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Cutoff probe using Fourier analysis for electron density measurement

Byung-Keun Na,[1] Kwang-Ho You,[1] Dae-Woong Kim,[1] Hong-Young Chang,[1] Shin-Jae You,[2,a)] and Jung-Hyung Kim[2]
[1]*Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon 305-701, South Korea*
[2]*Center for Vacuum Technology, Korea Research Institute of Standards and Science, Daejeon 305-306, South Korea*

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This paper proposes a new method for cutoff probe using a nanosecond impulse generator and an oscilloscope, instead of a network analyzer. The nanosecond impulse generator supplies a radiating signal of broadband frequency spectrum simultaneously without frequency sweeping, while frequency sweeping method is used by a network analyzer in a previous method. The transmission spectrum (S21) was obtained through a Fourier analysis of the transmitted impulse signal detected by the oscilloscope and was used to measure the electron density. The results showed that the transmission frequency spectrum and the electron density obtained with a new method are very close to those obtained with a previous method using a network analyzer. And also, only 15 ns long signal was necessary for spectrum reconstruction. These results were also compared to the Langmuir probe's measurements with satisfactory results. This method is expected to provide not only fast measurement of absolute electron density, but also function in other diagnostic situations where a network analyzer would be used (a hairpin probe and an impedance probe) by replacing the network analyzer with a nanosecond impulse generator and an oscilloscope. © *2012 American Institute of Physics*. [doi:10.1063/1.3680103]

I. INTRODUCTION

Diagnostics of plasma parameters is important for characterizing the plasma's properties and processing result. While there are many instruments to measure plasma properties, including a Langmuir probe,[1–5] a microwave interferometer,[6,7] and laser Thompson scattering,[8–10] most of them are not suitable for application in industrial plasma diagnostics, because the systems include a complicated radio frequency (RF) compensation circuit or they are bulky, heavy, and expensive. Additionally, the analysis includes very complicated theories and assumptions. Therefore, to overcome the disadvantages of the diagnostics, a cutoff probe which is a very simple and easy diagnostic tool has been developed by Kim *et al.*[11,12] The construction and installation of the cutoff probe is relatively simple, as is the analysis of the probe spectrum to determine electron density. The cutoff probe is also usable even in a processing plasma, because it is not affected by the dielectric deposition on tip.[13] The frequency of cutoff peak and the electron density was also known to be well matched.[13–15]

Since the cutoff probe was developed, a lot of remodeled versions of the cutoff probe have been developed, including phase-resolved method,[16] hybrid-type of cutoff probe with absorption probe,[17,18] and cutoff probe with box-car mode for pulsed plasma measurement.[19] Normally, the cutoff probe consists of two coaxial cables with their cores exposed to and immersed in the plasma. Depending on the method of analysis, researchers measured the transmission frequency spectrum (S21), reflection frequency spectrum (S11), or phase frequency spectrum (ϕ) between the two antennas by using a network analyzer to determine the electron density. However, a network analyzer is not suitable for fast measurement (at least several hundred milliseconds are needed in generating spectra). Therefore, the development of cutoff system without the help of a network analyzer was one of the challenging issues in the cutoff probe diagnostics.

In this paper, we proposed a new method[20] for cutoff probe, named "*Fourier cutoff probe*" (FCP) using a nanosecond impulse generator and an oscilloscope, instead of a network analyzer. Because the short impulse signal in time domain means a broadband spectrum in frequency domain, the nanosecond impulse generator can supply a radiating signal of broadband frequency spectrum simultaneously without frequency sweeping which is normally performed by the network analyzer in the previous method. The transmission frequency spectra (S21) were obtained through a Fourier analysis of the transmitted impulse signals detected by the oscilloscope, and then they were used to measure the electron densities. The results showed that the transmission frequency spectrum and the electron density obtained using the Fourier cutoff probe method were very close to those obtained using network analyzer method. These results were also compared against the Langmuir probe's measurements with satisfactory results. This method also provided a time resolution of only 15 ns.[20] This method can be applied to any other diagnostic tools[21–25] using a network analyzer for fast measurement.

II. EXPERIMENTAL SETUP

A schematic diagram of experimental setup is shown in Fig. 1. The experiment was performed in an argon inductive

a)Electronic mail: sjyou@kriss.re.kr.

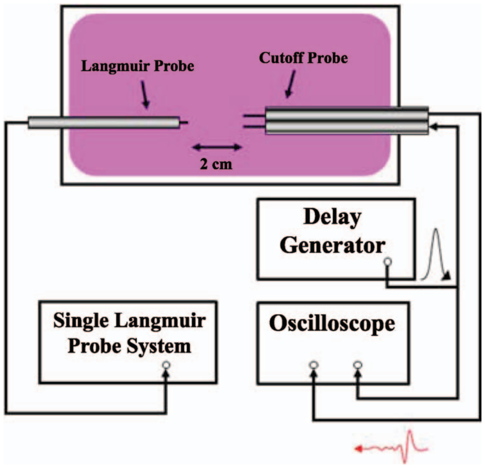

FIG. 1. (Color online) Schematic diagram of experimental setup.

discharge. Plasma was generated by a 13.56 MHz inductive discharge in a 700 mm diameter and 290 mm long cylindrical vacuum vessel. Four ports 630 mm in diameter were installed on the side of the vessel. A chuck with a 550 mm diameter and 160 mm height was located at the bottom of the vessel in contact with ground. A 30 mm thick alumina plate 670 mm in diameter was mounted on the top of the vessel. Double stacked antenna (DoSA; Ref. 26) 450 mm in diameter, a type of inductive discharge source and specially made for azimuthally uniform plasma, was used for the power coupler. Up to 3000 W of RF power could be delivered to the antenna via L-type matcher. Argon gas was fed with a mass flow controller from the side of the vessel and pumped out by a turbo molecular pump of 500 l/s and rotary pump of 600 l/m. The gas pressure was adjusted using a gate valve. The cutoff and Langmuir probes were mounted at the two opposing side ports. The cutoff probe was made of two coaxial cables in a stainless steel holder. The end tips of the cables were exposed to the plasma. In normal use of the cutoff probe measurement, a network analyzer was used to make a transmission spectrum. However, the Fourier cutoff probe used a delay generator for nanosecond impulse generation (DG645, Stanford Research Systems) and an oscilloscope (X8600A, LeCroy) to detect transmitted signal, instead of a network analyzer. The delay generator made an impulse with 100 ns delay with respect to trigger signal, we used it as an impulse generator with variable width and amplitude. The oscilloscope measured the source and transmitted signals. The probe mounted at the discharge chamber was connected to a network analyzer and a Fourier cutoff probe system in sequence.

To check the reliability of the both measurements above, a Langmuir probe measurement was also taken and the electron density was calculated from electron energy distribution function (EEDF).[2,3,27] The cutoff and Langmuir probes were situated 2 cm apart at the center of the chamber. A RF compensation probe with a choke filter was used to block RF distortion at 13.56 MHz, 27.12 MHz, and 40.68 MHz. A comparison of the three methods was performed in 10 and 30 mTorr of argon gas, in 100–900 W of RF power. In each condition, the three kinds of measurements were performed in sequence.

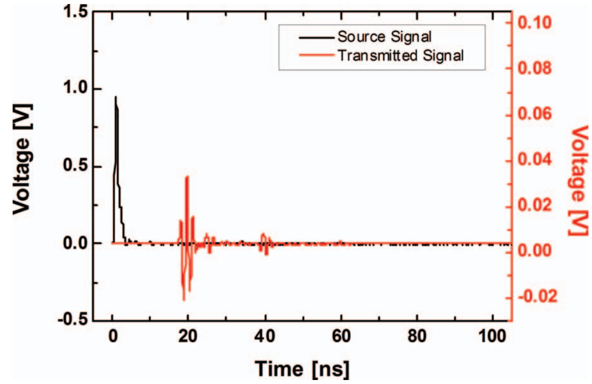

FIG. 2. (Color online) Source and transmitted signals at Ar 10 mTorr and 165 W of RF power, where plasma frequency was 1.0 GHz.

III. RESULTS

As previously mentioned, instead of using network analyzer, a short impulse source signal was used to make a broadband frequency spectrum. An example of the short impulse is shown in Fig. 2. The amplitude of this source signal was 1.0 V. The width of the impulse was about 3.5 ns, and full width half maximum (FWHM) was 0.75 ns. The transmitted impulse detected by the oscilloscope at the plasma condition of 10 mTorr and 165 W is also shown in Fig. 2. The maximum and minimum of voltage of the transmitted signal are 0.03 V and −0.02 V, respectively. The width of transmitted impulse was about 6.3 ns. As shown in Fig. 2, the shape of the transmitted signal was much different from that of the input signal. This discrepancy originates from the intrinsic dispersive characteristic of plasma. The phase velocity of the wave in the plasma medium is a function of the wave frequency constituting the impulse signal.

Fig. 3 shows the frequency spectrums of input and transmitted signal measured by the proposed method using a delay generator and an oscilloscope. The spectra were obtained through fast Fourier transform. The spectrum analysis shows that the power spectrum of source signal has a bandwidth of about 1.5 GHz, while the spectrum over 1.5 GHz is very noisy. Although there is a peak around 0.1 GHz, the spectrum of

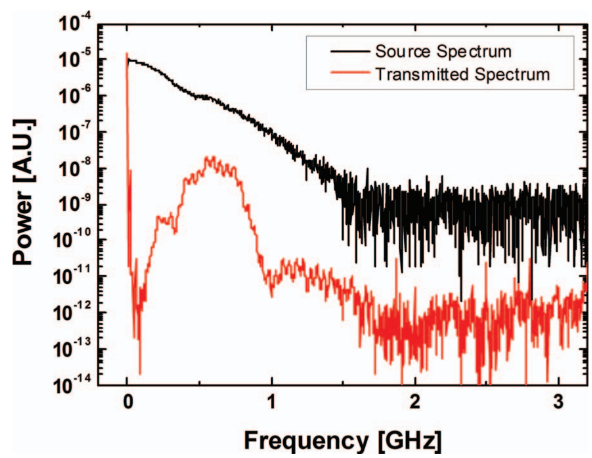

FIG. 3. (Color online) Spectra of source and transmitted signals at Ar 10 mTorr and 165 W of RF power.

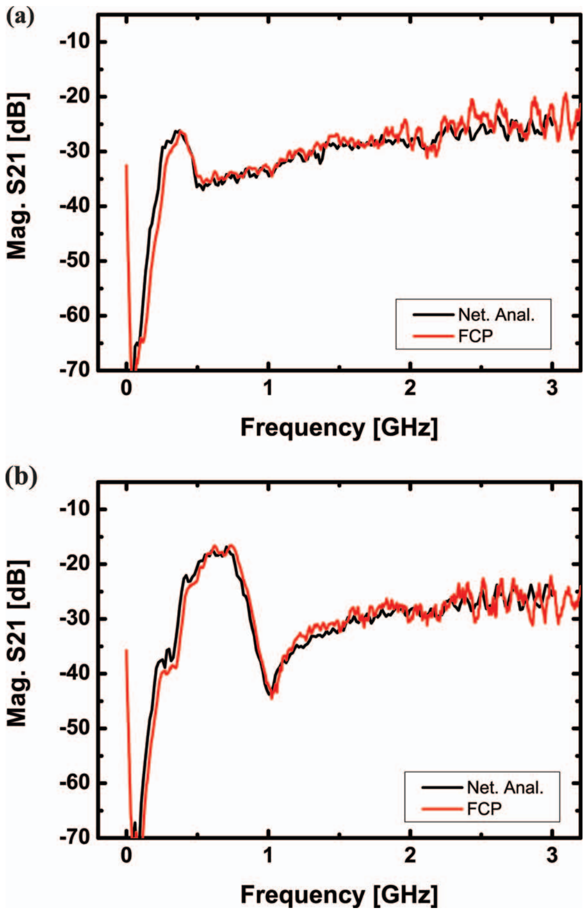

FIG. 4. (Color online) Transmission spectra at (a) 10 mTorr, 56 W, (b) 10 mTorr, 165 W.

transmitted signal may indicate a cutoff-like minimum point around 1.0 GHz in the frequency spectrum. The clear transmission characteristic of the probe can be seen in the transmittance (S21) defined by the following equation:

$$\mathrm{S21} = 10 \times \log_{10}\left(\frac{P_{out}}{P_{in}}\right), \tag{1}$$

where P_{in} and P_{out} are the source signal power and a transmitted signal power, respectively. Fig. 4 shows some examples of transmission spectra from the network analyzer cutoff probe and the Fourier cutoff probe at different experimental conditions. As shown in Fig. 4, the overall spectra of the Fourier cutoff probe are very similar to those of network analyzer cutoff probe and the cutoff frequency points coincide with each other.

However, an unexpected discrepancy was shown at the low frequency part around 0.1 GHz in S21 spectra of all the experimental conditions as shown in Figs. 4(a) and 4(b).[20] The RF noise (13.56 MHz and its harmonics) is also mixed in the transmitted signal and the S21 spectra. The unexpected peak appeared at 0.1 GHz, where the RF noise becomes negligible. If the source power uses higher frequency like 100 MHz, this discrepancy can be a problematic. This problem can be reduced with many times of averaging, because triggered impulse signal will be enhanced and non-triggered RF will die out in averaging. This discrepancy frequency is fortunately sufficiently distant from the cutoff frequency. However, if the cutoff frequency were near 0.1 GHz, which may take place in the measurement of low electron density plasma ($n_e \sim 1.2 \times 10^8$ cm^{-3}), this part may cause a problem for determining cutoff frequency in the S21 spectrum. Most plasma systems used in industry are operated at a density higher than the electron density $n_e > 1.2 \times 10^8$ cm^{-3}, so this irregularity should not pose a problem in the application of the Fourier cutoff probe method for the measurement of industrial processing plasma.

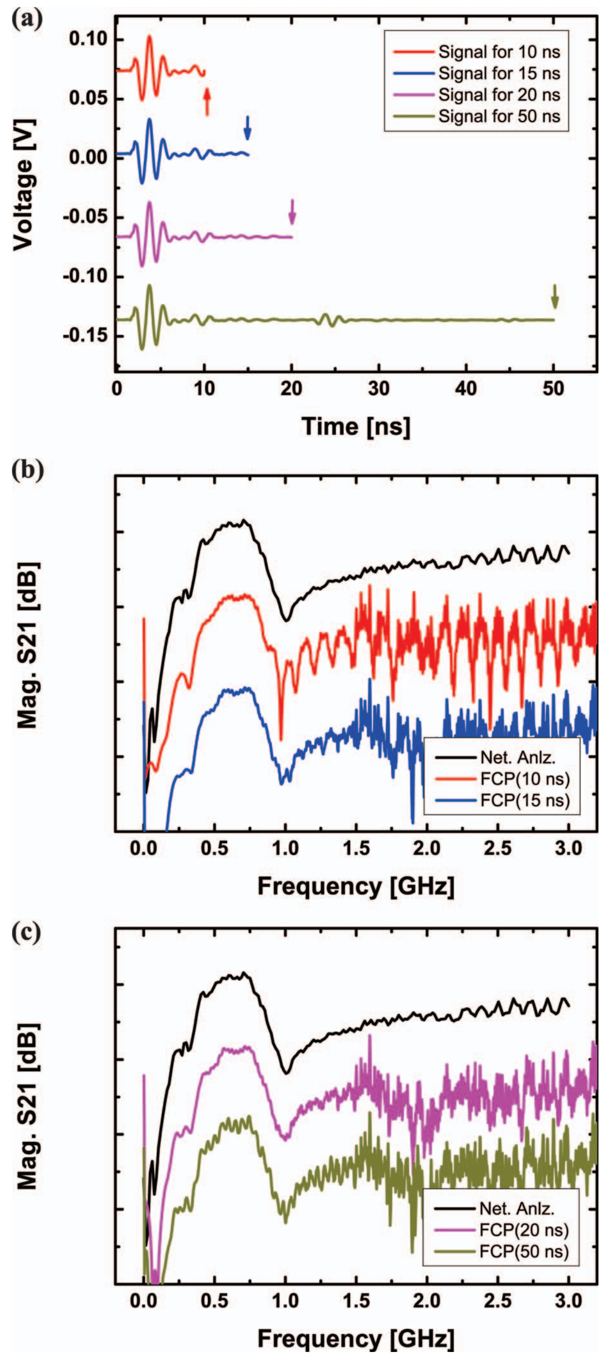

FIG. 5. (Color online) (a) Transmitted signals by signal length. Only 10 ns, 15 ns, 20 ns, and 50 ns long parts of transmitted signals are shown. (b) and (c) Transmission spectra by the signals presented at (a). The black graph is a transmission spectrum by a network analyzer.

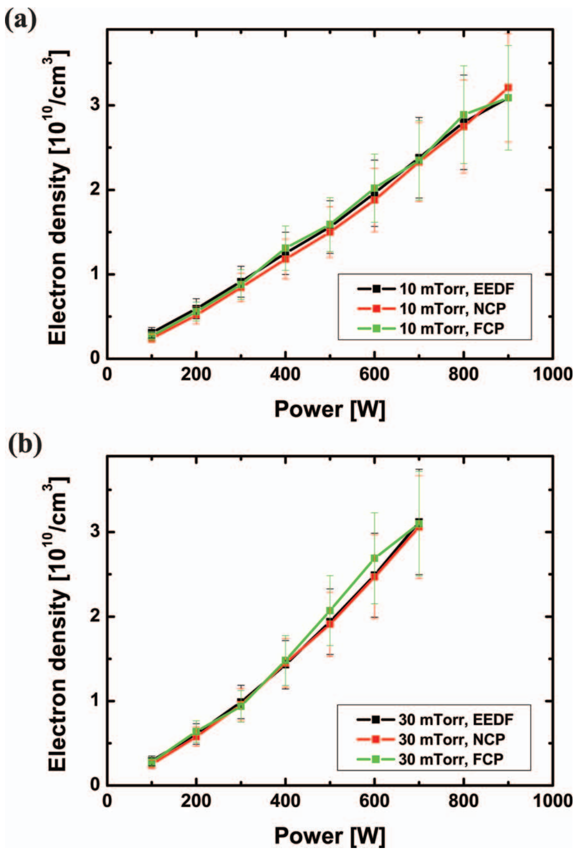

FIG. 6. (Color online) Comparison of electron density measured by a Langmuir probe, a network analyzer cutoff probe, and a Fourier cutoff probe.

In using the Fourier analysis, the length of the transmitted signal is important. Long signal can make the frequency resolution to be high, and it can also include a lot of information of plasma parameters. However, too long signal means the waste of storage, and this method can lose the time resolution. Hence, finding an adequate length of the transmitted signal is important. Figure 5 shows the transmission spectra by the transmitted signal length. Longer signals than 15 ns could reconstruct the transmission spectrum with a good agreement with network analyzer's spectrum. The longer the signal length is, the better the spectrum quality becomes. The 15 ns signal is necessary for spectrum reproduction, hence 15 ns is the time resolution of this method.[20] Even though the time resolution is extremely short, the time resolution can be enhanced using a shorter impulse source.

To confirm the reliability of the Fourier cutoff probe, we compared the electron densities from Fourier cutoff probe to network analyzer cutoff probe and Langmuir probe's measurement. Fig. 6 shows the electron densities from the Fourier cutoff probe are in good agreements with those of the network analyzer cutoff probe and Langmuir probe within 10% error.

In the case of Langmuir probe, the standard uncertainty of the electron density measurement is about 20%,[28] which is from surface area and statistical error. In the case of cutoff probe, the error usually comes from the cutoff frequency determination, which contains double peaks problem, cutoff peak broadness, and frequency resolution. For example, the cutoff peak does not always appear in one sharp peak. In Fig. 4(b), the spectrum by FCP shows two peaks at around cutoff frequency. The frequency resolution was set to be about 30 MHz for network analyzer, 13 MHz for FCP. The error by frequency resolution is less than 10%. The uncertainty by the broadening of cutoff peak, including the error by frequency resolution, is considered to be about 20%.[13] In spite of these matters, electron density measurement by FCP showed remarkable results. Therefore, we can conclude that the Fourier cutoff probe method can measure the electron density without a network analyzer, with reliability and a very high-time resolution. A disadvantage of this method is that the maximum measurable electron density is not as high (1.5 GHz $\rightarrow$ 2.8 $\times$ 10^{10} cm^{-3}). Introducing a shorter impulse source generator can solve this disadvantage, and it can even enhance the time resolution also.

IV. CONCLUSION

In conclusion, we proposed a new type of cutoff probe using a nanosecond impulse generator and an oscilloscope, instead of using the network analyzer which is essential one in the previous cutoff probe method. The transmission frequency spectrum and the electron density obtained with the Fourier cutoff probe method were very close to those obtained with both the previous methods using network analyzer and Langmuir probe methods. In addition, by virtue of this method, the cutoff frequency point can be measured without a network analyzer and the speed of cutoff probe measurement was enhanced more than a million times without loss of measurement accuracy compared to the previous one. This new method is expected to have applications not only in the fast measurement of absolute electron density with a cutoff probe, but also to other previously developed diagnostics where a network analyzer is used, specifically a hairpin probe,[21,22] and an impedance probe,[23–25] by replacing the network analyzer with a nanosecond impulse generator and an oscilloscope.

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