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Research Article

A Novel Compact GNSS Antenna with Plasma Frequency Selective Surface

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ABSTRACT

In this study, a plasma frequency selective surface (PFSS) was designed with an array of ordinary fluorescent lamps backed by a conducting plate. The proposed PFSS structure was used as a reflector with the spiral two arms Archimedean type Global Navigation Satellite System (GNSS) antenna to reduce the overall size of the antenna system. Characteristics and the performance of the proposed system were presented by using the results of simulations and experiments in the GNSS band. The optimum distance between antenna and PFSS was found to be around 35 mm to achieve a maximum gain in the simulation which is a lower profile than antenna with conventional conductive plate (66 mm at the GNSS center frequency). Experimental results show that the antenna system has mean values of around 6.7 dBiC gain, 1.27 dB axial ratio and less than -10 dB return loss in the range of 1.14 and 1.61 GHz. All these results show that the proposed novel antenna system is suitable for the reception of the GNSS signals with the advantage of its low profile design.

1. Introduction

Global Navigation Satellite System (GNSS) has been a key element of significant technological devices and finds an important role in many areas of the life including navigation, transportation, mining, mapping, and road pricing [1-3]. This technology has been subject to research studies in terms of new antenna designs, anti-jamming, and improving positioning performance in recent years [4-6].

The emergence of the multiple GNSS service providers GPS L1 (1575.42 ± 1.023 MHz), BDS B1 (1561.098 ± 5 MHz), and GLONASS L1 (1602.5 ± 4 MHz) for the navigation systems has made antennas, covering all GNSS bands, to play an indispensable role [4]. All-band GNSS antennas should cover the range between 1146 MHz-1610 MHz band, have high front to back ratio, and acceptable axial ratio with a large beam-width for a better satellite coverage [7-9]. In addition, high accuracies, and low profile characteristics are needed for many high precision applications [9]. Spiral antennas, which satisfy the necessary electrical properties, are widely used in GNSS applications [10].

In general, one of the major factor which prevents designing low profile antennas is the use of high electric conductor materials. These materials are placed $\lambda/4$ away from the antenna, to increase the gain of the receiver and to improve the directivity of the radiating antennas. In this type of directive antennas, $\lambda/4$ value is the optimum distance between the antenna and high electric reflector, due to the ($\lambda/2$) out of phase reflected wave. There is no design flexibility in

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such systems. However, the use of a modified reflector [9] or plasma frequency selective surface (PFSS), which was proposed in this study, can be used to decrease the λ/4 distance value. The PFSS is an artificial magnetic conductor that gives a design flexibility, and it can be used in many novel applications such as radar cross section reduction, wide band absorber, and photonic band gap devices because of its adjustable electrical characteristics [11-13].

PFSS structures can be formed by using energized fluorescent lamps which are also plasma medium. The fluorescent lamp has frequency dependent adjustable electrical conductor properties. In other words, by applying variable electric potential to the fluorescent lamps, collision and plasma frequencies can be changed. Consequently, the optical and the electrical properties can be adjusted. In this way, a band pass filter mechanism can be achieved to transmit and reflect some of the frequency band region of the radiation.

For instance, in our previous study, the PFSS structure for GNSS frequency band with high impedance and in-phase reflection characteristics were presented [14]. Plasma antennas also are widely studied in research studies such as development of intelligent reflective surfaces [15-16], and corner reflectors [17] to improve the performance of the systems. Although the plasma and electromagnetic radiation interaction investigated in many studies as mentioned or used as reflector or antenna structures [14-17]. Best to our knowledge, the utilization of a plasma structure to minimize the antenna system size without compromising the radiation performance has not been published yet and we believe that the results of this study can contribute to the research on both plasma and electromagnetic wave interaction.

In this paper, the design of a two arm Archimedean antenna with PFSS structure realized by fluorescent lamps array and a conductor plane was presented.

The fluorescent lamp array, as a low cost plasma source, which is placed under the antenna behaves like a plasma frequency selective surface (PFSS) since its refractive index, and so reflectivity depends on the plasma parameters of the gas in the energized lamps. The simulation and the experimental measurement outcomes of the antenna for the parameters of the return loss, axial ratio, and gain were investigated by considering plasma properties of PFSS structure. To the best of our knowledge, this is the first time shown that such PFSS surfaces can be used to reduce the size of the system without compromising the radiation performance of the antenna.

2. Theory and Experimental Results

2.1. Experimental design

The designed system consists of a GNSS antenna, a PFSS structure, assembled of the florescent lamp array and a metal reflector, is illustrated in Figure 1 (a). Circular polarized antennas are generally used with a reflector surface to detect the radiation especially by satellites in GNSS applications. The main reason to choose these types of antennas is that the circularly polarized signals are less affected while passing through the ionosphere. In this study, one of the circular polarized antennas, the two arm Archimedean type was used because of providing stable results in terms of gain and axial ratio values in a certain bandwidth.

The parameters of the antenna were determined for the GNSS band of 1.146-1.610 GHz. The physical dimensions of the antenna were calculated using well known antenna equations [18]. Thereafter the antenna was simulated using CST software by using calculated parameters and the target parameters were found for the fabrication. The designed antenna was fabricated to have 12 turns of copper lines width of 1 mm and the line spacing of 1 mm by using 1 mm thick FR4 material of the relative dielectric constant of 4.5 and the loss tangent of 0.02 (Figure 2 (a)).

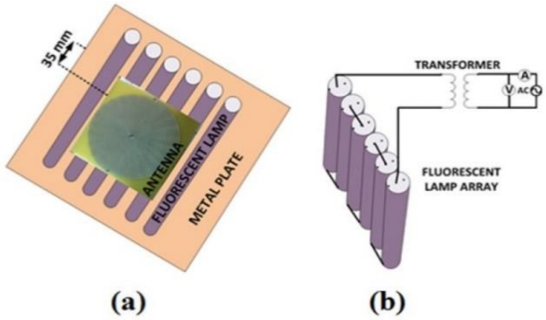

Figure 1. a) The illustration of the proposed system, b) the illustration of fluorescent lamp array

The PFSS structure was designed by integrating an array of easy access fluorescent lamps and a conducting surface. In the system, serially connected lamps were excited by a transformer system (Figure 1(b)). Alternative voltage of 220 Vrms and 50 Hz was applied to the transformer input. The transformer primary and secondary windings were selected as 500 and 10000 turns respectively to obtain around 4400 Vrms. The plasma was formed in the lamps by applying this voltage to the lamp array. The PFSS structure was placed 35 mm (Figure 1 (a) and Figure 2 (b)) below the antenna. A network analyzer (Rohde Schwarz NWA ZVA-24) was used for the S parameters measurements, a signal generator (Rohde Schwarz model) (10 kHz-12 GHz) and Rohde Schwarz model spectrum analyzer (100 kHz-30 Ghz) were used for the gain and axial ratio measurements.

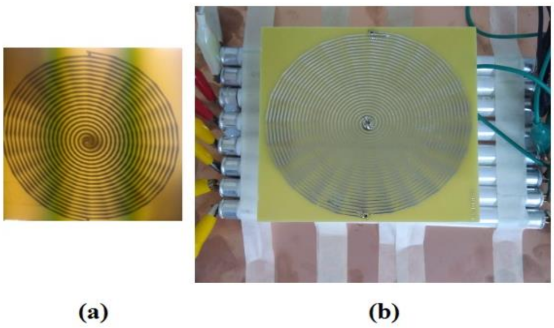

Figure 2. a) Radiator part of the GNSS antenna, b) the actual experiment setup

The array was formed with 6 identical fluorescent lamps which emit white light and each has 6 W power (Global T5/6W, RPC). The diameter, length, and glass thickness of each lamp are 16 mm, 225 mm, and 0.8 mm respectively. These lamps were placed 5 mm apart from each other as shown in Figure 2(b).

2.2. Plasma characteristics

Dielectric constant is a parameter which determines the electrical properties of the materials in theoretical and experimental physics. Electrical and optical properties such as conductivity, reflection, transmission, and absorption can be calculated by using the dielectric constant. The dielectric constant and optical properties can be tuned by using applied voltage in plasma mediums like fluorescent lamps. Relative dielectric constant ε_r of a plasma medium can be characterized by using the Drude model as given in equation (1).

$$\varepsilon_r = 1 + \frac{w_p^2}{jw(jw+v_C)} \quad (1)$$

where w is electromagnetic wave frequency, ν_c is collision frequency and w_p is the plasma frequency. The plasma frequency is defined as:

$$w_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \quad (2)$$

Here, n_e is the electron concentration, e is the charge of an electron, m_e is the electron mass, ε_0 is the dielectric constant of the vacuum. It can be seen in Eq (1), if an electromagnetic wave frequency is less than the plasma frequency, there will be a high reflection from the lamps. If $w > w_p$, the reflectivity decreases and the transmissivity increases. Therefore, when the electromagnetic wave frequency ω is smaller than ω_p, it will be reflected with a high reflectivity. However, the phase difference between the incident and reflected waves will be different from π/2 when the reflected medium is the PFSS which is a combination of the dielectric, plasma and metallic components [19]. This effect is exploited in our study to design a low profile antenna system.

The summary of experimental antenna parameters and plasma simulation parameters are summarized in Table 1.

3. Results and Discussion

The Archimedean antenna and PFSS structure were designed and studied to present the reduction the size of the system without compromising the radiation performance.

Table 1. The antenna and plasma parameters

Antenna Parameters		*Plasma Parameters*	
r1	40 mm	w_p:	48.4 GHz
H (antenna height)	35 mm	ν_c:	287 GHz
Turn number	12		
Width of the arm	1 mm		
Spacing between arms	1 mm		
Distance between lamps	5 mm		

The measurement and simulation results of the proposed antenna system were presented in this section. In order to analyze the influence of the plasma structure on the antenna characteristics, the return loss S_{11}, the axial ratio AR, and the right hand circular polarized RHCP gain parameters were investigated. During all measurement and simulations, the two arm Archimedean spiral antenna and PFSS structure were used together. The study was first started with the simulation and measurement of the S_{11} parameter to determine the signal ratio returning from the antenna and 50Ω compatibility.

The return loss values in the range of 1.05 GHz - 1.70 GHz frequency band with the plasma and without the plasma cases were shown in Figure 3. The number of the resonance frequencies and ripples were decreased in plasma cases. These results can be attributed to the change of the reflected electric field which affects the power on the antenna and input impedance in the presence of plasma. The S_{11} parameters were expected to be lower than -10 dB to satisfy the requirement of low return loss condition.

All the results of the measurements of the antenna with and without plasma correlate this condition except some frequency bands in the simulation. The S_{11} parameter of the measurement results with plasma presented in Figure 3 show that the S_{11} lies between -10.32 and -17.17 dB. Especially at GPS frequency 1.575 GHz, the values were approximately -17.00 dB. Measured and simulated results of S_{11} parameters have differences as can be seen in Figure 3. The possible reasons for these differences can be SMA connector losses, fabrication tolerances and external disturbances which are not considered in the simulations. For this study these differences are ignored and only checked if S_{11} values are below -10 dB. The S_{11} values below -10 dB in this frequency range indicate that the input impedance value of the antenna is compatible with 50 Ω and the antenna system can be used in the GNSS band.

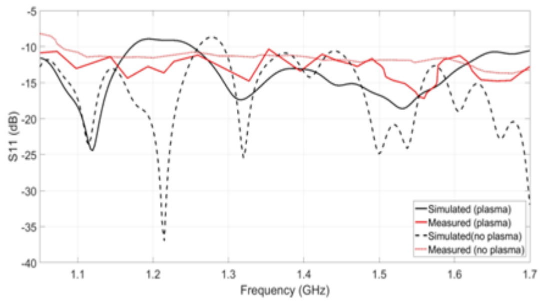

Figure 3. The S_{11} parameter of antenna with PFSS

The AR value gives the information about the polarization of an antenna. The axial ratio values were determined by measuring the difference of power values of two orthogonal components. The orthogonal components obtained by rotating a linearly polarized transmitter antenna in 90 degrees in azimuth. Figure 4 shows the measured and simulated AR characteristics of the proposed antenna system. Although the axial ratio value was higher than 3 dB at low frequencies of the GNSS band in simulation, it was found that the AR value was observed to lie below the limit value of 3 dB in measurements. Hereby, it was understood that the deviation from circular polarization is less than 3 dB and the antenna can be assumed to be circularly polarized.

Especially at the GPS center frequency (L1 Band) that is the 1575.42 MHz, the measured axial ratio values were in the range between 0-1 dB (measured with plasma 0.6 dB, measured without plasma 0.45, simulatated with plasma 1.63, simulated without plasma 1.52). This means that the desired circularly polarized antenna characteristic was obtained very closely for the antenna at GPS L1 frequency band.

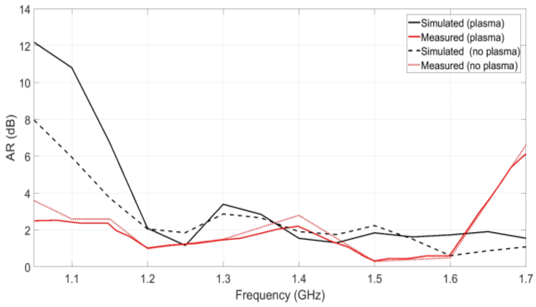

Figure 4. The AR of the antenna with PFSS

The antenna gain, one of the most important parameter was measured and simulated with and without plasma conditions in Figure 5. When the plasma lamps were energized, it was observed that the gain value was highly increased in the whole in the GNSS frequency range both in experimental and also simulation cases. At the GPS center frequency (L1 Band), the measured gain values were as follows. The measured plasma 7.01 dBic, the measured without plasma: 3.94 dBic, The simulation plasma 6.97 dBic, the simulated no plasma 4.18 dBic. The obtained gain showed that the reflection from PFSS surface was near to the inphase component.

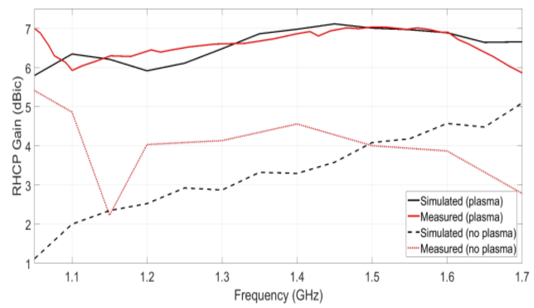

Figure 5. The RHCP gain of the antenna with PFSS

Radiation patterns in CST simulation of the proposed system are given in Figure 6. As it is seen that, when plasma is activated, the radiation pattern is changed for all degrees. Half power beam width (HPBW) of the radiation pattern of the antenna which has PFSS is 88.5 degree and it is larger than the no plasma version of the antenna which has the HPBW is 72 degrees. Both of them have hemispherical shapes that radiate toward the upper side of the atmosphere. In addition, there is a difference between radiation strength of the antennas because of the inconsistent heights of the radiation part of the antennas.

The height must be 66 mm which is the quarter wavelength of the resonant frequency for the no plasma version. Because reflected waves from the reflector must be in phase with the radiation of the radiator. In the plasma case, PFSS behaves as a high impedance surface so reflected signals are not out of phase. So it does not need a larger air gap. Detailed information of the antenna without lamps can be found in [20].

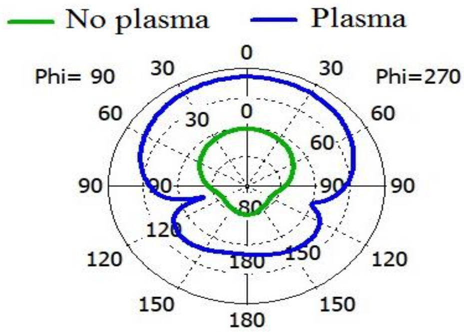

Figure 6. Radiation patterns of the proposed system

Several GNSS antennas dimensions and operating frequencies were presented in Table 2 to compare them with the proposed antenna. Designed metamaterials were used as a reflector for the other antennas presented in Table 2 [21-24]. As can be seen, except the single frequency antenna in reference [24] all the other ones have larger volume than our antenna. The antenna presented in this work, being wideband and also low profile has advantages over the antennas in Table 2.

The simulation results show that the optimum distance of the conductor is around 66 mm. For the ideal case, when the conducting plate is λ/4 (66 mm for 1.14 Ghz) apart from the antenna, the mean values of S_{11}, axial ratio, gain are -17.50 dB (max: -26.70 dB, min: -11.80 dB), 1.20 dB (max:2.10 dB, min:0.25) and 6.90 dBic (max:7.05 dBic min:6.45 dBic) are obtained in GNSS band respectively. The measured performance of the antenna without lamps and when a metal reflector is placed under the antenna (66 mm below) is summarized as follows: the S_{11} parameter was lower than -10 dB, the gain was between 6.0 dBic and 6.2 dBic, axial ratio was between 0.9 dB and 1.4 dB at 1.1-16 Ghz range [20]. The detailed results can be found in the study of Yiğit [20].

Table 2. The antenna and plasma parameters

REF.	Dimensions	Operating Frequency
[21]	130 mm x 30 mm (RxH)	Wideband (1.1-1.6 Ghz)
[22]	200 x 200 x55 mm (WxLxH)	Single frequency (1.575 GHz)
[23]	280x280x29 mm (WxLxH)	L1 and L2 band
[24]	44x44x19 mm (WxLxH)	Single frequency (1.575 GHz)
This work	80x80x35 mm (WxLxH)	Wideband (1.1-1.6GHz) Reconfigurable

*RxH: RadiusxHeight; WxLxH:WidthxLengthxHeight

The mean values of S_{11}, axial ratio, and gain are -12.86 dB (max: -17.08 dB, min: -10.35 dB), 1.27 dB (max:2.37 dB, min:0.36) and 6.70 dBic (max:7.04 dBic min:6.29 dBic) are measured for the proposed system respectively. These results show that the system performance is close to that of the ideal case. It is worth mentioning that the proposed antenna system can be utilized in small GNSS platform applications when it is upgraded to a portable one. It is possible to make the system portable with a miniature 36 W high voltage source since there are 6 lamps with 6W rating. This kind of high voltage source can be designed or commercially available ones can be used [25]. As a conclusion, the proposed wide band GNSS antenna system with low profile is realized with the proposed PFSS.

4. Conclusion

The performance of an Archimedean type GNSS antenna with a PFSS structure, formed via fluorescent lamp array as a plasma source and conducting plate, was investigated. The proposed antenna parameters showed promising results such as having a low axial ratio and a high gain in all GNSS band. In addition, a smaller size compared to the antenna with a single conducting plane was obtained by exploiting the reflection properties of the PFSS.

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The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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