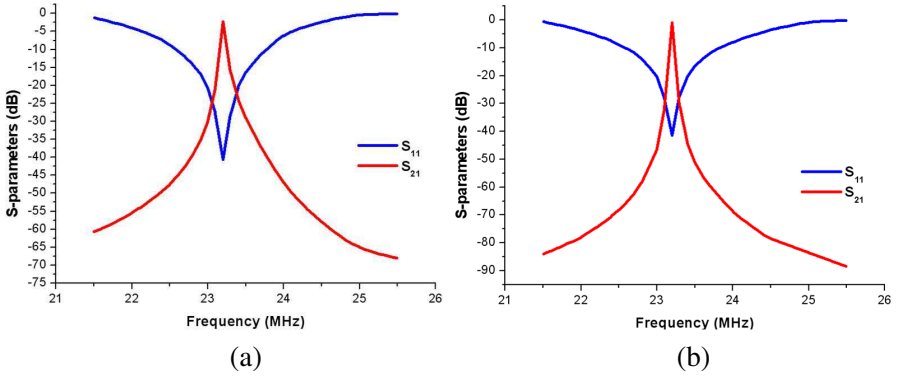**Figure 4.** Extracted effective permeability vs. frequency for normally incident wave.

Figure 5. Simulation results of transmission and reflection properties (S_{21}, S_{11}) of wireless energy transmission. (a) Without negative permeability metamaterial structures. (b) With negative permeability metamaterial structures.

transmission consisted of only two coupling loops without the negative permeability metamaterial structures is -2.22 dB at the resonance frequency of 23.20 MHz, and that of the wireless energy transmission with the negative permeability metamaterial structures is -0.88 dB at the resonance frequency of 23.20 MHz. The efficiency of energy transmission of the former structure is 60.00%, and that of the latter structure is 81.70%. In these two cases, the transmission distance is 1.5 m. These efficiencies of energy transmission are the simulation results after matching at 50 Ω. Namely, the efficiencies of energy transmission of the wireless energy transmission without and with the negative permeability metamaterial structures were compared with the
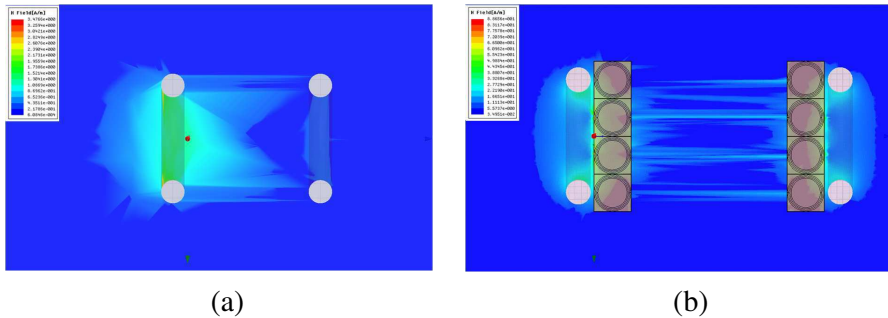
(a)   (b)

Figure 6. Simulation results of magnetic field of wireless energy transmission. (a) Without negative permeability metamaterial structures. (b) With negative permeability metamaterial structures.

same reflection loss condition. From these simulation results, it is clear that the efficiency of energy transmission was further improved by using the negative permeability metamaterial structures as the magnetic flux guide. On the other hand, the radiation loss further reduced by focusing the magnetic field to the receiving device. Fig. 6 shows the simulation results of the magnetic field of the wireless energy transmission without and with the negative permeability metamaterial structures. Compared with the magnetic field between the source and receiving devices of the wireless energy transmission without the negative permeability metamaterial structures, the magnetic field between the source and receiving devices of the wireless energy transmission with the negative permeability metamaterial structures is strongly focused to the receiving device. From the flow of the magnetic field, it is demonstrated the fact that the magnetic field can be focused by the negative permeability metamaterial structures.

4. FABRICATIONS AND MEASUREMENT RESULTS

Figure 7 shows the fabrication of the negative permeability metamaterial structure. The negative permeability metamaterial structure is fabricated on a Taconic's CER-10 substrate with a dielectric constant of 10.2 and thickness of 31 mils. The outside of the cubic unit cell is fabricated on the dielectric substrate that the CLSRRs are patterned by the metallic strips, and the inside of the cubic unit cell is filled with the air. As shown in Fig. 7, the negative permeability metamaterial structure is designed by using the 3D 4×4 periodic array of the unit cell that the CLSRRs are periodically arranged in the cubic dielectric surfaces. The size of the fabricated negative permeability
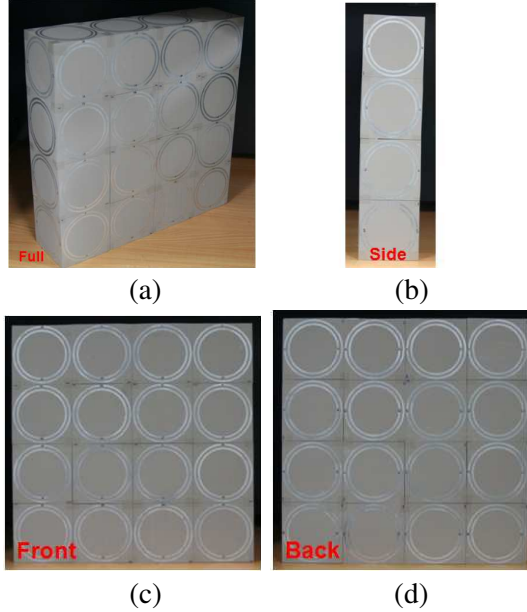
Figure 7. Fabrication of negative permeability metamaterial structure. (a) Full view. (b) Side view. (c) Front view. (d) Back view.

metamaterial structure is $480 \times 480 \times 120$ mm as the size of the negative permeability metamaterial structure of the simulation model.

Figure 8 shows the fabrication and the measurement results of the transmission and reflection properties (S_{21}, S_{11}) of the wireless energy transmission consisted of only two coupling loops without the negative permeability metamaterial structures. In Fig. 8(b), the frequency range of x-axis is from 21.5 MHz to 25.5 MHz. As shown in Fig. 8(b), when the transmission distance is 1.5 m, the transmission and reflection properties of the wireless energy transmission consisted of only two coupling loops without the negative permeability metamaterial structures are -2.27 dB and -37.80 dB at the resonance frequency of 23.20 MHz, respectively. When considering the reflection condition, the radiation loss and efficiency of energy transmission of the wireless energy transmission without the negative permeability metamaterial structures are 40.67% and 59.30%, respectively. Fig. 9 shows the fabrication and the measurement results of the transmission and reflection properties (S_{21}, S_{11}) of the wireless energy transmission with the negative permeability metamaterial structures. In Fig. 9(b), the frequency range of x-axis is from 21.5 MHz to 25.5 MHz. As shown in

Fig. 9(b), when the transmission distance is 1.5 m, the transmission and reflection properties of the wireless energy transmission with the negative permeability metamaterial structures are -0.95 dB and -38.50 dB at the resonance frequency of 23.20 MHz, respectively. When considering the reflection condition, the radiation loss and efficiency of energy transmission of the wireless energy transmission with the negative permeability metamaterial structures are 19.62% and
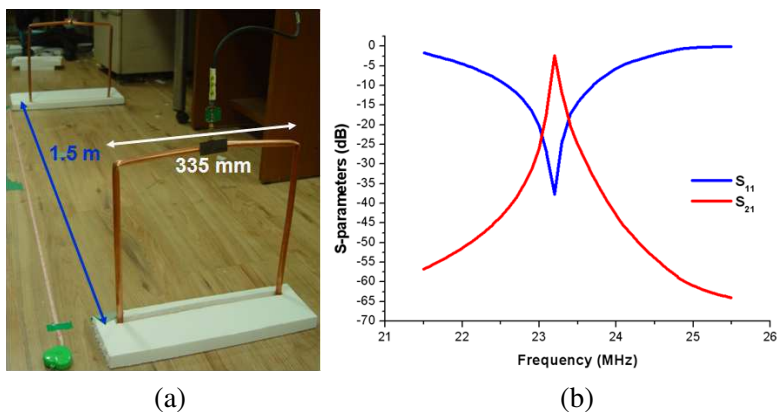

(a)   (b)

Figure 8. Wireless energy transmission without negative permeability metamaterial structures. (a) Fabrication. (b) Measurement results of transmission and reflection properties (S_{21}, S_{11}).
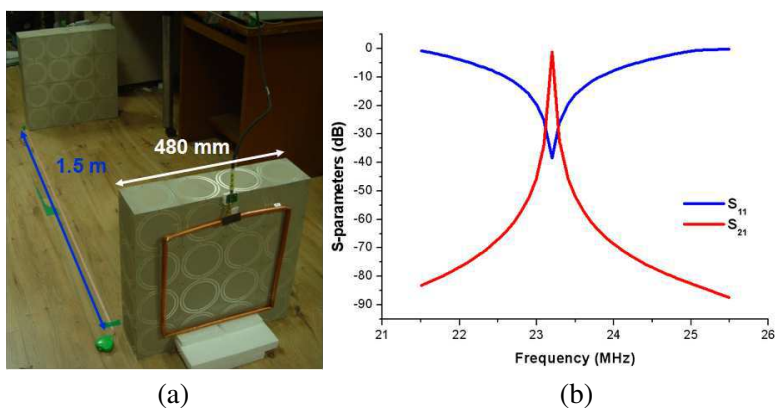

(a)   (b)

Figure 9. Wireless energy transmission with negative permeability metamaterial structures. (a) Fabrication. (b) Measurement results of transmission and reflection properties (S_{21}, S_{11}).

80.35%, respectively. From these measurement results, it is clear that the efficiency of energy transmission was further improved by using the negative permeability metamaterial structures as the magnetic flux guide. On the other hand, the radiation loss further reduced by focusing the magnetic field to the receiving device. Compared with the simulation results of the simulation models, we have obtained the similar measurement results of the fabrication structures in the wireless energy transmission. The size of the rectangular coupling loop used to the fabrication structures of the wireless energy transmission is 335×335 mm. Fig. 10 shows the measured efficiency of energy transmission versus the transmission distance in the cases both the wireless energy transmission structures with and without the negative permeability metamaterial structure. As shown in Fig. 10, the decrease rate of the efficiency of energy transmission with the transmission distance increase of the wireless energy transmission structure with the negative permeability metamaterial structure is lower than that of the wireless energy transmission structure without the negative permeability metamaterial structure. Table 1 shows the summary of the operation performances of the wireless energy transmission without and with the negative permeability metamaterial structures. As shown in Table 1, when using the negative permeability metamaterial structures to the wireless energy transmission, the radiation loss reduced in half by focusing the magnetic field to the receiving device. The efficiency of energy transmission was improved as reducing the radiation loss.
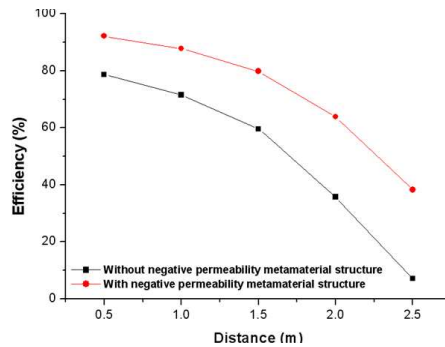

Figure 10. Measured efficiency of energy transmission vs. transmission distance.

Table 1. Summary of measured operation performances.

Parameters	Units	Without NRI Metamaterial Structures	With NRI Metamaterial Structures
Frequency	MHz	23.20	23.20
Distance	m	1.5	1.5
Transmission	dB	−2.27	−0.95
Return Loss	dB (%)	−37.80 (0.03)	−38.50 (0.03)
Radiation Loss	%	40.67	19.62
Efficiency	%	59.30	80.35
Size (Coupling Loop/ NRI Metamaterial Structure)	mm	335 × 335 /NA	335 × 335 /480 × 480 × 120

5. CONCLUSIONS

The negative permeability metamaterial structure is implemented as the magnetic flux guide to enhance the efficiency of energy transmission of the wireless energy transmission. The negative permeability metamaterial structure is designed by using the 3D 4×4 periodic array of the unit cell that the CLSRRs are periodically arranged in the cubic dielectric surfaces. The efficiency of energy transmission was improved as reducing the radiation loss by focusing the magnetic field on a distant receiving coil. The distance able to transport the energy with maintaining same efficiency of energy transmission has been increased by the same mechanism. The efficiency of energy transmission is approximately 80% at a transmission distance of 1.5 m.

ACKNOWLEDGMENT

REFERENCES

1. Kurs, A., A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljacic, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, Vol. 317, 83–86, 2007.

2. Karalis, A., J. D. Joannopoulos, and M. Soljacic, "Efficient wireless non-radiative mid-range energy transfer," *Annals of Physics*, Vol. 323, No. 1, 34–48, 2008.

3. Cannon, B. L., J. F. Hoburg, D. D. Stancil, and S. C. Goldstein, "Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers," *IEEE Transactions on Power Electronics*, Vol. 24, No. 7, 1819–1825, 2009.

4. Wiltshire, M. C. K., J. B. Pendry, I. R. Young, D. J. Larkman, D. J. Gilderdale, and J. V. Hajnal, "Microstructured magnetic materials for RF flux guides in magnetic resonance imaging," *Science*, Vol. 291, No. 2, 849–851, 2001.

5. Veselago, V. G., "The electrodynamics of substances with simultaneously negative values of permittivity and permeability," *Soviet Physics Uspekhi*, Vol. 10, 509–514, 1968.

6. Dolling, G., C. Enkrich, M. Wegener, C. M. Soukoulis, and S. Linden, "Simultaneous negative phase and group velocity of light in a metamaterial," *Science*, Vol. 32, No. 5775, 892–894, 2006.

7. Grbic, A. and G. V. Eleftheriades, "Dispersion analysis of a microstrip-based negative refractive index periodic structure," *IEEE Microwave and Wireless Components Letters*, Vol. 13, No. 4, 155–157, 2003.

8. Iero, D., T. Isernia, and A. F. Morabito, "Optimal constrained field focusing for hyperthermia cancer therapy: A feasibility assessment on realistic phantoms," *Progress In Electromagnetics Research*, Vol. 102, 125–141, 2010.

9. Gong, Y. and G. Wang, "Superficial tumor hyperthermia with flat left-handed metamaterial lens," *Progress In Electromagnetics Research*, Vol. 98, 389–405, 2009.

10. Navarro-Cia, M., M. Beruete, F. Falcone, and M. Sorolla, "Polarization-tunable negative or positive refraction in self-complementariness-based extraordinary transmission prism," *Progress In Electromagnetics Research*, Vol. 103, 101–114, 2010.

11. Valentine, J., S. Zhang, T. Zentgraf, E. Ulin-Avila, D. A. Genov, G. Bartal, and X. Zhang, "Three-dimensional optical metamaterial with a negative refractive index," *Nature*, Vol. 455, No. 7211, 376–379, 2008.

12. Shelby, R. A., D. R. Smith, and S. Schultz, "Experimental verification of a negative index of refraction," *Science*, Vol. 292, No. 5514, 77–79, 2001.

13. Marques, R., F. Mesa, J. Martel, and F. Medina, "Comparative analysis of edge- and broadside-coupled split ring resonators for metamaterial design — Theory and experiments," *IEEE Transactions on Antennas and Propagation*, Vol. 51, No. 10, 2572–2581, 2003.

14. Marques, R., F. Martin, and M. Sorolla, *Metamaterial with Negative Parameters: Theory and Microwave Applications*, Wiley-Interscience, New York, 2008.

15. Eleftheriades, G. V., "RF/microwave devices using negative-refractive-index transmission-line (NRI-TL) metamaterials," *IEEE Antennas and Propagation Magazine*, Vol. 49, No. 2, 34–51, 2007.

16. Markley, L. and G. V. Eleftheriades, "A negative-refractive-index metamaterial for incident plane waves of arbitrary polarization," *IEEE Antennas and Wireless Propagation Letters*, Vol. 6, 28–32, 2007.

17. Huang, H., Y. Fan, F. Kong, B.-I. Wu, and J. A. Kong, "Influence of external magnetic field on a symmetrical gyrotropic slab in terms of goos-hanchen shifts," *Progress In Electromagnetics Research*, Vol. 82, 137–150, 2008.

18. Ravaud, R., G. Lemarquand, and V. Lemarquand, "Mutual inductance and force exerted between thick coils," *Progress In Electromagnetics Research*, Vol. 102, 367–380, 2010.

19. Ozbay, E. and C. M. Soukoulis, "Observation of negative refraction and negative phase velocity in true left-handed metamaterials," *Proceedings of the 36th European Microwave Conference*, 959–962, 2006.

20. Sun, Z., M. Guo, F. Verhaeghe, J. Vleugels, O. Van der Biest, and B. Blanpain, "Magnetic interaction between two non-magnetic particles migrating in a conductive fluid induced by a strong magnetic field — An analytical approach," *Progress In Electromagnetics Research*, Vol. 103, 1–16, 2010.