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Research Article

Effects of Metamaterial Slabs Applied to Wireless Power Transfer at 13.56 MHz

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This paper analyzes the effects of a metamaterial slab (or a practical "perfect lens") with negative permeability applied to a two loop magnetically coupled wireless power transfer (WPT) system at 13.56 MHz, based on theory, full-wave electromagnetic- (EM-) simulations, and measurements. When using lossless slabs with ideal negative permeability in EM-simulations, the WPT efficiencies have been found to be enhanced close to 100% due to the magnetic field focusing. For the case of using a realistic slab made of ring resonators (RR) ($\mu_r = -1 - j0.23$) with $s/d = 0.5$ (s: slab width, d: distance between the transmitting and receiving loops), the WPT efficiency has been found to significantly decrease to about 20%, even lower than that of a free space case (32%) due to the heavy power absorption in the slab. However, some efficiency enhancement can be achieved when s/d is optimized between 0.1 and 0.3. Overall, the significant enhancement of efficiencies when using a lossless slab becomes moderate or only marginal when employing a realistic slab.

1. Introduction

The concept of WPT was conceived by N. Tesla in 1914, but, until recently, it had not been developed to any commercial application due to its low efficiency. In 2007, a magnetically coupled WPT system based on coupled mode theory (CMT) was first demonstrated [1], and following that paper, various types of resonators have been proposed to enhance the WPT efficiencies. However, an ongoing problem is the limited maximum efficiency determined by a given system figure of merit, which is defined by the product of a magnetic flux coupling coefficient and resonator quality factor [2]. One approach to overcome this limit is to use a metamaterial slab between the two loop resonators. The realization of media having negative permittivity and permeability has become feasible after Pendry et al. proposed a method using an array of thin wires [3] in 1998 and split ring resonators (SRRs) [4] in 1999. In [5], a perfect lens was proposed and it was theoretically shown that a transverse electromagnetic wave generated from a point source and incident on a metamaterial slab with $\mu_r = -1$ and $\varepsilon_r = -1$ is focused in the slab and refocused at a point in the other side of the slab. It was also suggested that a longitudinal quasi-magnetostatic field can be focused by a $\mu_r = -1$ slab and its dual case may also be possible with an $\varepsilon_r = -1$ slab. Loss effects of SRR were already examined in [5] and some new structures were proposed in [6, 7] to decrease losses in the resonators for the medium. Nevertheless, a slab with $\mu_r = -1 - j0.25$ at 63.87 MHz was applied to magnetic resonance imaging [8–10] resulting in a considerable enhancement of MRI images. Besides, there have been some initial trials of employing metamaterial slabs in WPT problems to enhance efficiencies. In [11], it was reported that even with a realistic magnetic loss tangent of 0.1, the WPT efficiency with a $\mu_r = -1$ slab can be an order of magnitude greater than free space efficiency. The experiments with a slab made of double-side spiral resonators [12] showed that power transfer efficiency of a WPT system could be improved from 17% to 47%. In a recent review paper [13], many promising features of metamaterial slabs for WPT problems were summarized. Another approach in WPT is to use relays, of which main function is to guide the magnetic flux from a Tx resonator to an Rx resonator. The configuration and design methods of relays are usually simpler than those of the metamaterial slab. It was reported in [14] that although conventional wireless electric systems can only achieve about 10% efficiency over a 30 cm distance, the efficiency of the relayed system can reach up to 46%. In fact, in a separate work, we could also observe that if a simple loop resonator is used as a relay, the efficiency is considerably enhanced typically by three to four times compared with that of the free space case. The working mechanisms of metamaterial slabs (focusing) and relays (guiding) are completely different [5, 14]. In our analysis and examinations, the enhanced WPT efficiencies reported in [12, 13] seem to be due to the effect of the guided magnetic flux by a relay, not due to the focused magnetic fields by a metamaterial slab, considering that the thickness of the used slab in [12] is much thinner than that theoretically required in [5].

In this paper, we examine the effects of a practical "superlens" when applied to a typical WPT problem, sticking to the theory of focusing fields in [5] as much as possible. A metamaterial slab made of ring resonators is placed between a Tx loop resonator and an Rx loop resonator to focus quasi-static magnetic fields and enhance the efficiencies. In the first place, a simple design equation is derived for the cases of using slabs with arbitrary negative permeability, based on [5, 15]. Based on this formula, two loop WPT systems at 13.56 MHz employing lossless metamaterial slabs with effective permeability of −1, −2, and −3 are examined in terms of coupling coefficients and WPT efficiencies. Then, a near-isotropic slab consisting of planar-type ring resonators (referred to as an isotropic RR slab) is designed and fabricated to have $\mu_r = -1$ (evaluated later to be $\mu_r = -1 - j0.23$ due to losses on the ring resonators) at 13.56 MHz. The measured WPT efficiencies are compared with the full-wave simulation results based on the same slab and an ideal isotropic slab with $\mu_r = -1 - j0.23$ (irrespective of frequency). The effects of a practical "perfect lens" are quantitatively discussed in terms of an optimum load in the Rx loop, coupling coefficients, effective Q-factors of the loop resonators considering slab losses, and efficiencies.

2. WPT System Using Lossless Metamaterial Slabs

Figure 1 shows a simple WPT system consisting of two loop resonators and a metamaterial slab placed between them. At the very low frequencies used in WPT systems (i.e., from several MHz down to kHz), the system size is usually very small compared with the wavelength. Thus, quasi-magnetostatics may be adopted. The loop is loaded with a chip capacitor for resonance at a design frequency. The loop resonator may also be understood as a small magnetic dipole consisting of Q_m and $-Q_m$. Since the magnetic fields from the loop (or magnetic dipole) are dominantly in the longitudinal direction in the near field, they may be approximated as those from a point magnetic charge as shown in Figure 2. Based on

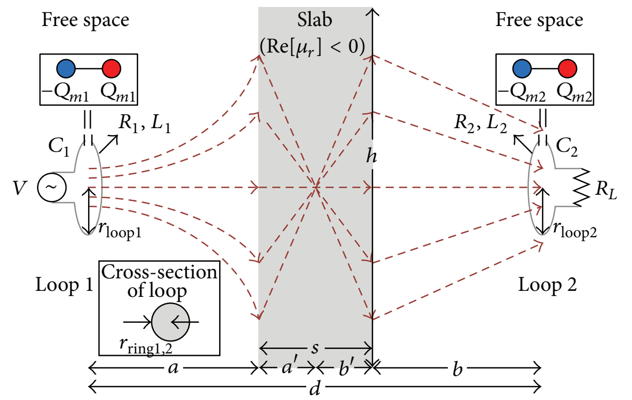

FIGURE 1: Magnetically coupled WPT system using two loops and a metamaterial slab.

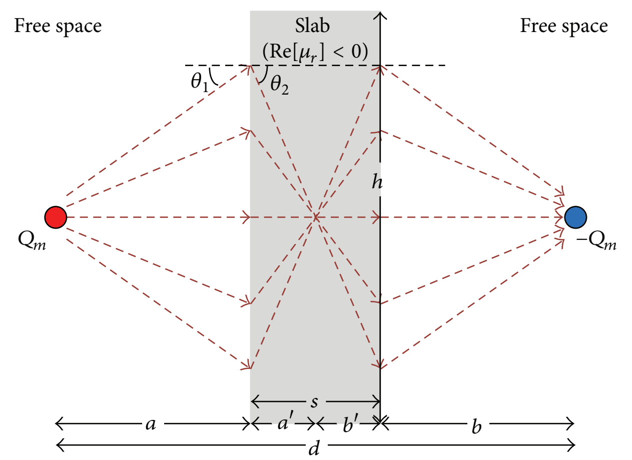

FIGURE 2: Effects of magnetic flux focusing using two magnetic point charges and a metamaterial slab.

this approximation and the proper boundary conditions for the magnetostatic fields [15], we can obtain

$$\frac{\tan\theta_2}{\tan\theta_1} = \frac{a}{a'} = \frac{b}{b'} = -\mu_r, \tag{1}$$

where θ_1 is the incident angle, θ_2 is the refraction angle, d is the distance between the two loops ($d = a+a'+b'+b$), h is the height of the slab determined to capture as much magnetic field from the loop as possible, and μ_r is the relative effective permeability usually realized with ring resonators (RR) or split ring resonators (SRRs). Note that μ_r must be negative to satisfy (1). The sum of a' and b' is the width (s) of the slab. The focusing of the fields from the loop mainly depends on the permeability (not on the permittivity) of the slab since magnetic fields are dominant in the near region of the loop.

Based on (1), a simple design equation that does not depend on the position (a) of the slab is given by

$$\frac{d}{s} = 1 - \mu_r. \tag{2}$$

For example, if $d/s = 2$, $\mu_r = -1$, and if $d/s = 3$, $\mu_r = -2$. In fact, if two elements among d, s, and μ_r are given first, the rest can be simply determined based on the rest two. For the dual case of using electric dipoles instead of magnetic dipoles (loops), μ_r in (2) has only to be replaced by ε_r. For this case, the slab can be realized using thin wires [3].

By simultaneously solving the two coupled circuit equations using KVL (Kirchhoff's voltage law), the WPT efficiency (η_L) at an angular frequency (ω_0), defined as the ratio of the received power (P_L) at the load (R_L) and the input power (P_{in}) from the source (Figure 1), is given by [16]

$$\eta_L = \frac{P_L}{P_{in}} = \frac{{F_m}^2}{\left(1 + b\sqrt{1 + {F_m}^2}\right)\left(1 + (1/b)\sqrt{1 + {F_m}^2}\right)}, \quad (3)$$

where F_m is the figure of merit of a WPT system (not dependent on R_L), defined by

$$F_m = k\sqrt{Q_1 Q_2} = k\sqrt{\frac{\omega_0 L_1}{R_1 + R_{s1}} \cdot \frac{\omega_0 L_2}{R_2 + R_{s2}}}, \quad (4)$$

where k is the magnetic flux coupling coefficient dependent on r_{loop1}/d and r_{loop2}/d, shown in Figure 1. L_1 and L_2 are the self-inductances of loop 1 and loop 2, respectively. R_1 and R_2 are the sum of the ohmic resistance and radiation resistance of loops 1 and 2, respectively. R_{s1} and R_{s2} are the equivalent resistances to take slab losses into account. Based on the EM-simulated or measured input impedance (at ω_0) with loop 2 removed in Figure 1, we can estimate the sum of R_1 and R_{s1} (the imaginary part of input impedance is zero at ω_0). R_1 can be extracted using the input impedance with both of loop 2 and the slab removed. The sum of R_2 and R_{s2} can be similarly estimated. Q is the quality factor of the loop resonator considering the slab loss. b is the deviation factor of a load, defined by

$$b = \frac{R_L}{R_{L,\text{opt}}}, \quad (5)$$

where $R_{L,\text{opt}}$ is the optimum load with which a maximum WPT efficiency is achieved, given by

$$R_{L,\text{opt}} = \left(R_2 + R_{s2}\right)\sqrt{1 + k^2 Q_1 Q_2} = \left(R_2 + R_{s2}\right)\sqrt{1 + {F_m}^2}, \quad (6)$$

which may be understood as a generalization of $R_{L,\text{opt}}$ in [16], applicable irrespective of the slab presence. It is reminded that without the slab, $R_{s1} = R_{s2} = 0$. The WPT efficiency (3) computed by the analytical expression is always the same as $|S_{21}|^2/(1 - |S_{11}|^2)$ using S-parameters obtained by EM-simulations or measurements. The expression (3) also tells us that the use of $b = 1$ ($R_L = R_{L,\text{opt}}$) ensures a maximum power efficiency. The use of b greater (under-coupled) or less (over-coupled) than 1 leads to a lowered WPT efficiency. Without the slab ($R_{s1} = R_{s2} = 0$), the coupling coefficient (k) can be extracted using S-parameters [1, 17]. With the slab, k may still be conveniently estimated using (6) based on the $R_{L,\text{opt}}$ with which a maximum of $|S_{21}|^2/(1 - |S_{11}|^2)$ is obtained in the EM-simulations.

Table 1: Comparison of WPT efficiencies when using lossless slabs.

μ_r	s (cm)	a, b (cm)	h (cm)	k	F_m (kQ)	$R_{L,\text{opt}}$ (Ω)	Efficiency (%)
1	—	—	—	0.0038	2.68	0.07	47.4
−1	12	6	60	0.6808	480	12	98.2
−2	8	8	80	0.1715	121	7.3	97.3
−3	6	9	100	0.0795	56	1.4	95.8

(f_0 = 13.56 MHz, r_{loop} = 5 cm, r_{ring} = 0.2 cm, d = 24 cm, and Q = 705).

To validate the formulation (2)–(6), EM-simulations are performed for the cases of using lossless slabs. The Tx and Rx loop resonators made of copper are assumed to be identical and designed to resonate at 13.56 MHz. The radius (r_{loop}) of the loop is 5 cm and the radius (r_{ring}) of the ring is 0.2 cm. The inductance of the loop is 0.207 μH and the capacitance of the loaded chip capacitor for the resonance is 0.666 nF. The resistance of the loop is 0.025 Ω, and the Q-factor is 705 at the resonant frequency. Table 1 summarizes the coupling coefficient (k), figure of merit (F_m), maximum WPT efficiencies (when $R_L = R_{L,\text{opt}}$) for a fixed d = 24 cm, and different a, s, and h based on (2)–(6) and EM-simulations using HFSS. The free space case has been included as a reference. For all cases, $R_{s1} = R_{s2} = 0$ and the Q-factors as given in (4) are calculated to be 705. For the cases of using ideal lossless slabs with μ_r = −1, −2, and −3, the coupling coefficients are shown to considerably increase to 0.6808, 0.1715, and 0.0795, respectively, from 0.0038 of the free space case. If a magnetic point charge was used (not possible in reality) instead of the loop resonator and the slab height $h \to \infty$, k's, F_m's, and efficiencies would approach 1, 705, and 100%, respectively, as may be evaluated from (3) and comparison of Figures 1 and 2. The efficiencies obtained using the loop resonators and the used finite h's are shown to be still close to 100% (enhanced from 47.4% for the free space case).

3. WPT System Using Practical Lossy Metamaterial Slabs

The effective medium with negative permeability can be realized by SRRs and other structures [5, 9, 10]. In this work, we choose to use a planar-type ring resonator loaded with a chip capacitor due to its simple working mechanism. The dimensions of the ring resonator and its orientation with respect to the incident magnetic field are depicted in Figure 3(a). The side length of a unit is p, the radius of the ring is r, and the width of the ring is t. The chip capacitor with capacitance (C) is loaded for resonance of the ring resonator which has some inductance (L) [15]. The total resistance (R) of the ring resonator is, in general, the sum of the ohmic and radiation resistances. The radiation resistance is negligible when r is much smaller than the wavelength. When a magnetic field is incident at the ring resonator as shown, the induced voltage around the ring produces a current,

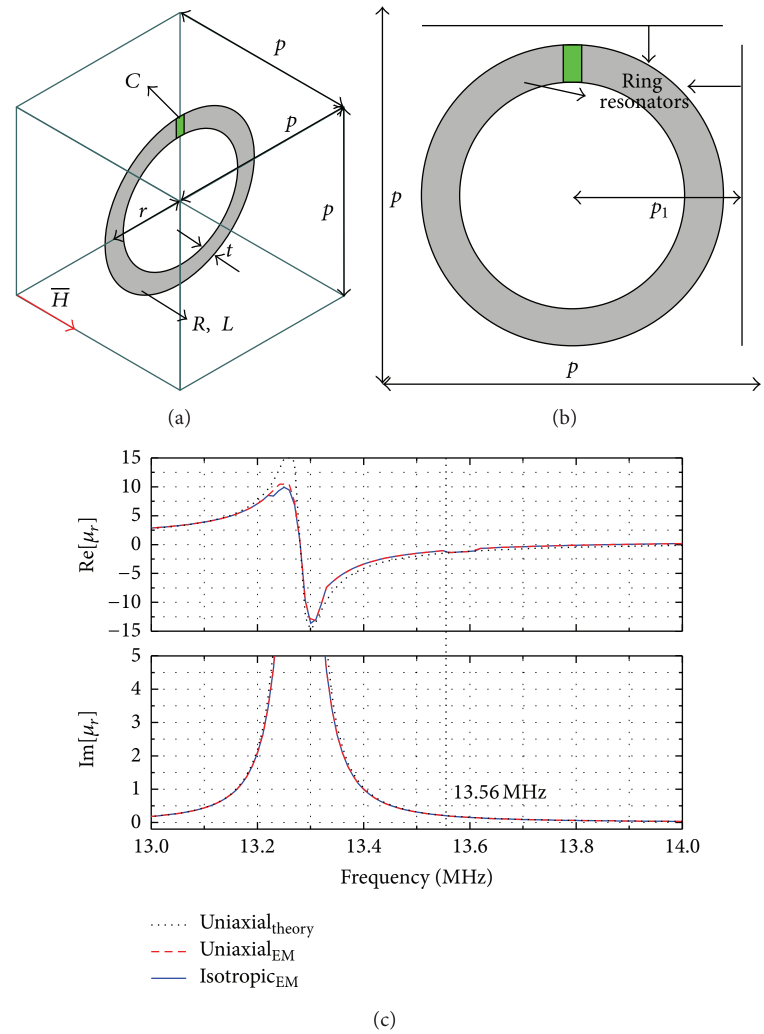

Figure 3: Ring resonators and their relative effective permeability. (a) Uniaxial unit cell, (b) isotropic unit cell ($p_1 = 5.5$ cm), and (c) theoretical (7) and extracted permeability using S-parameters.

and using the usual definition of magnetization, the relative effective permeability [18] can be shown to be given by

$$\mu_r = 1 - \frac{j\omega\mu_0\left(\pi r^2\right)^2}{p^3\left[R + j\sqrt{L/C}\left(\omega/\omega_0 - \omega_0/\omega\right)\right]}, \tag{7}$$

where ω is the angular frequency, ω_0 is the resonant angular frequency given by $1/\sqrt{(LC)}$, $\sqrt{(L/C)}$ is the reactance slope parameter of the ring resonator, and μ_0 is the permeability in free space. Figure 3 shows the uniaxial unit cell (a), the isotropic unit cell (b), and the theoretical (7) and extracted effective permeability (c) based on S-parameters using EM-simulations [18, 19]. In Figure 3(a), $p = 12$ cm, $r = 3.5$ cm, $t = 1$ cm, $L = 0.12\,\mu$H, $C = 1.28$ nF, and $R = 0.04\,\Omega$. The side length (p) is roughly 1/170 of the free space wavelength at 13.56 MHz. In Figure 3(b), p_1 is 5.5 cm. In Figure 3(c), the values of the extracted relative effective permeability (μ_r) are shown to be about $-1 - j0.23$ at 13.56 MHz. They are shown to be in good agreement with the theoretical one (7) over a wide frequency band.

Figure 4 shows the measurement setup for the two loop WPT system using a metamaterial slab made of isotropic unit cells depicted above. The loop radius (r_{loop}) is 5.5 cm and the ring radius (r_{ring}) is 0.1 cm. The inductance of the loop is 0.278 μH and the capacitance of the inserted chip capacitor is 0.496 nF for resonance at 13.56 MHz. The resistance (sum of ohmic and radiation resistances) of the loop is 0.05 Ω and the Q-factor is 473 at 13.56 MHz.

In Figures 5(a) and 5(b), we examine the real and imaginary parts of the input impedances seen at loop 1, with loop 2 removed, for some conditions of the slab. For the case of $\mu_r = 1$ (free space), the measured resistance is shown to be roughly 0.05 Ω (mainly due to ohmic resistance) at 13.56 MHz. The Q-factor ($\omega_0 L/R$) of the loop without the slab is calculated to be 473. The reactance is shown to cross 0 near 13.56 MHz. For the case of using an ideal lossless slab with $\mu_r = -1$, the EM-simulated real and imaginary parts of the input impedance are shown to be almost the same as those for the free space case. This implies that the lossless slab does not affect the impedance seen at the input terminal of loop 1 and simply

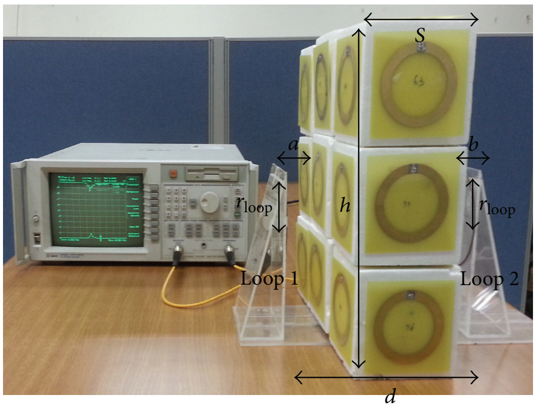

Figure 4: Measurement setup for two loop WPT system using a metamaterial slab ($r_{\text{loop}} = 5.5$, $r_{\text{ring}} = 0.1$, $d = 24$, $s = 12$, $h = 36$, and $a = b = 6$ (unit: cm)).

Table 2: Coupling coefficients, Q-factor, and WPT efficiencies for the free space case and for the cases of using lossless and lossy slabs.

	Slab (μ_r)	k	Q	F_m (kQ)	$R_{L,\text{opt}}$ (Ω)	Efficiency (%)
EM	Free space (1)	0.0036	473	1.7	0.1	32
	Ideal (−1)	0.6986	473	330.4	17	98
	Ideal lossy ($-1 - j0.23$)	0.1001	10.76	1.077	7	18.9
	RR slab ($-1 - j0.23$ at 13.56 MHz)	0.0965	10.96	1.057	6.8	18.5
Meas.	RR slab ($-1 - j0.23$ at 13.56 MHz)	0.1016	11.84	1.203	6.85	22

($r_{\text{loop}} = 5.5$, $r_{\text{ring}} = 0.1$, $d = 24$, $s = 12$, $h = 36$, and $a = b = 6$ (unit: cm)).

focuses the quasi-magnetostatic fields generated from loop 1. But, for the case of using an ideal lossy isotropic slab with $\mu_r = -1 - j0.23$ independent of frequencies, the EM-simulated resistance at loop 1 is shown to considerably increase from 0.05 Ω to about 2.2 Ω at 13.56 MHz. The reactance is shown to remain almost unchanged. This means that the slab seen at loop 1 is dominantly resistive due to losses in the slab. This reduces the effective Q-factor of loop 1 from 473 to 10.76 ($473 \times 0.05/2.2$). For the case of using the realistic RR (ring resonator) slab consisting of isotropic unit cells designed to have $\mu_r = -1 - j0.23$ at 13.56 MHz, as shown in Figure 3(b), the EM-simulated and measured resistances are shown to be about 2.16 Ω and 2 Ω, respectively, only near 13.56 MHz. These are the expected results when considering the highly dispersive nature of the realistic RR structures, as shown in Figure 3(c). The most important observation related with Figure 5 is that due to the increase of the input resistance from 0.05 to 2.0–2.2 (practical slab cases), effective Q-factors of the loops considerably drop roughly as 1/40.

Figure 6 shows the EM-simulated and measured (based on Figure 4) S-parameters when $r_{\text{loop}} = 5.5$ cm, $r_{\text{ring}} = 0.1$ cm, $d = 24$ cm, $a = b = 6$ cm, $s = 12$ cm, $h = 36$ cm, $R_L = 50\,\Omega$, and the reference impedance at the input terminal of loop 1 is 50 Ω. The EM-simulated and measured $|S_{11}|$ and $|S_{21}|$ for the case of using the practical slab made of isotropic ring resonators (RR slab) are shown to be in a good agreement, validating the formulation (1)–(7). They are also shown to approach those for the case of using the ideal isotropic slab, only near 13.56 MHz as expected.

Based on the system configurations in Figures 1 and 4, we summarize the performances in Table 2 in terms of the effective Q-factors of the loop resonators, the estimated coupling coefficients k, the figure of merit F_m, the optimum load $R_{L,\text{opt}}$, and the maximum efficiencies. Without the slab, $Q = 473$, $F_m = 1.7$, $R_{L,\text{opt}} = 0.1\,\Omega$, and the maximum efficiency is 32%. With the ideal lossless slab having $\mu_r = -1$, the effective Q-factor of the loop is unchanged but k is shown to increase to about 0.7 due to the effect of the magnetic field focusing and a significant improvement of the efficiency to 98% is achieved. For the cases of using lossy slabs ($\mu_r = -1 - j0.23$ at 13.56 MHz), however, the effective Q-factors decrease approximately as 1/40 as mentioned earlier. Nevertheless, the estimated coupling coefficients (k's) are shown to roughly increase 30 times compared with the free space case. This results in a decrease of F_m from 1.7 to about 1.1. Thus, the maximum efficiency using (3) with $b = 1$ decreases from 32% to about 20%. The RRs used for this work are of a planar type with width $t = 1$ cm. If a ring type RR with a diameter of 1 cm is used, the effective permeability can be improved to $\mu_r = -1 - j0.05$. It has been found that even for this case, the efficiency is about 27%, still less than 32% for the case without slab.

So far, we have analyzed the WPT system employing a slab with $s/d = 0.5$, which is the condition derived assuming that loop 1 is a magnetic point monopole source. Since the used loops are of a magnetic dipole nature and loss rate in the slab depends on s/d, we have further evaluated the maximum efficiencies varying s/d from 0 (without slab) to 0.8 for different r_{loop}/d values from 0.1 to 0.9 in Figure 7. In this plot, μ_r is again assumed to be $-1 - j0.23$, the Q-factors of the loop 1 and 2 are fixed at 473, the same for the loop with $r_{\text{loop}} = 5.5$ cm and $r_{\text{ring}} = 0.1$ cm, and $h/d = 1.5$. The efficiency with lossy slabs in Table 2 is a special case of those in Figure 7. The circled point in Figure 7 tells us that the efficiency for the case of $s/d = 0.5$ and $r_{\text{loop}}/d = 0.2$ is 20%, which is in reasonable agreement with the measured efficiency in Table 2. We can also see that for the case of $r_{\text{loop}}/d = 0.2$, similar to the case with lossy slabs in Table 2, if we use $s/d = 0.2$, the efficiency would be enhanced to about 48% from 32% for the case without slab ($s/d = 0$). The degree of enhancement due to the slab is shown to be more significant as r_{loop}/d becomes smaller. When $r_{\text{loop}}/d = 0.1$, for instance, the efficiency without slab ($s/d = 0$) is close to zero. However, if s/d is increased to about 0.3, the efficiency is shown to be enhanced to about 10%. It is also obvious that as $r_{\text{loop}}/d \rightarrow 0$, loop 1 behaves more like a magnetic point source (Figure 1 $\rightarrow$ Figure 2)

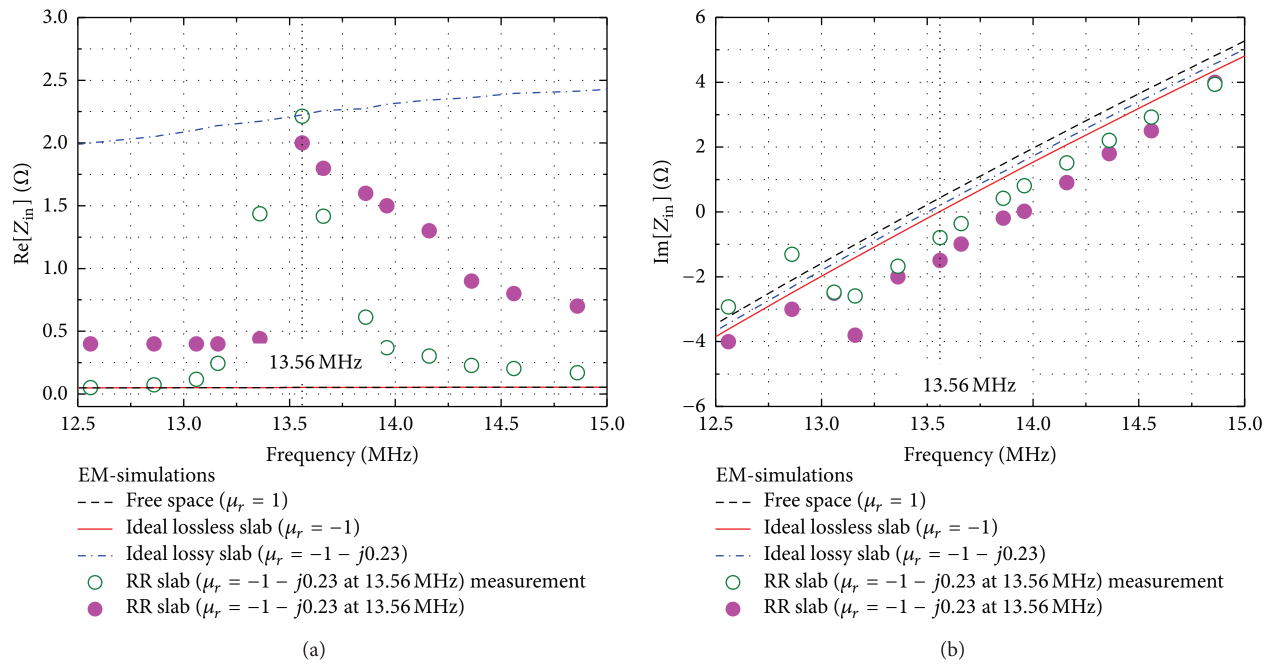

FIGURE 5: EM-simulated and measured input impedances with loop 2 removed (r_{loop} = 5.5 cm, r_{ring} = 0.1 cm, d = 24 cm, $a = b$ = 6 cm, s = 12 cm, h = 36 cm, and f_0 = 13.56 MHz). (a) Real parts and (b) imaginary parts.

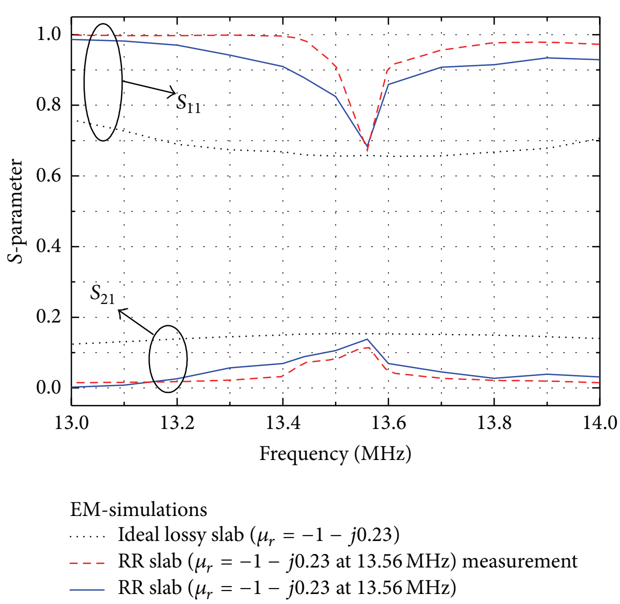

FIGURE 6: Comparison of S-parameters for the cases of using lossy slabs (r_{loop} = 5.5 cm, r_{ring} = 0.1 cm, R_L = 50 Ω, d = 24 cm, $a = b$ = 6 cm, s = 12 cm, and h = 36 cm).

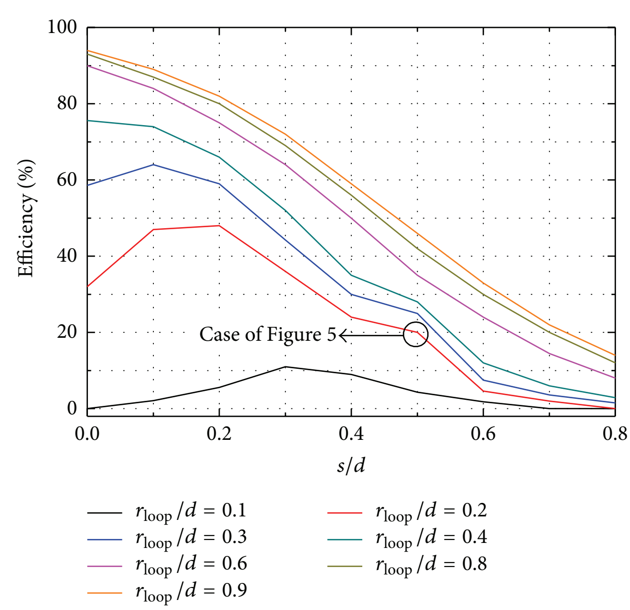

FIGURE 7: EM-simulated efficiencies as a function of s/d for different r_{loop}/d when the Q-factor of loops 1 and 2 is 473 and an ideal isotropic slab with $\mu_r = -1 - j0.23$ is used.

since s/d for a maximum efficiency approaches 0.5 [5]. Overall, we can say that with the use of a metamaterial slab in the WPT system, some enhancement in efficiencies can be achieved if r_{loop}/d is approximately less than 0.3 and s/d is optimized between 0.1 and 0.3.

4. Conclusion

The effects of employing metamaterial slabs with negative permeability in WPT systems have been examined based on theory, full-wave simulation, and measurements. For lossless slabs with $\mu_r = -1$, -2, and -3, the WPT efficiencies have been found to be enhanced close to 100% due to the magnetic field focusing effects. Due to the heavy power absorption in the designed practical slabs ($\mu_r = -1 - j0.23$) consisting of planar-type ring resonators when $s/d = 0.5$, the WPT efficiency with the slab has been found to significantly decrease to 20%, even lower than that of free space (32%). If $s/d = 0.2$, the efficiency is enhanced to about 48% from 32% for the case without slab. The condition of $s/d = 0.5$, exact for a point source, needs to be optimized to a smaller value for a practical loop source. Overall, some enhancement in efficiencies can be achieved if r_{loop}/d is approximately less than 0.3 and s/d is optimized between 0.1 and 0.3. The significant enhancement of efficiencies approaching 100% when using a lossless slab becomes moderate or only marginal when using a practical lossy slab due to relatively heavy losses in it.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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