Transmission of Plasmonic Energy through a Non-flat Surface

Louis Wai Yip Liu

Vietnamese German University, Le Lai Street, Hoa Phu Ward, Thu Dau Mot City, Binh Duong Province, Vietnam

Email: liu.waiyip@vgu.edu.vn

Abstract

Since the Maxwell's era, electromagnetic waves were believed to be travelling in a straight line in a manner not very different from a light ray. However, we have in this work proven the feasibility of transmitting energy through a curved surface. **Method:** To start with, a single-wire energy harvester was constructed and used to detect by contact an incoming surface plasma wave. Separately, an RF plasma at 26 kHz was generated and transmitted from one beaker of pure water (transmitting end), then through a curved plastic water tube, finally to another beaker of pure water (receiving end). **Results:** An electromagnetic energy was successfully detected with no conductor at the receiving end using the single-wire receiver. The transmission channel was a curved water tube, thus ruling out of any possibility of LOS transmission. The voltage detectable at receiving end was in general lower than that at the transmission end. However, the transmission efficiency as observed at the receiving end was found to be weakly dependent of the transmission range. No voltage was detected when the surface of the curved water tube was in contact with a human. **Conclusion:** Overall, an electromagnetic energy was successfully transmitted through a curved surface in the absence of any conductor. Our results suggest that harvesting lightning energy through a wet surface is close to a reality.

Keywords: surface waves, Avramenko diode configuration, monopole antenna, harvesting lightning energy, LOS, Line of sight

1. Introduction

Wireless power transfer is currently a hot research topic because of many reasons. One of the reasons is because the existing means of charging a battery through a cable is not very convenient. Just like electric plugs, different countries have different standards for the charging sockets. Wireless power transfer is one way to overcome the problem of charging plugs being incompatible. Another reason is because some of the renewable energy sources are believed to be able to be wirelessly harvested.

At the time of this writing, most of the research groups around the globe are focusing on transmission of energy over a couple of meters through magnetic coupling. The idea of transmission of electromagnetic energy through magnetic coupling is nothing new. Magnetic coupling over a long distance is theoretically impossible.

Wireless power transfer requires a means of transmission of electric power over a much longer distance without a conduct cable. Transmission of electricity without a conducting cable was first originated by Maxwell, who was the first researchers hypothesizing the link between the light and the electromagnetic wave. Since then, Hertz was another researcher who experimentally validated the Maxwell’s hypothesis of electromagnetism using a dipole antenna. According to Hertz and Maxwell, however, electromagnetic waves were believed to be not very much different from light which propagates strictly in a Line of Sight (LOS). The concept of LOS propagation was so unshaken in the scientific community until the Marconi’s time [1-7]. Marconi was among the first researchers proving the feasibility of long range transfer of electromagnetic wave through surface waves. In his prize winning research, Marconi has successfully demonstrated how a high-voltage plasmonic energy was successfully transmitted from England to New York over the Atlantic Ocean. The success of this experiment suffices to prove the feasibility of the non-line-of-sight propagation of a wireless power over the curvature of the Earth’s surface.

The medium of wireless transmission of electromagnetic energy in Marconi’s experiment was surface waves capable of following the contour of a non-flat surface, instead of a beam of light that travels in a straight line.

Over the last century, there have been numerous attempts to mathematically explain Marconi's work. Sommerfeld and Zenneck were among the first researchers who proposed their version surface wave theory [7-9], but their theory has an error. Since then, the concept of surface waves was almost non-existent in the scientific community. Following the unsuccessful attempt by Sommerfeld and Zenneck to propose the theory of surface waves, the research into wireless power transfer had completely lost favour for almost 50 years.

Fortunately, towards the end of the last century, Wait came forwards with a concept of trapped surface waves in a multi-layered ground [13] as a means to explain the non-line-of-sight nature of surface waves. Trapped surface wave is an evanescent wave propagating by successive internal reflections through an optically dense dielectric medium in very much the same manner as optical signal propagating in an optical fibre. In almost the same decade, King proposed another much more promising concept known as lateral wave to explain the non-line-of-sight nature of surface electromagnetic waves [15]. In King's theory, the lateral wave is a vertically polarized electromagnetic wave on the top surface of a ground as a result of an incident electromagnetic wave striking the air-ground interface from the below at exactly the critical angle. This critical angle exists only in the dielectric medium with a higher refractive index. To excite this lateral wave, all that is needed is to bury the radiating energy source into the dielectric medium with a higher refractive index in much the same manner as grounding a monopole antenna in Marconi's experiment [16-32].

Like many other research groups in the same field, we have already proven the feasibility of wireless energy transmission using an RF plasma over a flat water surface [31]. In this work, the concept of wireless power transfer by an RF plasma is further explored by an unconventional means. We begin our presentation by developing a mathematical model, which is not based on the Maxwel equations.

Not every energy harvester works [32-34]. The energy harvester for receiving a wirelessly transmitted electromagnetic energy should have single wire input port interfacing with the medium, which in this case is the ground. In our case, the energy harvester was based on a rarely known device known as Avramenko's diode configuration. In this work, another mathematical model was developed to describe the high frequency behaviour of Avramenko diode configuration.

2. Methodology

The hypothesis of this work is based on two scientific facts: 1) harvesting power can be done through one wire; and 2) power can be transmitted on the surface of water. In this work, the hypothesis is theoretically and experimentally validated.

a) Transfer Function of a Avramenko Diode Configuration

To capture a wireless energy, the energy harvester need a monopole port capable of capturing a time-varying energy through one wire. Ideally, the circuit to be used as a harvester should be an open-circuit relying on no batteries or any other power sources. The circuit fulfilling these criteria is Avramenko's diode configuration (see Fig. 2.2). For the first time, the relationship be the monopole input and output is reused and derived again using the work of Liu's [1].

To start with, one needs to understand the current voltage relationship of a diode when it is open-circuited as shown in Fig. 2.1

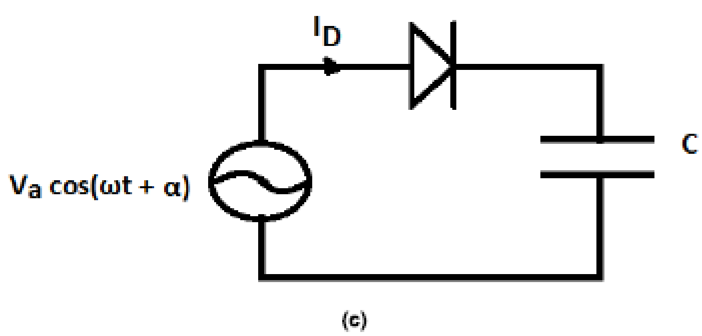


Fig. 3.1 Single diode with extremely small capacitance to model the open circuit behaviour of a diode.

Under a normal circumstance, the IV characteristic of a diode is given by the following equation.

$$I = I_s\left(exp\left(\frac{V_D}{V_T}\right) - 1\right)$$

(1)

Where V_D, I_s, I and V_T are respectively the voltage across the diode, the reverse saturation current, the actual current flowing through the diode and the thermal voltage.

Using the conventional circuit theory, it is not difficult to come up with the following equation that describes its time-varying IV characteristic when it is open-circuited.

$$C\frac{d}{dt}(V_a cos(\omega t + \alpha) - V_D) = I_s\left(exp(\frac{V_D}{V_T}) - 1\right)$$

(2a)

With some algebraic manipulation, we obtain:

$$V_D \approx V_T ln\left(I_0\left[\frac{V_a}{V_T}\right]\right) + V_T ln\left(\frac{I_s}{2CfV_T}\right)$$

(2b)

If two identical diodes are connected in the following manner (see Fig. 2.2), which is known as Avramenko's diode configuration, then the output voltage in response an AC monopole input is, according to Liu [1], given by:

$$V_1 - V_2 \approx 2V_T ln\left|1 - \frac{I_s}{2C_g f V_T} I_0\left[\frac{V_b}{V_T}\right]\right|$$

(3)

Where V_b is the amplitude of the sinusoidal voltage source. With further algebraic manipulation, we will end up with a positive and linear co-relation between the amplitude of the monopole input V_b and the differential output voltage V_1-V_2.

$$V_1 - V_2 \approx 2V_T ln \left| \frac{I_s}{2C_g f V_T} \sqrt{\frac{V_T}{2\pi V_b}} \right| + 2V_b$$

(4)

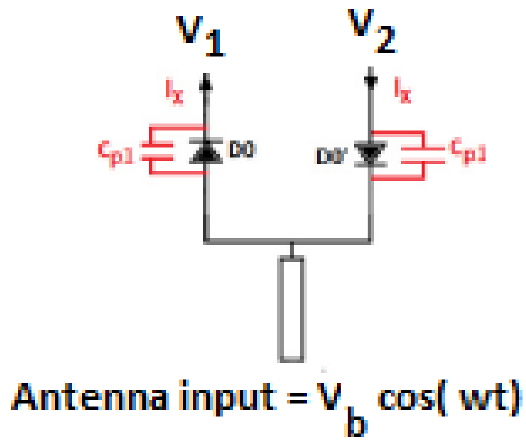


Fig. 2.2. Avramenko Diode Configuration

In Fig. 2.2, the junction capacitance of the diode C_{p1} and C_{p2} can be converted into an equivalent similar to C_g using Miller's theorem. This means that each of the junction capacitances has a grounding effect leading to a behaviour similar to a high frequency pole in linear network analysis.

In the right side of Equation (4), the second term is much greater than the first term, implying that that the DC voltage V_1-V_2 is proportional to the amplitude of the AC voltage at the monopole input port.

b) Prediction of Harvestable Surface Waves

Liu's work has given enough coverage of electromagnetic waves over a flat surface. Electromagnetic waves are known to be unable propagate in or penetrate into an over-dense plasma energy which can be easily formed over the surface of water. The electromagnetic wave is reflected at the plasma surface as a result of the skin effect. The successive reflections in close vicinity of a plasma surface results in an evanescent wave, with its penetration depth corresponding to to the skin depth δ. The skin depth δ is a function of frequency given by the following formula:

$$\delta \approx \frac{c}{\sqrt{\omega_p^2 - \omega^2}} \tag{1}$$

where ω_p is the plasmonic frequency and ω is the frequency of the travelling wave at free space.

The non-zero skin depth implies that the presence of an evanescent wave, which has sufficient energy heat up a plasma. On the other hand, the conductivity of the plasma enables the wave to propagate along the plasma surface as a surface wave that can be harvested by a sensor. This surface wave has an energy component that is perpendicular to the surface and that decays exponentially with the skin depth as it travels along the direction of propagation.

The implication of this theory is simple. Surface waves can be transmitted over a flat or non-flat surface that is modulated by a high density plasma. It is not unusual for a plasmonic energy source to possess multiple harmonics. The higher harmonics can be used as a high density plasma waves to turn a non-conducting surface into a conducting one. The lower harmonics can use the conducting surface formed by the higher harmonic to transmit electromagnetic energy from the source to the destination.

2.1) Experiments

We have conducted altogether two experiments: a) one for proving the linear co-relation between the monopole input of the energy harvester and its DC output, and b) the other for proving the transmission behaviour of the plasmonic surface waves.

a) <u>Linear co-relation between the monopole input of the energy harvester and its DC output</u>

To prove the linear co-relation between the monopole input of the energy harvester and its DC output, the experiment setup as shown in Fig. 2.3 has been constructed. The AC voltage source came from the amplified output from the port 1 of a vector network analyser. The frequency of the voltage from the vector network analyser was adjustable by adjusting the power level of the network analyser. The voltage from the network analyser was less than 1 mV. In order to supply enough energy to the energy harvester, the output of the network analyser needs to be amplified using a wideband microwave amplifier. The frequency and the amplitude of the amplifier output was measuring using a spectrum analyser. The DC output of the energy harvester was measured using a multi-meter.

In implement this experiment, we have used the following equipment: RS C42 vector network analyser, XXXX spectrum analyser; RS multiplier meter; and an energy harvester based on the circuit as described in Fig. 2.3

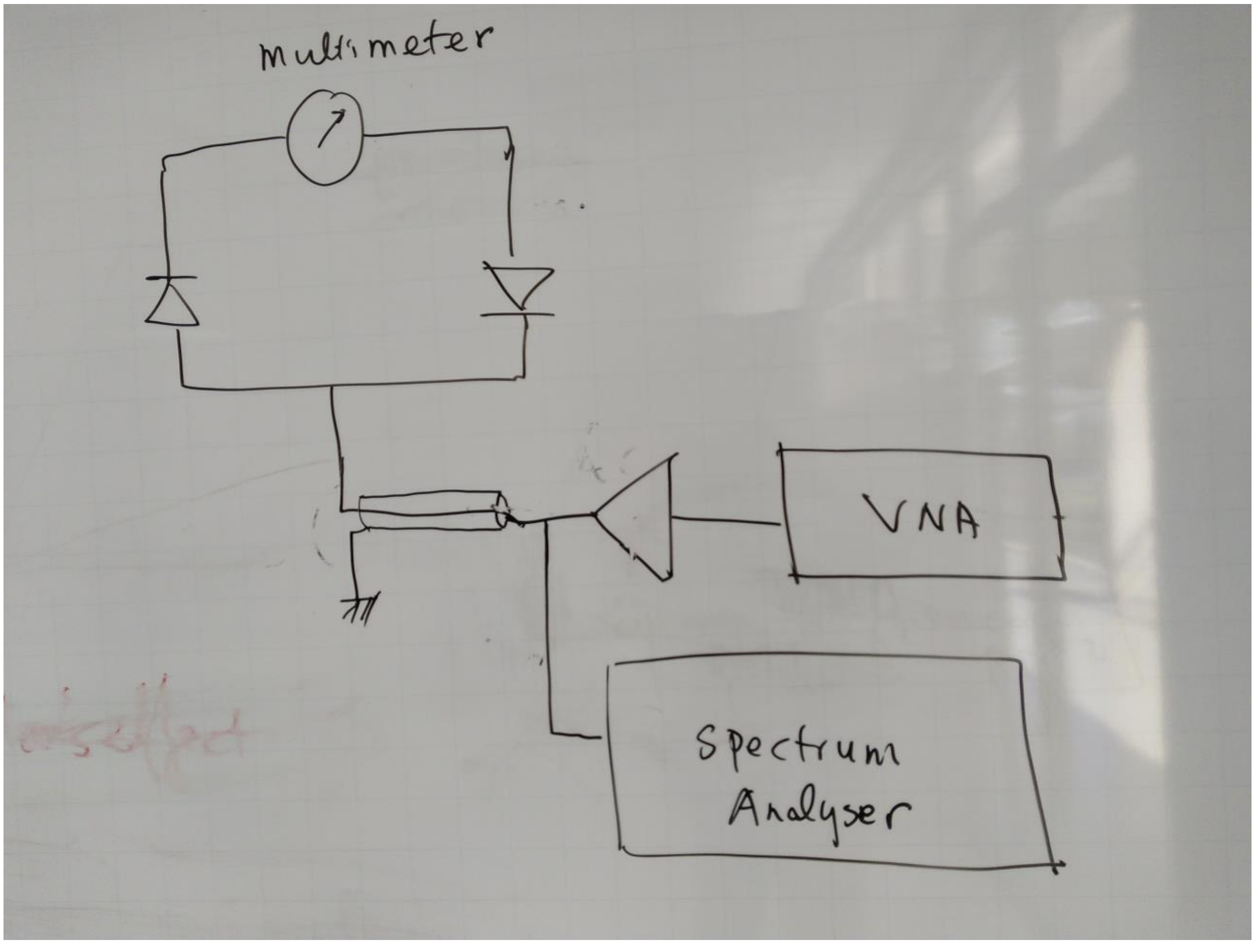


Fig. 2.3. Experimental setup for measuring the high frequency behaviour of the Avramenko's diode configuration.

b) Transmission of electromagnetic waves over a plasmonic surface

The conventional wisdom dictates that an electromagnetic wave has to travel in a straight line. This is so called line of sight. This was what Maxwell has conclusively proven in his discovery of the electromagnetic nature of light. The purpose of this experiment is to dispute this misconception. To do this, the experiment as shown in Fig. 2.4 has been constructed:

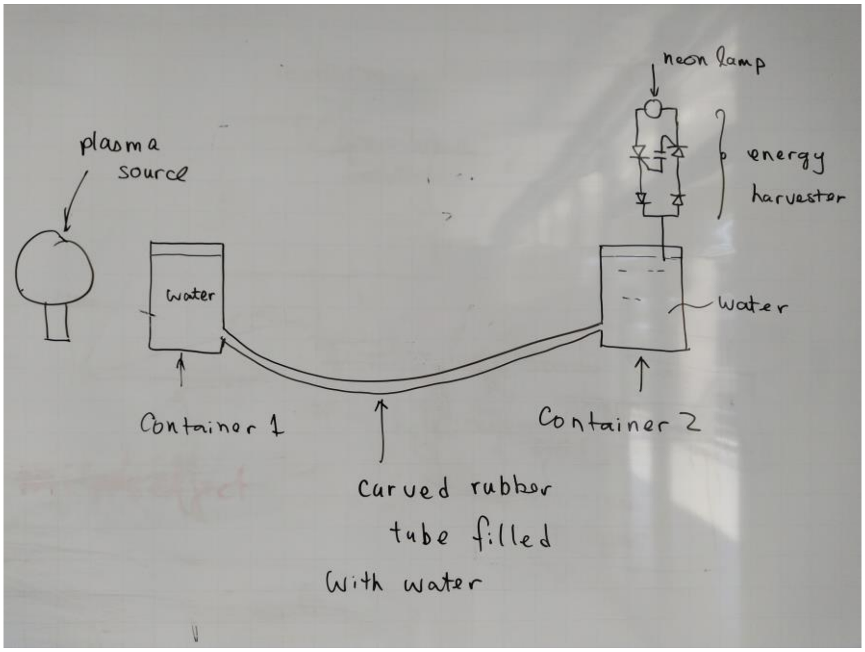


Fig. 2.4: Experiment setup for observing the behaviour of plasmonic surface waves

In this experimental setup, the transmitter was a plasma source. The plasma source was model sold by a cross-border seller between China and Vietnam. The plasma source released energy into a container of water without any physical contact. The power level of this plasma source was 27 dbm. The receiving end was mounted with another water container containing water. Two containers were connected with each other through a rubber tube. This rubber tube was a curved tube filling with water.

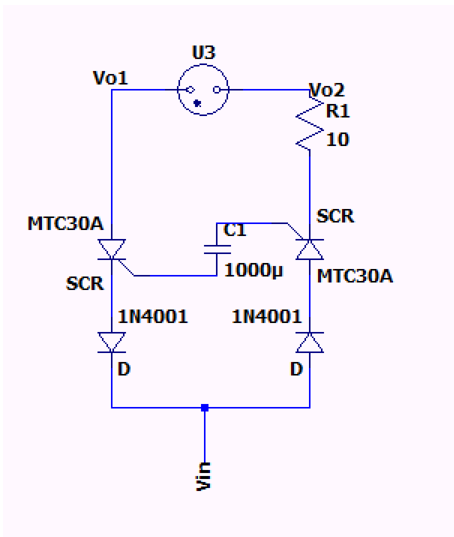
At the receiving end, the proposed energy harvester was mounted on the surface of water and its voltage and current were measured using a multimeter.

During the experiment, the circuit performance was carefully monitored if the density of the plasma channel was disrupted. We disrupted the density of the plasma by touching the rubber tube.

3. Results

A series of experiments were conducted to detect the presence of the surface waves on the surface of water. To conduct our experimentation, we have first constructed an energy harvesting circuit as shown in Fig. 3.1. Based on the results of our experiments, the energy harvesting circuit was fully functional as expected. The energy harvesting can detect and capture voltage from a plasma source without any physical contact between the source and the harvester. A plasma energy has been successfully transmitted over the surface of water in a home-based container, proving the feasibility of wireless power transfer using surface waves.

Fig. 3.1 shows the circuit of our energy harvester constructed using discrete components obtainable from the market. In the schematic as shown in Fig. 3.1, the 10 ohm resistor was used to measure the current under a high voltage condition. According to our observation, the current was in the neighbourhood of 0.7mA. The input port of the circuit is a monopole antenna of 3 inches long.



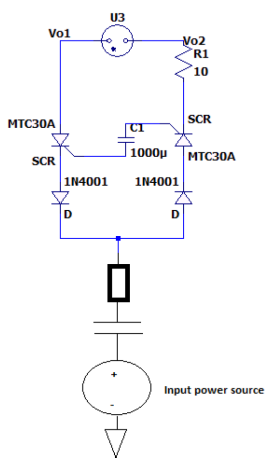
(a)

(b)

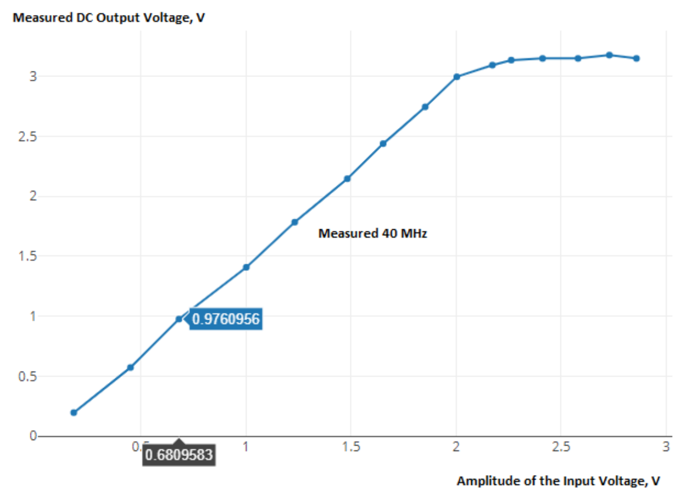
Fig. 3.1 Energy harvester implemented Using the proposed topology: a) the schematic; and b) the realized circuit

a) Test on the functionality of the energy harvester

The circuit as shown in Fig. 3.1 has been measured independently using high frequency instruments (see Fig. 3.2). The test setup for measuring the energy harvester is an open-circuit, with the monopole antenna as a single wire input for the energy harvester. When the input port of the energy harvester was put in contact with the output of a high frequency AC source, a DC voltage was noticeably observed at the output of the energy harvester. The measured DC voltage was found to be linearly proportional to the amplitude of the input (see Figs. 3.2 b and 3.2c). The proportionality constant was higher when the frequency is lower. The results of the experiment as shown in Fig. 3.2a has sufficiently proven the fact that the circuit realized as shown in Fig. 3.1 was indeed an open-circuit energy harvester.



(a)



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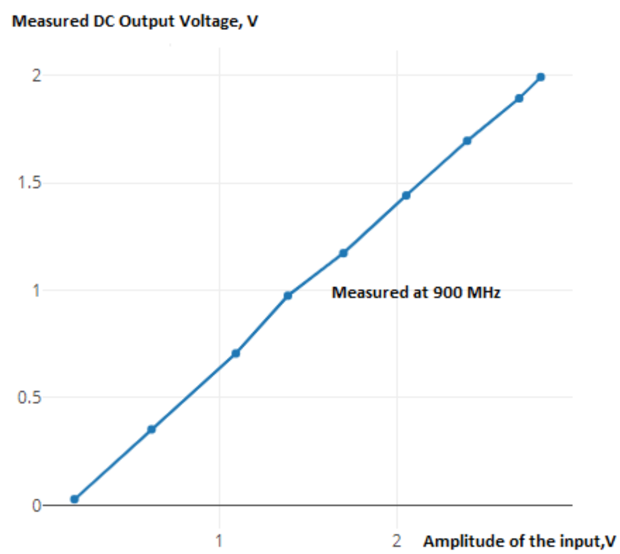

(c)

Fig. 3.2. Experiment for characterising the energy harvester. a) experimental setup; b) Measured output voltage as a function of the amplitude of the input for the energy harvester when the frequency was at 40 MHz. c) Measured output voltage as a function of the amplitude for the input of the energy harvester when the frequency was at 900 MHz.

b) Experiment on proving the existence of the surface waves

Separately, we have also conducted another experiment to the prove the existence of surface waves (see Fig. 3.3). A rectangular container was first filled with water. A plasma was operating as an energy radiator at the corner of the water container. The energy harvester of Fig. 3.1 was placed at the opposite corner of the water container to detect and measure the captured voltage. The monopole antenna of the energy harvester was immersed on the surface of the water. There was no physical contact between the water and the plasma power source.

The power source used in the experiment as shown in Fig. 3.2 was an ordinary plasma source purchased at XXXX. Fig. 3.3 shows the power spectrum of the plasma source. Plasma was operating at 25 kHz and its power measured by contact was -19 dBm.

When the plasma source was switched on, a DC voltage was observed at the output of the energy harvester. When the energy was placed too close to the plasma source (within 10mm), the output voltage of the energy harvester was low but its measured output current was almost 7mA. When the spacing between the plasma source and the energy harvester was in excess of the 10 mm, the measured voltage at the output of the energy harvester was found to be independent of the separation and its value was constant at 50 V.

The rubber tube was bent but, at the receiving end, the neon lamp was lit with diminished brightness. When the rubber tube was touched by a human figure. The neon lamp was unlit. The rubber tube was an insulator, ruling out any possibility of any ohmic contact on the surface of the rubber tube.

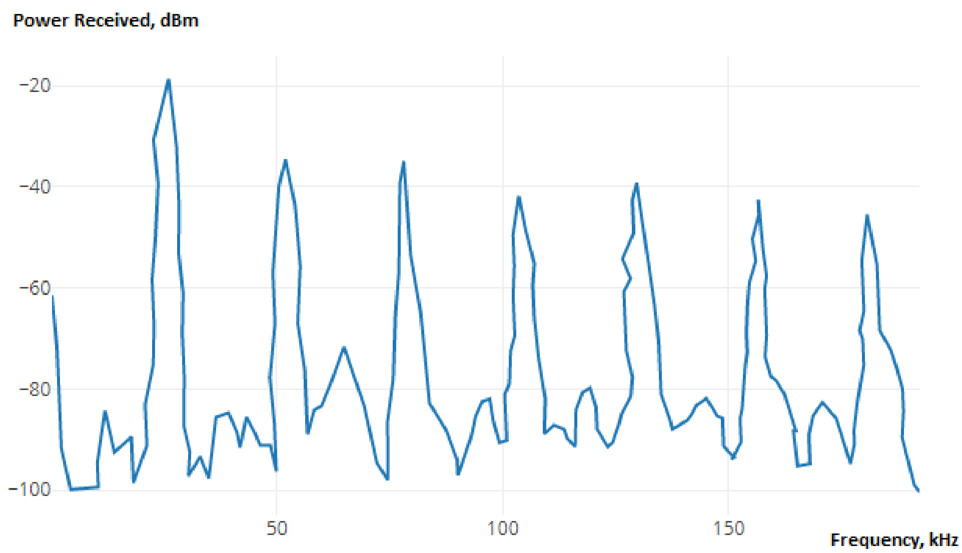

Fig. 3.3 Power spectrum of the plasma source

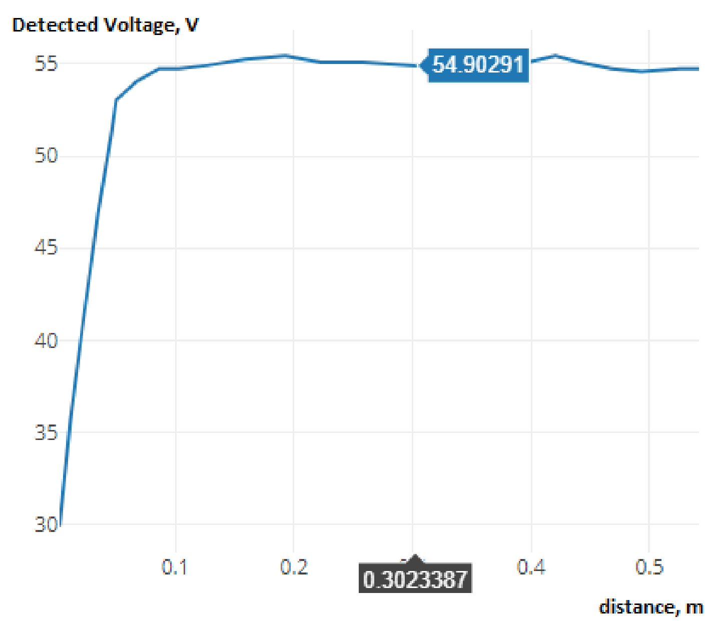

Fig. 3.3 Experiment on proving the surface waves: a) Power spectrum of the plasma source b) Harvester's output voltage measured over the surface of water when the plasma source was radiating

4. Discussion

In this work we have designed and realized a single-wire detecting circuit which can turn on a neon lamp in the presence of a plasma energy. The circuit does not need any battery to operate. The detected voltage was over 50 volts while the current is about 0.7 mA, which is enough to produce useful work for some daily applications. The detector circuit was eventually found to be able to capture a plasma energy without any physical contact. These findings have proven two points:

1) single-wire transfer of electrical energy was for the first time found to be a reality; and

2) wireless energy harvesting in the presence a nearby plasma source is another reality. The energy harvesting process can be done in the absence of any battery or power supply.

In our first experiment, we have measured the voltage across the output terminals of the energy harvest in the presence of a high-voltage AC power at the input. The output DC voltage was found to be proportional to the amplitude of the AC power input, suggesting that the amount of power that can be captured is more or less a linear function of the AC input. We have not been able to measure any current in air or on the water surface. However, we were able to measure at least 0.7 mA. Most of the existing devices for wireless power transfer are based on the concept of magnetic coupling. For the first time, the outcome of this work results in a fundamentally new wireless energy harvesting circuit that is based on an entirely different concept. Magnetic coupling is not possible over a long distance, whilst surface waves can propagate over a much a longer distance.

The energy harvester was based on a backbone of the Avremenko diode configuration. According to our theoretical derivation (see Equation 4), there exists a linear and positive correlation between the amplitude of the monopole input voltage and the DC output voltage. Our experimental results agree with our theoretical hypothesis.

According to Equation 4, the DC output voltage is dependent on the frequency as well.

The original objective of the second experiment was to prove the feasibility of wireless power transfer over the water surface. Unlike other devices that are based on magnetic coupling, our proposed energy harvesters can harvest a plasma source that was half a meter away. Magnetic coupling requires a large current to operate, whilst surface waves can be generated with much less current.

Unlike ordinary electromagnetic waves, which always travel in a straight line, surface waves can propagate along any curved surface. The experimental result of the second experiment has proven this fact without any doubt.

The plasmonic surface wave is a high density energy that is no difference from a conductor. When the density of this plasmonic surface wave is high, it serves as a conductor that supports propagation of electromagnetic waves. When its density is lost, just like what has happened in this experiment, the surface is not conducting any more. That was the reason why the neon lamp was unlit when somebody touched the rubber tube.

According to our observation (see Fig. 3.3), the captured power does not appear to be dependent on the separation between the plasma source and the energy harvester. Electromagnetic waves in air or any dielectric medium travel in a straight line, while surface waves propagate over a flat or non-flat surface. However, the captured power in this work does not appear to correlate to the distance. This mode of power propagation is to some extent similar to far field transfer of electromagnetic waves, as predicted by our theoretic analysis.

The results of this work strongly suggest the feasibility of energy harvesting from a light strike. Light strikes are highly unpredictable events, but we do record a high number of light strikes over some areas like Vietnam. If this is true, we will have another renewable energy sources. We should be able to harvest the lightning energy on the surface of an ocean in a manner as proposed in Fig. 4. We have no idea where the lighting strike is going hit. However, for sure, the energy will fall on the surface and spread. The nature of those lightning strikes is not very different from the nature of a high voltage plasma. If we have an energy harvester similar to what we have implemented, we should be able to collect the energy over a period of time. If this is true, then there will be another source of renewable energy from the nature.

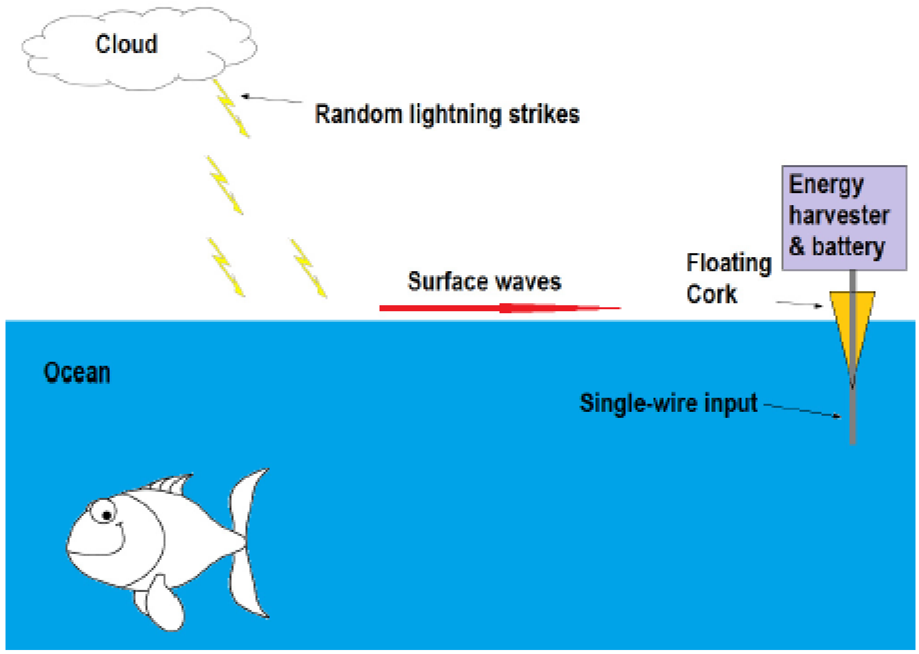

Figure 4. How a lightning energy will be harvested using our proposed energy harvester.

More research needs to be done in this area, particularly in the area of mathematical modelling of plasma surface waves, because the findings of this work are related to energy sustainability of this planet. The energy of lightning strikes from the nature is definitely a clean energy that produces no pollution. If we realize an energy harvester to capture the energy from a lightning strikes, there will be another field of science in our community.

4. Conclusion

Whilst Line-of-Sight propagation (LOS) of electromagnetic surface wave is known to be possible, we have in this work further proven theoretically and experimentally the feasibility of transmitting energy through a curved surface. In this work, an RF plasma at 26 kHz was electromagnetically transmitted without any conductor from one beaker of pure water (transmitting end), then through a curved plastic water tube, finally to another beaker of pure water (receiving end). At the receiving end, which is the electromagnetic surface energy was detectable by a contact using a single-wire receiver based Avramenko diode configuration, ruling out any possibility of LOS transmission. The detected voltage was high at the transmitting end but was weaken at the receiving end. When observing at the receiving end, the transmission efficiency was found to be independent of the transmission range. The findings of this work further implicate the feasibility of harvesting an plasmonic energy by contact with a non-flat and wet surface.

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