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Wireless Power Transfer by Spoof Surface Plasmon Polaritons at Ultrasonic Frequencies

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ABSTRACT: Long-range wireless power transfer (WPT) is difficult with unguided radio waves or magnetic coupling. In this work, a plasma-assisted quasi-parallel planar waveguiding medium is proposed for overcoming the transmission range issues. **Method:** A dielectric layer sitting on a conductive object or grid was used as a medium for WPT. At the transmitting end, a plasma ball shielded with a spark-gap activated hemispheric metal cap was used to ionize the air in the space, thereby forming the top cladding layer of the quasi parallel-plate waveguide. At the receiving end, the transmitted power was coupled out of the waveguide over the entire ultrasonic spectrum using Avramenko diode configurations. A Kretschmann-like configuration was used at both ends for conversion between a plasmonic current and the surface waves. **Results:** In the proposed experimental setups, the transmitted power was successfully harvested over a frequency range from near DC to 230 MHz, with the ratio of the received power to the transmitted power significantly surpassing the value predicted by the Friis' two-ray ground reflection model. **Conclusion:** WPT based on surface waves is technically feasible with the help of Kretschmann-like configurations.

1. INTRODUCTION

Owing to the emergence of battery-powered electric vehicles, wireless power transfer (WPT) is currently receiving considerable attention from the research community. Electric vehicles are currently powered by rechargeable batteries which usually have a limited battery lifespan. In Taiwan and many other countries, recharging a battery at a charging station normally takes at least an hour. There is no way to shorten the recharging time in the charging station unless the battery in the electric vehicle is charged in advance while moving. This is an important area which necessitates wireless power transfer.

In recent years, there have been some attempts to realize far-field wireless power through radio waves, but none of these attempts have successfully defied the prediction by Friis' 2-ray ground-reflection model of transmission, which dictates that the radio power received in the far field always decreases as the inverse fourth power of the distance. There have been some attempts to transmit a directed radio power using an antenna array, but the tested transmission ranges were less than 1 m [1, 2].

In recent years, magnetic or inductive coupling has been most broadly accepted for wireless charging. By far, it is the least costly method to implement. With the near-field magnetic coupling approach, the transmission ranges that have been achieved were generally limited to less than 1 m in an unconfined environment. There have been attempts to extend the transmission range to a few meters by resonance at the expense of efficiency.

To date, the transmission range remains an issue to be resolved. Lasers are perhaps one of the few options that can remotely transmit power over long distances. Lasers have been successfully used to deliver light power to the receiving end, where the received light beam can be reshaped using a homogenizer and converted into electricity using photodiodes [3]. However, lasers are appropriate for one-to-one transmission only. If multiple receiving ends need to be targeted, multiple lasers will be required. The cost of transmission lasers can be high.

In this work, the use of surface waves is proposed for extending the transmission range beyond what is not achievable by conventional radio transfer. These surface waves are low-frequency spoof surface plasmon polaritons propagating along the upper and lower interfaces of a quasi-parallel waveguide [4].

2. MATERIALS AND METHOD

In this study, the primary objective was to form a quasi-parallel-plate waveguide as shown in Fig. 1. A radio frequency (RF) plasma was used to modulate the surface permittivity to facilitate the transmission of vertically polarized transverse electromagnetic (TEM) waves along the reflective interface between a dielectric layer and a conducting or partially conducting medium underneath (or on the top of) the dielectric layer. This TEM wave is also known as the spoof surface plasmon polariton. The polarized TEM waves are delivered at an MHz frequency range in almost the same manner as how a signal

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propagates in a mirror waveguide, with the exception that, due to the presence of the noise caused by the plasma, the surface current was saturated with high-order harmonic components.

2.1. Quasi-Parallel-Plate Waveguide Model

Consider the cross-sectional view of a sandwiched structure as shown in Fig. 1 under the following assumptions: Medium 1 is assumed to be air or partially ionized air. Medium 2 is assumed to be a lossless dielectric layer that supports propagation of transverse electromagnetic waves. Medium 3 is assumed to be either a buck metal or a metal grid acting as a dilute plasma that reflects off the incident electromagnetic waves in the upward direction.

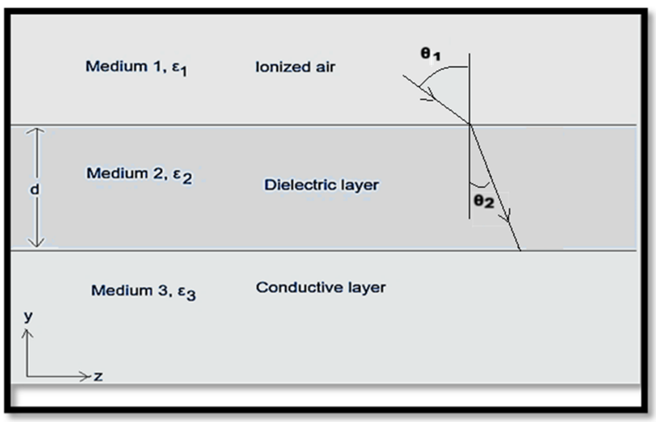

FIGURE 1. Quasi-parallel-plate waveguiding structure.

Let us temporarily focus on medium 1. Medium 1 is an ionized medium filled with partially ionized particles. Assuming that medium 1 is not magnetized, the force experienced by a single charged particle is given by $\vec{F} = q\vec{E}$, where $\vec{E}$ is the electric field vector. Under Newtonian mechanics, we have

$$m^* \frac{d\vec{V}}{dt} = e\vec{E} \tag{1}$$

where $\vec{V}$ is the velocity, m^* the mass of the charged particle, and e the charge carried by an electron. According to (1), the velocity of the charged particle can be expressed as

$$\vec{V} = \frac{e\vec{E}}{j\omega m^*} \tag{2}$$

Plasma does not travel far. The concentration of charged particles should not be constant along the z-direction. It is reasonable to assume that the number of charged particles in a unit volume is $N(z)$, which is also a function of the distance in the direction z.

The current per unit area in medium 1 can be thought as a stream of ions with a unit cross-sectional area moving in the direction of z with velocity $\vec{V}$, and can be mathematically expressed as

$$\vec{J} = N(z)e\vec{V} = \frac{N(z)e^2\vec{E}}{j\omega m^*} = \sigma\vec{E} \tag{3}$$

where $N(z)$ is the distance dependent charge density, e the electron charge, and $m*$ the mass of charge carriers. According to Maxwell's equations, the relative permittivity of ionized air can be obtained using $\varepsilon_r = 1 - \frac{j\sigma}{\omega\varepsilon_o}$. Hence, the relative permittivity of the partially ionized air is a real number given by

$$\varepsilon_1 = 1 - \left(\frac{N(z)e^2}{\omega^2\, m^*\varepsilon_o}\right) = 1 - \left(\frac{\omega_{p1}(z)^2}{\omega^2}\right) \tag{4a}$$

where $\omega_{p1}(z)$ is the range-dependent plasma frequency given by $\omega_{p1} = \sqrt{\frac{N(z)e^2}{m^*\varepsilon_o}}$. Suppose that an ionization source is mounted right at $z = 0$; then, according to (4a), both $N(z)$ and the plasma frequency will exponentially decrease as the distance z increases toward the right end. The refractive index of medium 1, as obtained using $n_1 = \sqrt{\varepsilon_1}$, can be obtained using:

$$n_1 = \sqrt{1 - \left(\frac{\omega_{p1}(z)^2}{\omega^2}\right)} \tag{4b}$$

When $\omega > \omega_{p1}$, the refractive index of medium 1, n_1, becomes real and positive. This situation usually occurs when somewhere in medium 1 runs out of charge particles. Without sufficient charged particles at one location, an electromagnetic wave propagating along medium 2 will eventually escape through this location in an unguided manner into medium 1 as a leaky wave. An antenna is required to capture the energy from this leaky electromagnetic wave. Owing to the nature of space electromagnetic waves, the power harvested using an antenna is unlikely large.

In Fig. 1, when $\omega < \omega_{p1}$, the refractive index of medium 1, n_1, becomes imaginary. This situation occurs when medium 1 is saturated with moving charge particles called ions. The ions in medium 1 reflect the low frequency electromagnetic waves incident from medium 2, which is a dielectric layer. This happens in much the same manner as how the ionosphere bends the low-frequency electromagnetic wave from the base station. This form of reflection does not abruptly occur at the interface between medium 2 and medium 1. Instead, a minor portion of the low-frequency electromagnetic waves will leak from medium 2 to medium 1, or other way round, in the form of refraction or bending. With enough charged particles in medium 1, medium 1 literally becomes a cladding layer for medium 2.

Now, let us turn our attention to media 2 and 3. The interface between media 2 and 3 is expected to support a surface wave commonly known as spoof surface plasmon polariton, with the longitudinal electric field given by [5]:

$$E_z = \pm E_o \frac{k_z}{k_y} \exp\left(j(k_y y + k_z z) - \omega t\right) \tag{5}$$

where k_y and k_z are respectively the wave-numbers of the x- and z-directions. For the interface between media 2 and 3 to be functional as intended, it has to be reflective. It means that medium 3 can be anything with a negative permittivity. When medium 3 is a metal grid, the interface between media 2 and 3 is literally a low-frequency metamaterial with a plasma frequency given by [4]

$$\omega_{pm}^2 = \frac{2\pi c^2}{a^2 \ln\left(\frac{a}{r_o}\right)} \tag{6}$$

where a is the spacing between two neighboring metal rods in the metal grid, r_o the thickness of a rod in the metal grid, c the speed of light, and ω_{pm} the plasma frequency in radians per second. The relative permittivity of medium 3 can be readily obtained using Drude's model given by

$$\varepsilon_3 = 1 - \frac{\omega_{pm}^2}{\omega^2} = 1 - \frac{1}{\omega^2}\left(\frac{2\pi c^2}{a^2 \ln\left(\frac{a}{r_o}\right)}\right) \tag{7}$$

Equation (7) suggests that ε_3 becomes negative at frequencies below this plasma frequency, ω_{pm}. Due to the presence of a negative ε_3 in medium 3, a surface wave known as spoof surface plasmon polariton can exist along the interface between media 2 and 3 with a wavenumber k_z given by

$$k_z = k_o\sqrt{\frac{\varepsilon_3\varepsilon_2}{\varepsilon_3 + \varepsilon_2}} \tag{8}$$

where k_o is the freespace propagation constant, and ε_2 is the relative permittivity of medium 2. By substituting the expression for ε_3 in Equation (7) into Equation (8), we obtain

$$k_z = k_o\sqrt{\frac{(\omega^2 - \omega_{pm}^2)\varepsilon_2}{(\omega^2 - \omega_{pm}^2) + \omega^2\varepsilon_2}} \tag{9}$$

For a spoof surface polariton to be closely bound to the interface between media 2 and 3, the velocity of the spoof surface plasmon polariton should be as slow as possible. In other words, k_z in Equation (9) should be maximized in order for the field components to be confined to the fullest extent along the interface between media 2 and 3. In Equation (9), the denominator $(\omega^2 - \omega_{pm}^2) + \omega^2\varepsilon_2$ can be forced to be zero to maximize k_z. By forcing $(\omega^2 - \omega_{pm}^2) + \omega^2\varepsilon_2$ to be zero or by equivalently attaining an infinity k_z, we obtain the maximum frequency of the spoof surface plasmon polariton given by:

$$\omega_{sp} = \frac{\omega_{pm}}{\sqrt{1 + \varepsilon_2^2}} \tag{10a}$$

where ω_{sp} is commonly known as surface plasma frequency. For a spoof surface plasmon to be efficiently transmitted along the interface between media 2 and 3, its frequency should be lower but close to ω_{sp}.

Because the proposed transmission medium is essentially a parallel waveguide, the wavenumber in the y-direction can be readily obtained using:

$$k_y = \sqrt{\varepsilon_2 k_o^2 - k_z^2} \tag{10b}$$

By increasing ω up to ω_{sp}, as suggested by Equation (10b), k_z is maximized, and k_y is accordingly minimized. Minimizing k_y maximizes not only the longitudinal electric field as given in Equation (5) but also the time-average power density.

On the other hand, with the plasma frequency given by $\omega_{pm} = \sqrt{Ne^2/(m^*\varepsilon_o)}$, an electrical current with positive ions also has an effect of lowering the plasma frequency.

Because both media 1 and 3 are reflective as far as medium 2 is concerned, the entire arrangement, as depicted in Fig. 1, will act like either a metasurface that supports propagation of non-radiative transverse magnetic (TM) modes or a parallel plate waveguide that supports propagation of transverse electromagnetic (TEM) modes. When the frequency of the wave is substantially lower than the surface plasma frequency given in Equation (10), the entire sandwiched medium becomes a parallel plate waveguide with the wave propagating by total internal reflection. However, if the width of the dielectric channel is not sufficiently large, the effects due to the fringing fields will induce transverse electric (TE) modes or transverse magnetic (TM) modes. If TE or TM modes dominate the transmission medium as depicted in Fig. 1, then there will be a minimum frequency known as cutoff frequency given by $\lambda_c = 2d/(mc)$, where m is the mode index. In practice, this cutoff frequency is unlikely large because, by satisfying the condition of field confinement along the interface, the velocity of the spoof surface plasmon polaritons will be extremely slow with virtually no fundamental frequency.

For the interface between media 2 and 3 to support propagation of spoof surface plasmon polaritons, the propagation constant on the interface must be equal to the propagation constant of the plane wave in medium 2. That is,

$$k_{z,2} = k_z \tag{11}$$

Using Equation (8), we can rewrite this equation as

$$\frac{\omega}{c}\sqrt{\varepsilon_2}\sin(\theta_2) = \frac{\omega}{c}\sqrt{\frac{\varepsilon_3\varepsilon_2}{\varepsilon_3 + \varepsilon_2}} \tag{12}$$

On the other hand, we have the condition of $k_{z,2} = k_{z,1}$ for the interface between media 1 and 2. Expanding this condition, we obtain

$$\frac{\omega}{c}\sqrt{\varepsilon_2}\sin(\theta_2) = \frac{\omega}{c}\sqrt{\varepsilon_1}\sin(\theta_2) \tag{13}$$

Merging Equations (12) and (13), we obtain

$$\sin(\theta_1) = \frac{\omega}{c}\sqrt{\left(\frac{1}{\varepsilon_1}\right)\frac{\varepsilon_2}{1 + \frac{\varepsilon_2}{\varepsilon_3}}} \tag{14}$$

Because ε_3 is negative, $\varepsilon_2/(1 + (\varepsilon_2/\varepsilon_3))$ is larger than 1 in Equation (14). If medium 1 is air or even partially ionized air, Equation (14) dictates that the incident angle θ_1 will be imaginary. In other words, the plane electromagnetic wave in medium 1 will not be turned into a spoof surface plasmon polariton along the interface between media 2 and 3 unless the relative permittivity of medium 1 is sufficiently large. Hence, as explained in the section which follows, we need a beaker of water to channel the plasmonic waves into a spoof surface plasmon polariton along the interface between media 2 and 3. This beaker of water is equivalent to Kretschmann configuration commonly used in the field of optics.

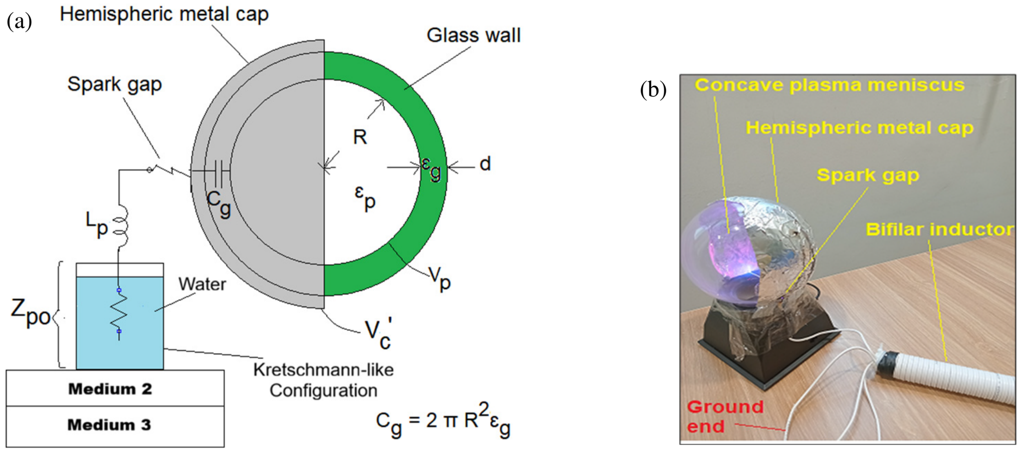

FIGURE 2. Transmitting end. (a) The equivalent circuit the plasma ball grounded to the service ground; (b) The photo of the plasma ball shielded with an indirectly grounded hemispheric metal cap.

Medium 3 can be any option from the following media: a seawater, a nearby metal frame(s), reinforcement steel bars hidden in a concrete structure, a metal fence along the pedestrian pathway, a rail track, or a service ground connection that comes with our household electricity supply. Medium 3 does not have to be a piece of buck metal. In a manner similar to the concept of metamaterials, even an array of disconnected, but closely coupled, pieces of metal objects can be used as a highly efficient medium 3. In this work, a table with a metal frame underneath will be tested for the feasibility of wireless power transfer in the sections that follow.

2.2. Transmitter

Figure 2 illustrates the construction of the transmitter in this study. The transmitter was a 5-inch plasma ball partially shielded with an indirectly grounded hemispheric metal cap (or so-called hemispheric reflector), as shown in Fig. 2(a) and 2(b). The plasma ball was the primary source of the high-frequency AC power. The power supplied to the plasma ball was about 2 W. The plasma ball was driven by a 22 Hz pulsation source through a common source amplifier configuration comprising a power Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) IRP260N and a high-voltage high-frequency ignition transformer. The plasma ball in this study was filled mainly with neon gas at a pressure substantially lower than the atmospheric pressure.

A hemispheric metal cap was used to partially shield the plasma ball. Because it was activated by a spark gap operating in ultrasonic frequencies, it generated an acoustic wave that pushed the ionized air preferentially toward the receiving end. According to our radiation meter, the radiated space waves from the transmitter were indeed slightly directional.

The nonlinearity due to the plasma in the plasma ball and the electric spark in the spark gap have manifested a spectrum of high order harmonic components, which occupied the entire high frequency (HF)/ultra-high frequency (UHF) spectrum, including the noticeably detectable harmonics at 23 MHz, 130 MHz, and 250 MHz.

When the plasma ball was isolated as shown in Fig. 2(a), it served as a spherical capacitor C_p with a capacitance of approximately 2 pF. The isolated plasma ball partially ionized the air in all directions. By the direct inspection of Equation (1), the magnitude of the AC voltage on the metal cap, V_c, is always smaller than the raw voltage extracted from the plasma ball, V_p.

However, when an inductive pathway was loosely suspended at the back of the hemispheric metal cap as shown in Figs. 2(a) and 2(b), the situation became completely different. The right end of this inductive pathway was approximately 1 mm away from the hemispheric metal cap, forming a narrow spark gap. The left end of the inductive pathway was submerged in water in the Kreschmann-like configuration (See Fig. 2(b) for more details). The inductance created by the inductive pathway, L_p, was formed by the bifilar inductor and the ground metal as shown in Fig. 2(a). Due to the presence of a large potential difference between the hemispheric metal cap and the right terminal of the inductive pathway, the narrow spark gap has sparked.

Because the spark gap was very narrow, the capacitance was much larger than C_p. The spark in this spark gap generated a broad-spectrum noise at a frequency much lower than that of the plasma ball. The low-frequency noise carried the major energy that could be delivered to the receiving end.

2.3. Receiving End

Figure 3(a) shows the circuit of the setup at the receiving end. Fig. 3(b) shows a photograph of one version of the receivers, which was adopted with some variation in the experiments as described in the next sections.

Because the plasma ball in conjunction with the spark gap on the back of the hemispheric metal cap was a nonlinear noise power source, it would not be logical to focus on the reception of power at only one single resonant frequency. Instead, the receiver was equipped with two Avramenko diode configurations for harvesting the RF power over a wide frequency band into DC power as shown in Fig. 3(a). The harvested power was consumed by the load resistor, *Rload*. *D1* and *D2* formed one Avra-

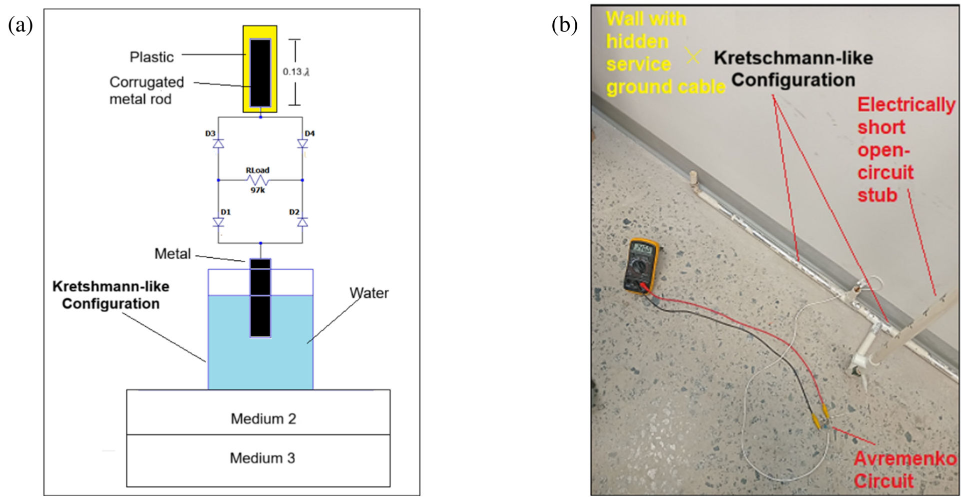

FIGURE 3. The receiver. (a) Circuit of receiver; and (b) photo of one version of the proposed receiver for harvesting energy.

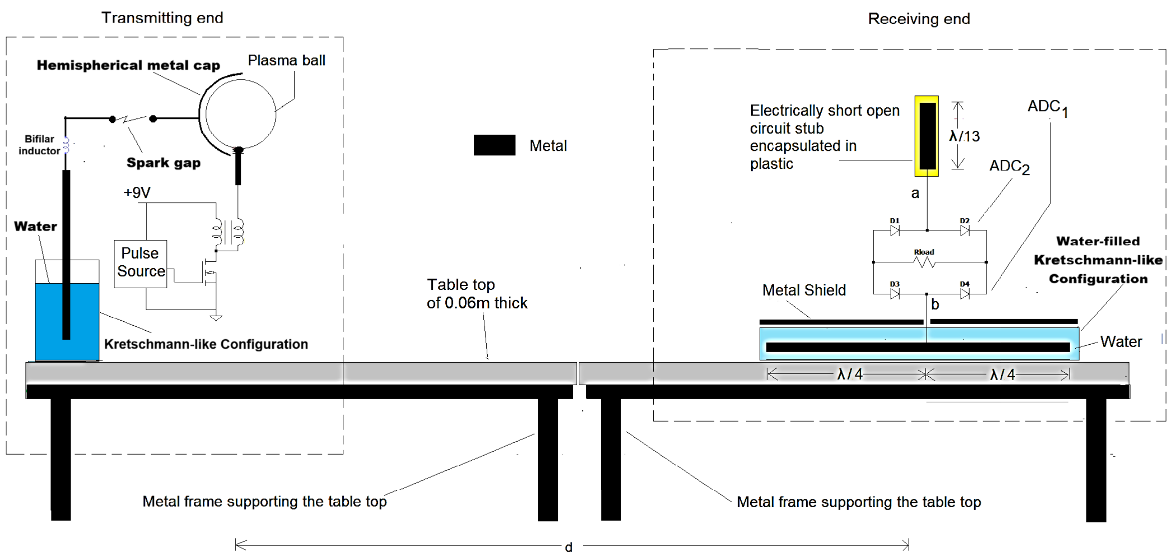

FIGURE 4. Experiment for testing wireless power transfer through metal frames (Condition 1).

menko diode configuration (say ADC A) for harvesting energy from medium 2 or medium 3. D3 and D4 formed another Avramenko diode configuration (say ADC B) for harvesting energy from space. The metal rod connected to the lower end of ADC A was immersed in water in a Kretschmann-like configuration. The metal rod connected to the upper end of ADC B was used as an monopole antenna with a length equal to 1/13 of the guided wavelength (i.e., approximately 1 m). The metal rod connected to the lower end of ADC A was used as a quarter-wave directional coupler.

The resistance of *Rload* was chosen to be 99 kΩ. The diodes in the circuit have an unbiased junction capacitance less than 5 pF.

2.4. Experimental Setup Based on a Metal-Frame Supported Table Top (Condition 1)

An experiment labeled "Condition 1" was conducted on a table top as shown in Fig. 4. The experiment has been conducted in a way to exclude any direct electrical contact between the transmitter and ground plane. As explained in the previous section, the hemispheric metal reflector was connected to a container of water through the bifilar inductor and spark gap. With the help of the Kretschmann-like configuration at the transmitting end, the power from the plasma ball was coupled into two tables, each of which had a metal frame underneath. The metal frames served as medium 3 of the proposed quasi-parallel-plate waveguide. By calculation using Equations (6) and (10), we determined that the surface plasma frequency of the interface between media 2 and 3 under Condition 2 was 17.8 MHz. The received DC voltage and power were measured against the transmission range using a meter and an oscilloscope.

2.5. Experiment Based on a Plasma Ball with No Spark Gap (Condition 2)

In addition to the above-mentioned experiments, we have conducted an experiment without any spark gap or Kretschmann-

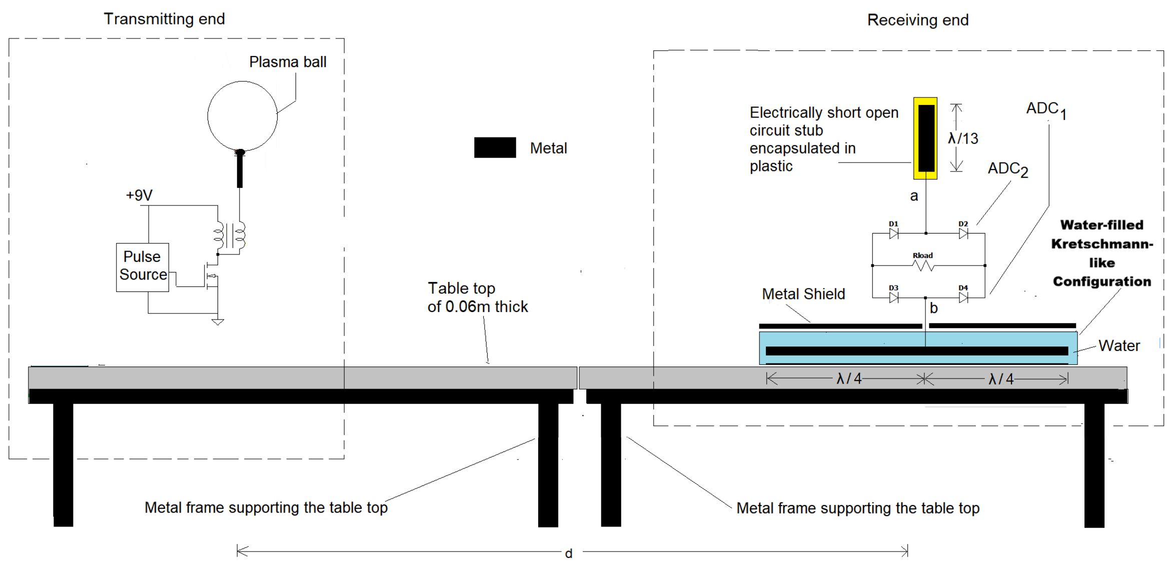

FIGURE 5. Experimental setup involving only space radio waves (Condition 2).

TABLE 1. Summarized general observations for different experimental conditions.

	Condition 1	**Condition 2**
Medium 3	Metal frame with a surface plasma frequency approximately at 17.8 MHz.	None
Medium 1	Kretschmann-like configurations were used at transmitting and receiving ends.	None
Transmission efficiency measured (dB)	Decaying at the first 2 m but, after that, the efficiency remained stable at -10 dB at transmission distance beyond 2 m.	Rapidly decaying at the rate of -42 dB/m.
Other Observations	• Very small high-pitch audible noise was heard. • No power was delivered if there was no spark in the spark gap. • Longest distance where power was successfully delivered was 10 m. • Capable of delivering power to multiple loads.	• No audio noise was heard. • No power was detected at distance greater than 1 m.

like configuration. This experiment was labeled as "Condition 2". The plasma ball and receiver were the same as the one used in Condition 1, but the hemispheric metal cap, spark gap, and bifilar inductor were removed from the plasma ball. The metal frame was not fed with any electric current, meaning that the table top was not used as a parallel-plate waveguide channel. Fig. 5 shows the schematic diagram of the experimental setup for Condition 2.

3. RESULTS

Consistent with the description in the previous section, the receiver and transmitter have been successfully realized and tested for Conditions 1 and 2 as defined in Section 2. In all of the experimental conditions described above, input power to the plasma was unchanged and remained constant at approximately 2 watts.

Figures 6(a) and 6(b) respectively show the spectrum measured with and without the spark gap activated in the inductive pathway attached to the hemispheric metal cap. As demonstrated in Fig. 6(a), without any spark-activated inductive pathway attached to the hemispheric metal cap that partially shielded the plasma ball, there was virtually negligible low-frequency power from the plasma ball. As highlighted in Fig. 6(b), the spark in the spark gap has induced a very significant amount of low-frequency noise power. This low-frequency noise power was the major portion of energy delivered to the receiving end.

Figures 6(c) and 6(d) respectively show the measured voltage and transmitted power for Conditions 1 and 2. The transmission efficiency was calculated as the ratio of the received power to transmitted power and plotted as the function of the transmission distance, d. Other observed findings, together with the main details of Fig. 6, are summarized in Table 1.

4. DISCUSSION

In this study, the above two conditions were chosen for our experimentation because these conditions highlighted the difference in terms of transmission efficiency between space electro-

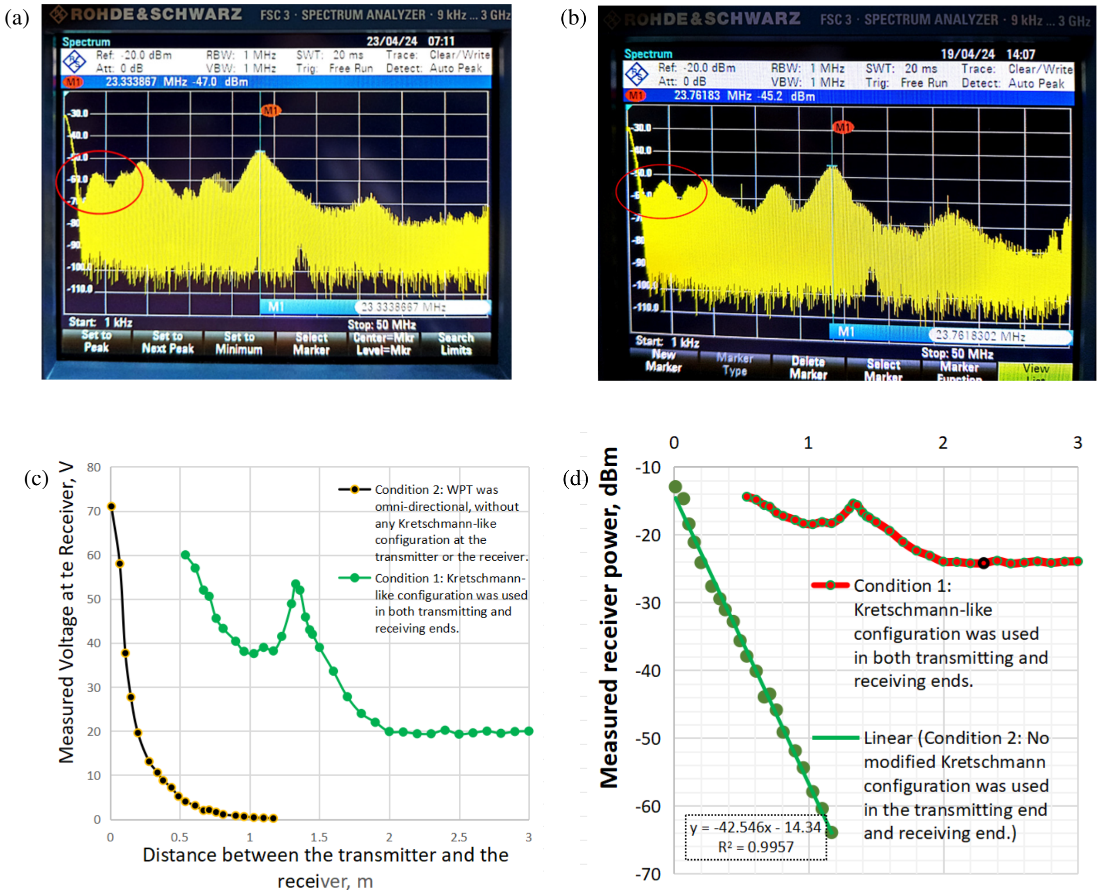

FIGURE 6. Measured results: (a) The spectrum of the radiations from the plasma ball when the hemispheric reflector was not connected to any Kretschmann configuration (i.e., Condition 2); (b) The spectrum of the radiations from the plasma ball when the hemispheric reflector was connected to water-filled Kretschmann-like configuration through a spark activated inductive pathway (i.e., Condition 1); (c) Measured output voltage of the load resistor *RLoad* against distance; (d) Measured received power against distance.

magnetic waves and surface waves. They also highlighted the role played by the Kretschmann-like configurations in WPT involving surface waves.

To minimize errors, not only meters but also oscilloscopes and a spectrum analyzer were used to monitor the measurements, which have been separately repeated by students of EEIT2019 at Vietnamese German University in 2024. All the results were found to be highly reproducible.

In Figs. 6(a) and 6(b), the curves marked with Condition 1 and Condition 2 respectively represent the results of wireless power transfer using surface waves and space waves. Surface waves propagated more efficiently than space radio waves. With space radio waves only, the ratio of transmitted power to the received power has inversely and linearly varied as the distance at the rate of -42 dB per decade, as opposed to -40 dB predicted by Friis' 2-ray model of transmission. With surface waves in the proposed quasi-parallel waveguide, the received power was almost invariant against distance.

The main reason that surface waves propagate much more efficiently than space radio waves is that the surface waves have a higher time-average power density than space radio waves. According to Fig. 6(b), the highest power was harvested at 23.76 MHz, as opposed to the calculated surface plasma frequency of 17.8 MHz. The power density of a surface wave can be maximized through field confinement, which can, in turn, be achieved by choosing the wave frequency sufficiently close to the surface plasma frequency. This advantage is impossible to get with space radio waves, whose power density spreads out and distance dependent.

As shown in Fig. 6(b), the low-frequency noise power became dominant when the Kretschmann-like configurations were used. Although plasma balls are not officially considered as ionizing sources, they are undoubtedly significant sources of electromagnetic interference (EMI). On the other hand, we have experimentally found that plasma can be focused as a beam by either ultrasonic means or arranging multiple plasma balls into a phase-antenna array. At this stage, it is unclear if a beam can be cost-effectively found in a metasurface. More research is needed.

In this work, the key to wireless power transfer was Kretschmann-like configurations which converted plasmonic waves into surface plasmon polaritions along the dielectric-on-metal grid interface, or the other way round. The methodology of this work can be potentially extended for continuously charging the moving electric vehicles on a road with the help of metal fences, lamp poles, or underground metal grids.

What is needed is a movable water-filled Kretschmann-like configuration, such as a car tire filled with water or any other high-K material. More research is definitely needed.

5. CONCLUSIONS

In this work, RF power was successfully transmitted as a spoof surface plasmon polariton over a distance of 3 m with the help of Kretschmann-like configurations mounted at the transmitting and receiving ends. The power source was a plasma ball. The transmission medium was a table top sitting on two disconnected metal frames. Consistent with the theoretical prediction, the transmission efficiency was found to be the highest with a surface wave propagating at a frequency approaching the surface plasma frequency of the interface. The proposed methodology has not only outperformed the method based on space radio waves, but also noticeably defied the prediction by the Friis' 2-ray model of transmission. Overall, the findings of this work reinforced the fact that WPT is feasible with surface waves if Kretschmann-like configurations are used. The methodology of this work can be potentially extended for non-contact and continuous charging of moving electric vehicles.

ACKNOWLEDGEMENT

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REFERENCES

[1] Costanzo, A. and D. Masotti, "Smart solutions in smart spaces: Getting the most from far-field wireless power transfer," *IEEE Microwave Magazine*, Vol. 17, No. 5, 30–45, 2016.

[2] Pakkangpalang, N., K. Phaebua, S. Pattaranavic, T. Lertwiriyaprapa, *et al.*, "Array antenna system for wireless power transfer (WPT) system at 6.78 MHz," in *2020 17th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, 816–819, Phuket, Thailand, 2020.

[3] Mitsubishi Heavy Industries, Ltd., "NTT and Mitsubishi Heavy Industries Achieved World's Highest Efficiency in Laser Wireless Power Transmission under Atmospheric Turbulence — Toward next-generation long-distance wireless power transmission for disaster-stricken areas, remote islands, and outer space," https://www.mhi.com/news/250917.html, Sep. 2025.

[4] Pendry, J. B., L. Martín-Moreno, and F. J. Garcia-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, Vol. 305, No. 5685, 847–848, 2004.

[5] Raether, H., *Surface Plasmons on Smooth and Rough Surfaces and on Gratings*, Springer-Verlag, New York, 1988.