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LETTER

Demonstration of wireless power coloring

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Abstract This letter aims to demonstrate the concept of wireless power coloring (WPC), i.e., frequency division multiplexing of wireless power transfer (WPT). Currently, to obtain significant received power in WPT, the power is generated from a single transmission source. Herein, we propose a method of transmitting wireless power through more than one (N $\geqq$ 2) multiplexed coloring source. To achieve this, we use power transmitting sources with different resonance frequencies in magnetic resonance-type WPT to selectively send power to a designated receiver.

Keywords: WPC, WPT, cubic law

Classification: Electromagnetic theory

1. Introduction

Since the announcement of magnetic resonance-type wireless power transfer (WPT) by the MIT group in 2007 [1, 2], in addition to the magnetic resonance method, the electric resonance and radiation methods (microwave, laser) are also being actively researched [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17]. In recent years, WPT with a relatively large separation distance and efficient transmission methods have been proposed [18, 19, 20, 21, 22, 23, 24, 25, 26]; however, power is still being transmitted via a single power transmission device. The predominant one-to-one transmission method is to receive electromagnetic waves with a power receiving device and then use them as electric power. In this transmission method, the amount of received power is determined by the total efficiency obtained by multiplying the power transmission device's efficiency with the power reception device's efficiency. As an improved power transmission/reception method, recently [27], a one-to-N method that consists of a large power source on the power transmission side and N receivers (N > 1) within the range of the power transmission source is illustrated [28, 29, 30]. In the present study, one power receiving device is placed to be surrounded by numerous sources (power transmitters), and WPT is performed from many different power-producing sources to potentially multiply power receiving devices. This method has numerous applications that prove WPT is acceptable to our society; for example, sending power for numerous purposes, including lighting, charging a mobile phone, and heating a room. To test this concept, our research group devised an N-to-1 power transmission/reception method by preparing N power transmission sources (N > 1) and connecting them to a single power reception device and conducted experiments based on this concept. For this, we considered two power transmission devices that can transmit and identify electric power at different frequencies. In this experiment, we demonstrate wireless power coloring, i.e., frequency division multiplexing of WPT, where frequency represents the resonance frequency in magnetic resonance-type WPT.

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2. Method

2.1 Experiment

The experiment was performed using the WPT transmission sources and the power reception device shown in Fig. 1. Both the power transmission sources and power reception device have a radius of 4 cm and 40 turns, respectively. Three types of coils, namely, resonant, drive, and output coils were used. Two ceramic oscillators with resonance frequencies of 4.0 MHz and 3.6 MHz were used as the oscillators, emitting transmission frequencies of 2.0 MHz and 1.8 MHz, respectively. A spectrum analyzer (Micronix MSA438) was used to measure the peak value of the spectrum on the power transmission sides A and B and the power reception side.

2.2 Experimental setup

In the experiment, the power transmitting sources A and B were brought close to the power receiving device so that wireless power could be transmitted from both sources to

Experiment apparatus

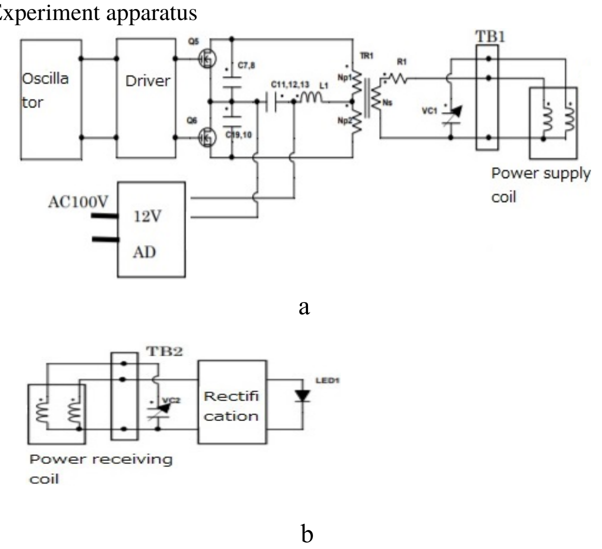

Fig. 1 (a) Block diagram of transmitter and (b) receiver.

the single receiver. The separation distance was 1 cm, and the transmitting sources were directed toward the receiving device.

2.3 Experimental results

Experiments were conducted using the setup shown in Fig. 2 and measured with a spectrum analyzer. The resonance frequency of transmitter source A is set to 1.8 MHz, and the resonance frequency of Transmitter source B is shifted using a ceramic oscillator such that Transmitter B is at 2.0 MHz, as shown in Fig. 3. Transmitter source A has a maximum peak spectrum of 1.7338 mW, and transmitter source B has a maximum peak spectrum of 2.0091 mW. Transmitter source B contained multiple spurious peaks in addition to the peak spectrum. When this power was transmitted, the receiver received 0.955 mW of power from Transmitter source A at a resonance frequency of 1.8 MHz (Transmitter A), while a suppressed power of 0.03281 mW at the non-resonant frequency as shown in Fig. 3(c). These results show that wireless power from multiple power sources can selectively be sent to a receiving device via the choice of the resonance frequency, that is, a selected WPT source's resonance frequency matches that of the receiving device. Additionally, Figure 3(d) shows the output characteristics of the receiver for source. The efficiency of the single source case is 62% which is higher than the efficiency 55% for the case of multiple transmitters. Thus, there is a certain tradeoff between transmitting efficiency and the number of multiple power sources.

Fig. 4 shows the fitting of the experimental result illustrated in Fig. 3(c) to a theoretical cubic law curve with a peak at a frequency of 1.8 MHz. This has been illustrated for received power, Lorentz distribution, and Gaussian distribution to compare the experimentally obtained values, wherein the distribution functions are as follows:

$$\text{Lorentzian: P} = \frac{0.018}{\pi}\frac{\gamma}{\Delta f^2+\gamma^2}\,[\text{mW}],\ \Delta f\,[\text{MHz}],$$
$$\gamma = 0.006\,[\text{MHz}] \qquad (1)$$

$$\text{Gaussian: } P = \frac{0.1221}{\sqrt{(2\pi\sigma^2)}}\exp\left(-\frac{\Delta f^2}{2\cdot\sigma^2}\right)\,[\text{mW}],$$
$$\sigma = 0.00051\,[\text{MHz}] \qquad (2)$$

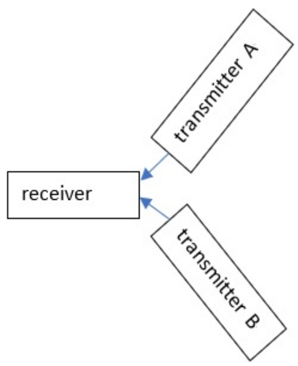

Fig. 2 Experimental setup

$$\text{Cubic: } P = \frac{\sqrt{2}}{70\pi}\frac{\beta^3}{(\Delta f^4+\beta^4)}\,[\text{mW}],$$
$$\beta = 0.0064\,[\text{MHz}] \qquad (3)$$

The values of full width at half maximum are 0.012 MHz (Gaussian, Lorentzian) and 0.0128 MHz (cubic law) for the case where the resonance frequency is 1.8207 MHz.

According to Ref. [1], the intensity of electromagnetic waves follows the Lorentzian equation, i.e., am (t) =

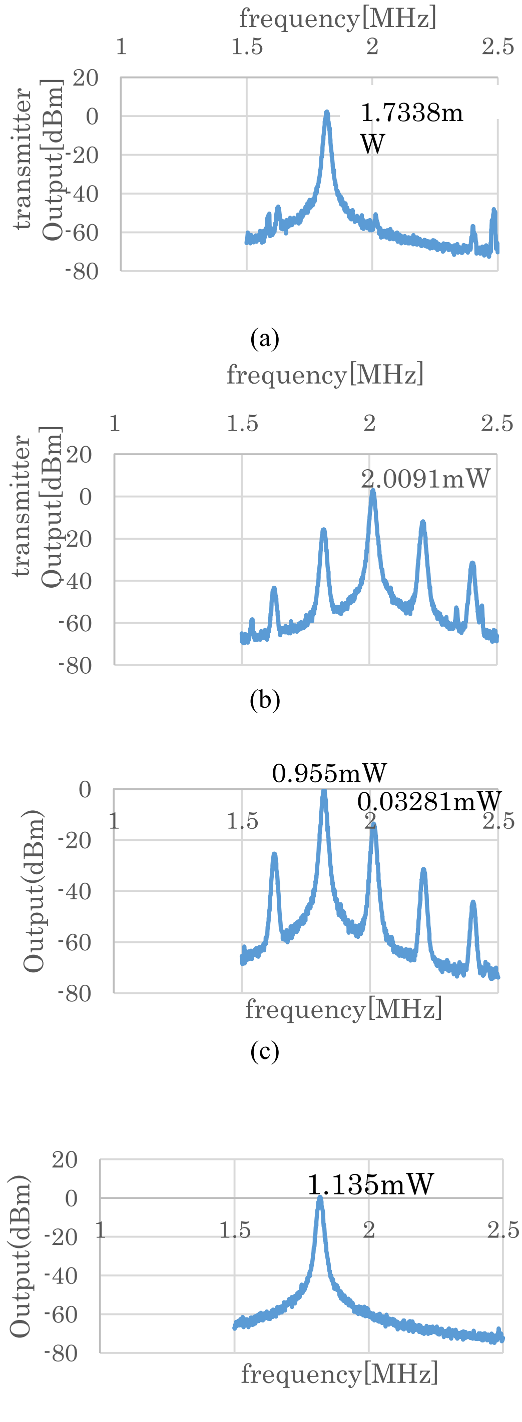

Fig. 3 Spectrum from each transmitter and receiver. (a) Transmitter A synchronized with peak frequency. (b) Transmitter B not synchronized with peak frequency. (c) Receiver synchronized with Sender A peak frequency. (d) Receiver for single source.

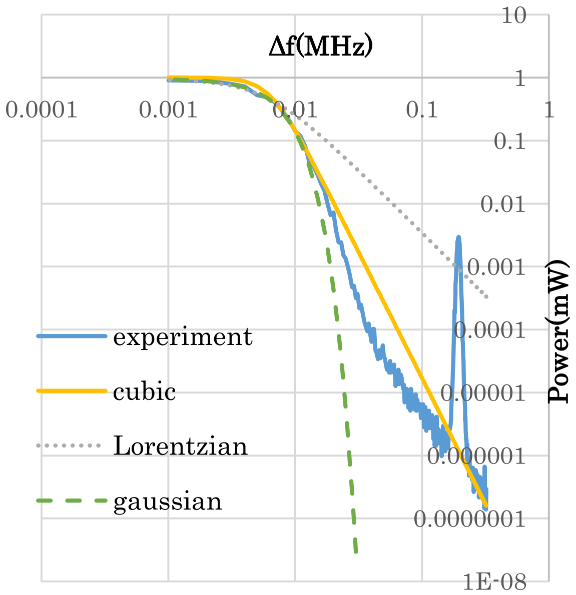

Fig. 4 Spectrum from receiver, fitting with gauss distribution and Lorentz distribution and cubic law

$\exp(i\omega_0 t - \Gamma_0 t)$. However, according to this experiment, the received signal significantly deviates from the Lorentzian. The received signal is a mixed wireless power signal obtained by superimposing two power transmission sources rather than one, which could be the reason for the deviation. Notably, it was observed that the mixed radio signal power follows the cubic law rather than the Lorentzian.

3. Discussion

The experiment was conducted using a power transmission method with two different power transmission sources and a single power receiving device. The frequency of the electromagnetic wave transmitted from the oscillator of the power transmission source A is 1.8 MHz, and that of the power transmission source B is 2.0 MHz. The resonance frequency at the receiver is set at 1.8 MHz, equal to the power transmission source A and has an offset from the power transmission source B. Consequently, the electromagnetic wave spectrum from transmission source A, matching the resonance frequency, produced a transmission efficiency of 55% with 0.955 mW of power received when the transmission power was 1.7338 mW at the peak level.

Conversely, it was found that the power received from the power transmission source B with the changed resonance frequency was 0.03281 mW compared to the power transmission of 2.0091 mW at the peak level, and the power transmission efficiency was substantially suppressed to approximately 1.6%. The result suggests that it is possible to selectively receive the transmitted electromagnetic waves from a plurality of wireless power transmission sources by changing the *resonance* frequency. For the WPC concept, if we can associate electric power with different resonance frequencies as coloring power, we can distinguish the desired color (frequencies) by a transmitted power suppression mechanism with the non-resonance frequency.

We also confirm that the efficiency 55% for multiple transmitter case is slightly lower than the efficiency 62% for single source case which shows that WPC has some impact on efficiency.

These results conform to the concept of WPT multiplexing, which corresponds to resonance frequency division multiplexing. In this experiment, we demonstrated the simplest transmission method in the case of N = 2 to one transmission, but this can be applied to N ≧ 2 to one multiplexing in WPT such as CDMA [31]. Furthermore, we found that the spectrum on the power-receiving side is closer to the cubic law rather than the Lorentzian [1], which can be derived from the classical theory of WPT. The cubic law is a distribution found in financial price fluctuations [32] in which the characteristic function is the superposition of two Lorentzian characteristic functions. The experimental results suggest that the superposition of the mixed power signal can be written by the superposition of the Fourier transform (characteristic function) of the Lorentz distribution.

4. Conclusion

This study demonstrates the WPC concept, and we experimented with WPT multiplexing according to the distribution of different resonance frequencies to validate the WPC concept. Consequently, we demonstrated that two-to-one power transmission and reception can be realized by changing the resonance frequency. It was also found that by changing the resonance frequency on the power transmission sources, the power reception device can selectively receive power from a power transmission source having a frequency equal to the resonance frequency, similar to a router. The spectrum of the mixed radio power signal obtained in the experiment was expressed by the cubic law [32] rather than the Lorentzian obtained by the theory proposed by the research group at MIT. Based on this investigation, we proposed a new power transmission method, namely wireless power coloring-multiplexing for WPT, by designing the distribution of different resonance frequencies.

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