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Improvement of Power Spectrum in Ultrashort Pulse Reflectometry Signals Using Three Chirp Configuration

Young-Su Roh*

Abstract

The flat power spectrum of the transmitter output signal for the desired frequency range is ideal to achieve the best performance of ultrashort pulse reflectometry. However, the power spectrum of a typical pulse generator decreases significantly as frequency increases. A configuration of three chirped waveforms was employed to improve the power spectrum of the transmitter signal at higher frequencies. To determine the amplification gain required for higher frequency components, three chirped waveforms were theoretically generated and their power spectra were measured using numerical band-pass filters. Based on the results of numerical computations, the three chirp configuration was successfully applied to the design of the transmitter for a broadband system..

Key Words : Ultrashort Pulse Reflectometry, Transmitter Signal, Three Chirp Configuration, Power Spectrum

1. Introduction

Reflectometry is a density measurement diagnostic for magnetic fusion plasmas [1]. It provides a spatially localized measurement of the electron density at a relatively distant location in the plasma without probing into the plasma interior. In reflectometry, the reflected waves from cut-off layers propagate back out of the plasma. Since only a single viewing chord is required to measure the electron density, reflectometry requires no assumption regarding plasma symmetry and has an access advantage of using only waveguides inside and nearby the fusion device. For these reasons, reflectometry has received considerable attention as a density measurement diagnostic for magnetic fusion plasmas [1-2].

Ultrashort pulse reflectometry (USPR) utilizes an extremely short pulse. USPR has several advantages over conventional reflectometry techniques [3]. Firstly, the data analysis does not depend on the time history of the reflectometry signals. Secondly, USPR is capable of eliminating spurious reflections easily in the time domain. Thirdly, USPR data analysis is very fast and real time monitoring may be possible because the

* Main author : Soongsil University, Dept. of Electrical Engineering
Tel : +82-2-820-0663, Fax : +82-2-817-7961
E-mail : yroh@ssu.ac.kr
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density profile can be reconstructed directly from the recorded group delay data. Due to such merits, USPR has been employed to measure electron density profiles and fluctuations on GAMMA 10 [4].

In the original concept on USPR, a single pulse was envisaged for broadband systems [5]. The pulse duration should be sufficiently narrow such that its frequency components can cover the full range of the plasma density. However, it is practically difficult to generate such ultrashort pulse. As an alternative, a technique of frequency conversion with a millimeter-wave mixer has been suggested [6]. This technique permits the use of a commercially available pulse generator where the pulse duration does not have to be extremely short as required in the original concept. For instance, a pulse source of 65ps pulse duration has been employed together with millimeter-wave mixers to provide USPR output signals with frequency components of 33~158GHz [6]. Generally, in the USPR transmitter, the operational frequency range of the chirp is chosen as 6~18GHz simply because it is the widest range at which most microwave components are commercially available. Unfortunately, the power spectrum of a typical pulse generator for such frequency range decreases drastically at higher frequencies [6]. Therefore, it is difficult to use a single chirp for the broadband system.

Instead of a single chirp, in this paper, three chirps are employed to improve the power spectrum of the higher frequency components of the transmitter signal. Detailed explanations on the design of the USPR transmitter based on the three chirp configuration seem to have not been found yet although much of the literature has reported the measurement results of plasma density profiles using USPR. In this regard, this paper analyzes the power spectrum of the three chirp configuration through numerical computation with the primary aim of designing a USPR transmitter relevant to a broadband system.

2. Power Spectrum of a Single Chirp

Fig. 1 shows a schematic diagram of the USPR system in the simplest form. Here, only a single waveguide/horn assembly is required to both transmit and receive the USPR signals. By separating different frequency components of the reflected signal and performing time-of-flight measurement for each frequency component, it is possible to obtain the electron density profile with a single pulse.

In the transmitter, a pulse generator (Model: Picosecond Pulse Lab 3500c, peak amplitude: 5V, pulse duration: 65ps) is used as the pulse source. A single waveguide or a set of waveguides can be used to transform the pulse into chirped waveforms. As a result, low cost microwave amplifiers can be utilized to increase the energy of the transmitter signal. This is to say, the chirped waveform of a pulse signal makes it possible to significantly improve the signal-to-noise ratio (S/N) of the USPR signals.

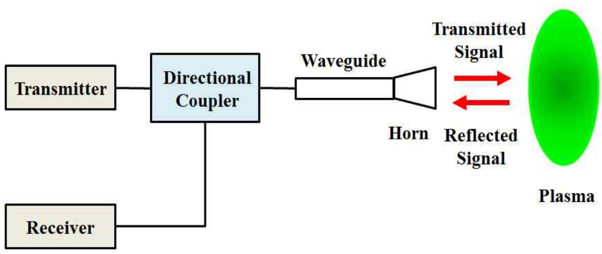

Fig. 1. Schematic diagram of the monostatic configuration of the USPR system

One of the most essential factors to determine the performance of USPR is the power spectrum of the chirp. For the design of the transmitter, therefore, it is important to theoretically analyze the power spectrum of the chirp. If the pulse is Gaussian, the chirped waveform of the pulse propagating along the z-direction through a rectangular waveguide can be expressed for $t \ge L/c$ (t is time, L is the waveguide length, and c is the speed of light in vacuum) as follows [7-8].

$$E(z,t) = A(t) e^{-\frac{\sigma^2 \omega_s^2}{2}} \cos\left(\frac{\pi}{4} + \omega_c t \sqrt{1 - \left(\frac{z}{ct} \right)^2} \right) \tag{1}$$

where

$$A(t) = \left[\frac{z^2 \omega_s^3}{2\pi c^2 t^3 \omega_c^2} \right]^{\frac{1}{2}} \tag{2}$$

$$\omega_s = \frac{\omega_c}{\sqrt{1 - [z/(ct)]^2}} \tag{3}$$

Here, σ is a parameter to determine the pulse duration and ω_c is the cut-off frequency of the waveguide. Fig. 2 illustrates an example of the chirp computed from Eq. (1) when the cut-off frequency and length of the waveguide are 5.8GHz and 0.6m, respectively. Eight numerical band-pass filters (center frequencies: 6.1, 7.8, 9.5, 11.2, 12.9, 14.6, 16.3, 18GHz) are used to measure the power spectrum of the chirp. Fig. 3 shows the measurement result. Here, the peak power can be calculated as

$$P = 20 \log \frac{E_{max}}{0.31618} \text{ dBm} \tag{4}$$

The constant power spectrum of the chirp regardless of frequency is ideal to generate the best transmitter signal. However, the power spectrum decreases significantly after 10GHz as can be seen in Fig. 3. The maximum deviation of the power spectrum is greater than 30dBm over a frequency range of 6~18GHz. Further, the insertion losses of most microwave components at higher frequencies increase dramatically compared to those at lower frequencies. Therefore, the transmitter based on a single chirp cannot be used for the broadband USPR.

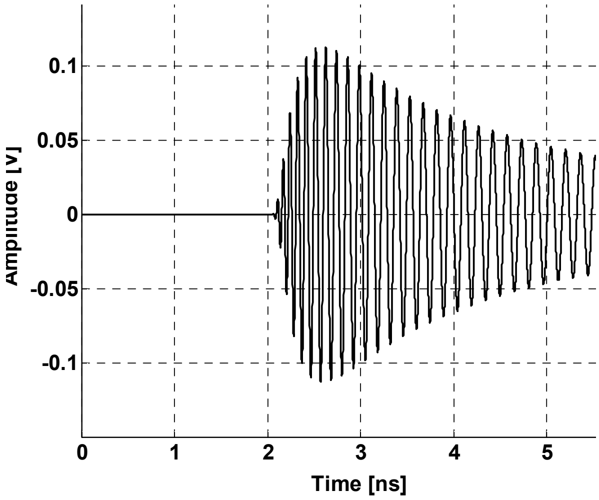

Fig. 2. Chirped waveform transformed from a 5V, 65ps duration Gaussian pulse

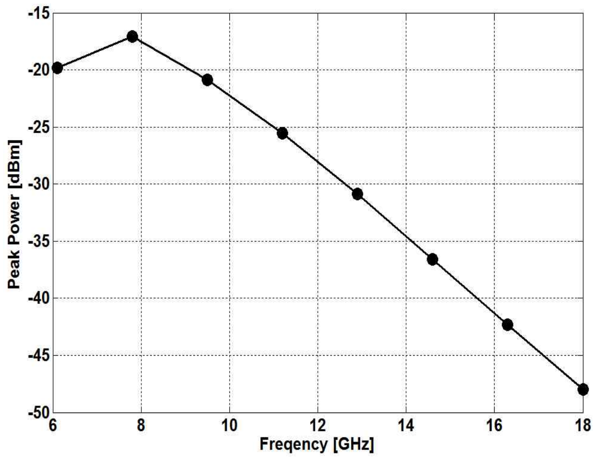

Fig. 3. Power spectrum of the chirp in Fig. 2

3. Improvement of Power Spectrum using the Three Chirp Configuration

In order to maintain an acceptable measure of S/N at higher frequencies, a microwave amplifier can be used to increase the power at higher frequencies. Before applying the amplifier, it is necessary to separate the higher frequency components from the chirp. Otherwise, the power at lower frequencies can be also amplified at the same time. The method to selectively amplify the power at higher frequencies is to split the pulse into two or three chirps using waveguides. Thus, it is possible to employ amplifiers only in the section of the higher frequency chirp. In this paper, three waveguides are utilized rather than two waveguides to further increase the energy content of the chirp at the higher frequencies (16~18GHz).

Fig. 4 depicts a simple configuration to make a three chirp output from the transmitter. Here, the pulse is divided into three chirps using two power dividers and three different cut-off frequency waveguides. For convenience, three chirps are called low frequency (LF: 6~10GHz), middle frequency (MF: 11~15GHz), and high frequency (HF: 16~18GHz) chirps. Two 2-way switches can be used to sequentially transmit LF, MF and HF chirps into the plasma. Figs. 5, 6 and 7 are numerical computation results of LF, MF and HF chirps, respectively. Note that the cut-off frequencies of the three waveguides are set to be 5.8, 11 and 16GHz.

To determine the amplification gain required for the higher frequency components, the power spectra of the three chirps are measured by the numerical band-pass filters mentioned previously. Measurement results are shown in Fig. 8. Here, black circles denote the power spectra of the three chirps before amplification. As can be seen, the difference of the power spectrum between LF and MF (or HF) chirps is approximately 17 (or 30)dBm. Therefore, the amplification gain of the MF (or HF) chirp must be 17 (or 30)dB to accomplish a power spectrum of similar magnitude (red circles) over the

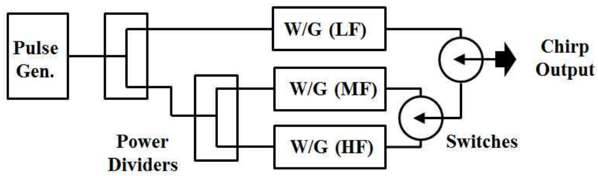

Fig. 4. Schematic diagram of splitting the pulse into three chirps using power dividers and waveguides

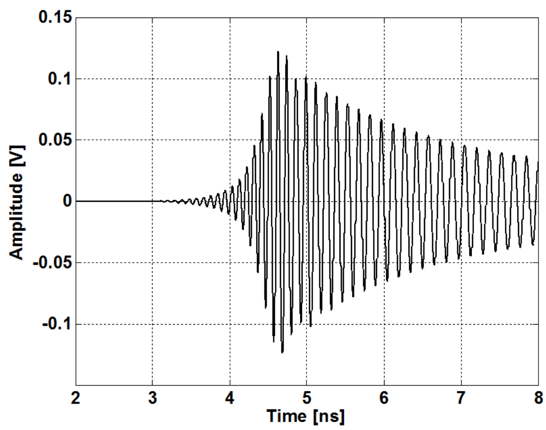

Fig. 5. Chirped waveform of LF (6~10GHz)

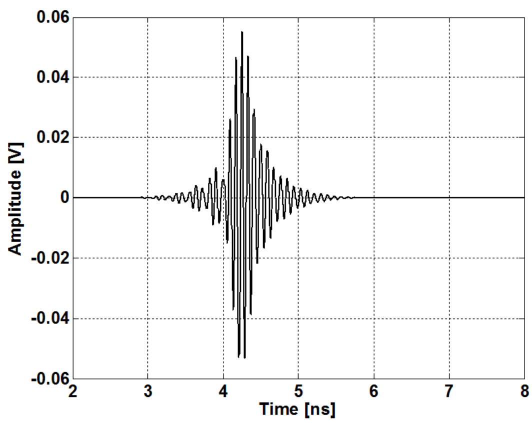

Fig. 6. Chirped waveform of MF (11~15GHz)

entire frequency range. Additional amplifiers can be employed in the sections of MF and HF chirps to increase the power spectra of these chirps to the necessary level while the original LF chirp becomes a portion of the final transmitter output.

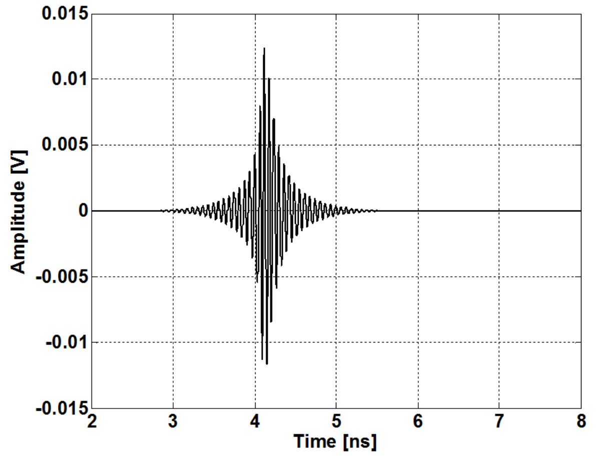

Fig. 7. Chirped waveform of HF (16~18GHz)

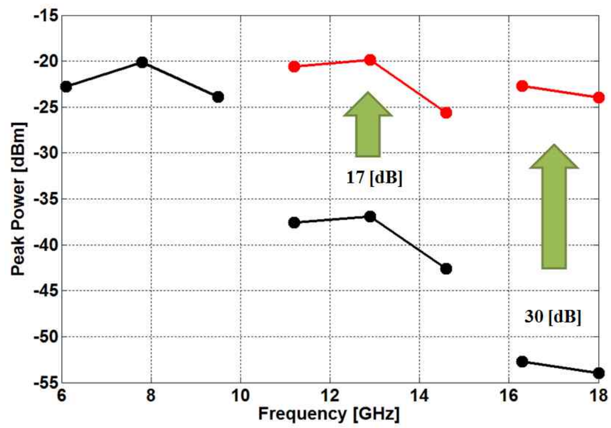

Fig. 8. Power spectrum of three chirps

4. Three Chirp Configuration for a Broadband USPR Transmitter

The concept of the three chirp configuration can be used for the design of the transmitter of a broadband USPR system. An example of the transmitter is shown in Fig. 9. Here, it is assumed that the USPR system can provide the output signals to cover the cut-off frequencies of 33~158GHz as required in Ref. [6]. These frequencies correspond to the peak electron densities of 0.5~$3x10^{14}cm^{-3}$.

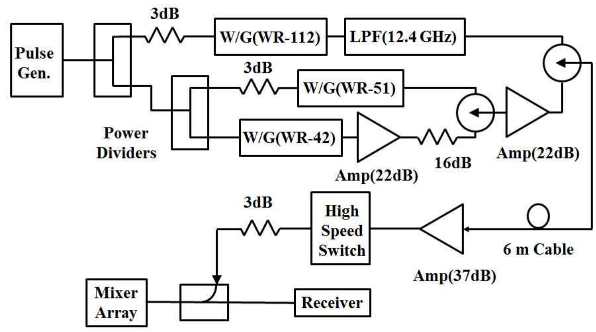

Fig. 9. Schematic diagram of the USPR transmitter for a broadband system using three chirps

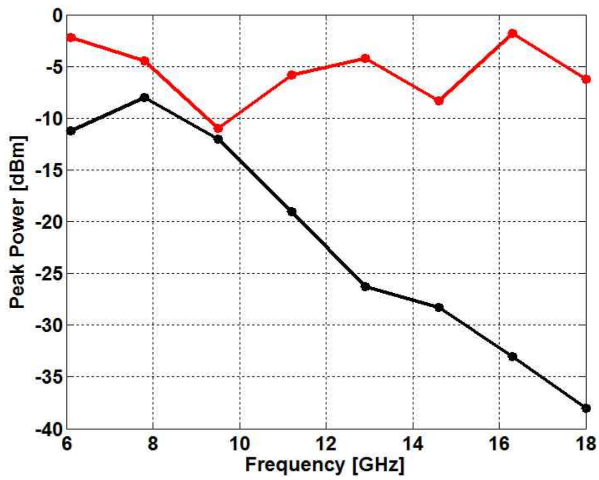

Fig. 10. Power spectra of the USPR transmitter signals for single chirp and three chirp configurations.

WR-112, WR-51 and WR-42 waveguides are chosen to yield LF, MF and HF chirps, respectively. Two amplifiers are employed to increase the powers of the MF and HF chirps. The use of attenuators is inevitable because amplifiers are limited by their peak input power capability. The duration of each chirp is controlled by the high speed switch. By adjusting the cable lengths in the waveguide sections, it is possible to make the durations of the three chirps identical. Fig. 10 shows the experimental results of the transmitter power spectra measured for both the three chirp and single chirp configurations. In this case, the chirp length is set to be approximately 4 ns. In comparison with the single chirp, the three chirp configuration shows remarkable improvement especially at the higher frequencies (>10 GHz).

5. Conclusion

Numerical computations were performed to transform the pulse into the chirped waveform. The power spectrum of the chirp was measured using eight numerical band-pass filters. The power spectrum of a single chirp decreases drastically as frequency increases above 10GHz. The three chirp configuration was suggested to selectively amplify the power spectrum at higher frequencies. Based on the computation results, the three chirp configuration was applied to the design of the transmitter relevant to a broadband USPR system. It was found in the experimental measurement that the three chirp configuration can remarkably improve the power spectrum at higher frequencies.

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◇ 저자소개 ◇

Young-Su Roh

Roh received his B.S. and M.S. degrees in Electrical Engineering from Seoul National University in 1984 and 1986, respectively. He received a Ph.D. degree in Applied Science from the University of California, Davis in 2001. From 1988 to 1996, he worked at the Korea Electricity Research Institute. He is now an associate professor of the Department of Electrical Engineering at Soongsil University. His research fields are plasma physics, nuclear fusion, and electrical discharges.