Development of Terahertz Pulse Wave Diagnostics for a Magnetized Fusion Plasma Reactor*)

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Terahertz wave diagnostics have been developed for current and future high-temperature and high-density fusion plasma measurements. Since the combined system of a reflectometer and a delayometer requires a wide-band frequency source for the density profile measurements, a terahertz pulse is a possible candidate. A test system using terahertz time-domain spectroscopy has been constructed to develop the diagnostics. The system utilizes a femtosecond fiber laser as a pumping source and a bow-tie-type photoconductive antenna as a THz wave emitter. An output THz pulse with a frequency of up to 2 THz has been obtained. Some investigations involving measurement of the refractive index of a test material are performed, and the transmission dispersion effects of an optical fiber are determined.

Keywords: THz-TDS, fusion plasma diagnostics, electron density, reflectometry, delayometry

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1. Introduction

In the future burning plasma experiments, electron densities will be quite high, on the order of 10^{22} m^{-3}. In strong radioactive and high-density fusion plasma, robust diagnostic techniques involving electromagnetic waves, such as radar reflectometry, will be expected to measure the electron density profile and its fluctuation. The desired frequencies reach the terahertz regime (0.1 - 10 THz) [1]. Figure 1 shows the estimated characteristic frequencies in a future Heliotron-type DEMO reactor (FFHR-d1 [2]). Therefore, we need to develop THz wave diagnostics for fusion plasma experiments. Recently, terahertz wave technologies have attracted much interest worldwide in various fields such as physics, biology, astronomy, information, and communication science. There are several techniques for these applications. Among them, THz time-domain spectroscopy (THz-TDS) has several attractive features [3–5] because can obtain broadband spectral information, covering from sub-100 GHz to a few tens of THz. Some observations have been already carried out in low-temperature plasma experiments [6, 7]. If this type of pulsed THz wave is used for burning plasma, we can obtain measurements of several plasma parameters. Especially, simultaneous measurements of the electron density profile by reflectometry and the line-integrated density by

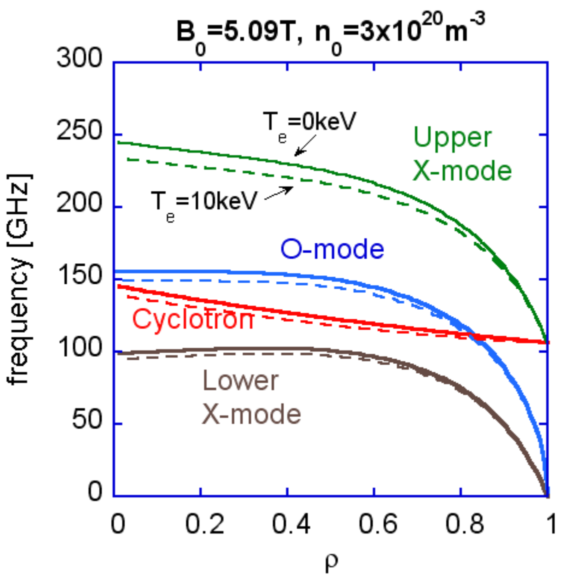

Fig. 1 Radial profile of characteristic frequencies in a typical plasma parameter of helical DEMO. “O-mode” means ordinary wave cut-off frequency that is the electron plasma frequency. “Cyclotron” means the electron cyclotron frequency. “Upper and Lower X-mode” mean the right-hand and left-hand extraordinary wave cut-off frequencies. Dotted line includes the higher temperature effect (relativistic effect).

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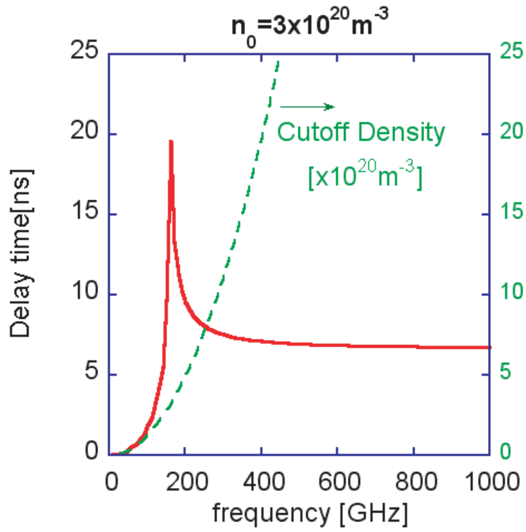

Fig. 2 Delay time of the launched THz wave as a function of frequency. Here, the estimated density profile is the same in Fig. 1.

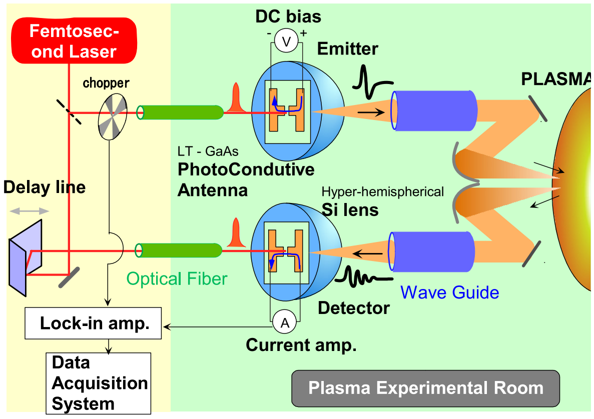

Fig. 3 Schematic drawing of THz reflectometer/delayometer system.

delayometry [8] will be possible. When the electromagnetic wave pulse is emitted into the plasma, the group delay (τ_{pe}) that occurs is expressed as

$$\tau_{pe} = \frac{2}{c}\int_{-a}^{a} \frac{1}{\sqrt{1-\dfrac{\omega_{pe}^2(x)}{\omega_0^2}}} - 1\,dx. \tag{1}$$

Here ω_{pe} is the electron plasma frequency, ω_0 is the probe frequency, c is the speed of light, and a is the plasma radius. The calculated delay time is plotted as a function of probe frequency (Fig. 2). In this graph, the plasma parameters are the same as those for Fig. 1 and a = 1 m. In the low frequency range (< 160 GHz), the system works as a reflectometer, while in the high frequency range (> 160 GHz), it works as a delayometer. This scheme is quite convenient and robust.

At present, however, the high power sources and the high time resolution detectors needed for the terahertz regime are inadequate for fusion plasma measurements. For applying this technique to the future burning plasma, it is necessary to investigate about the type of components to be developed. Therefore, it is necessary to clarify these points for future installation. In addition to selecting a diagnostics method for the DEMO reactor, we need to demonstrate a proof-of-principle of current high-temperature plasma experimental devices.

Recently, a THz-TDS test system was developed at the National Institute for Fusion Science (NIFS). This system will be applied to the Large Helical Device (LHD) plasma to demonstrate proof-of-principle. Before that, however, some technical issues must be tested. In particular, the transmission of the THz wave is an important issue because THz range waves are easily absorbed by humidity in air. To avoid this effect, one method is to use a dry air-filled or vacuum-filled waveguide. However, it is not easy to retrofit such waveguides in the LHD. Another method is to locate the THz generator near the plasma device and transmit the pumped laser light through an optical fiber. This concept for the system was originally suggested in Ref. 9.

A more detailed design is considered here. The system called as the THz reflectometer/delayometer is shown in Fig. 3. The system consists of a femtosecond laser as a pulse source, photoconductive (PC) antennas as a THz generator and detector, an optical fiber, and some optics. This system relies on the performance of the optical fiber. However, there is no guarantee of good performance because a normal optical fiber is intended to be used with a continuous wave (CW). The optical fiber also has its own dispersion coefficient. If a pulse wave, which has broad frequency components, is traveling through an optical fiber, the wave is dispersed and stretched. We need to determine the extent of this effect experimentally.

The THz-TDS test system is briefly described in Sec. 2. The characteristics of optical fiber transmission are expressed in Sec. 3. Then, we summarize in Sec. 4.

2. THz-TDS Test System

A photograph of the THz-TDS test system is shown in Fig. 4. A mode-lock fiber laser (Menlo T-light 780), with a wavelength of 780 nm, a pulse width of around 120 fs, and a repetition rate of 50 MHz, is used for excitation. In addition, this laser can simultaneously emit 1.5 µm light. We can use both laser lights for certain system tests. The output of the laser is focused on the THz radiation antenna, which is a bow-tie-type PC antenna made on low-temperature-grown GaAs (Hamamatsu G10620-12). Part of the laser output is directed to the delay section for optical sampling detection. For fast scanning of the delay section, a linear motor stage with a speed of 1000 mm/s is used. The excited power of the THz wave is collimated via

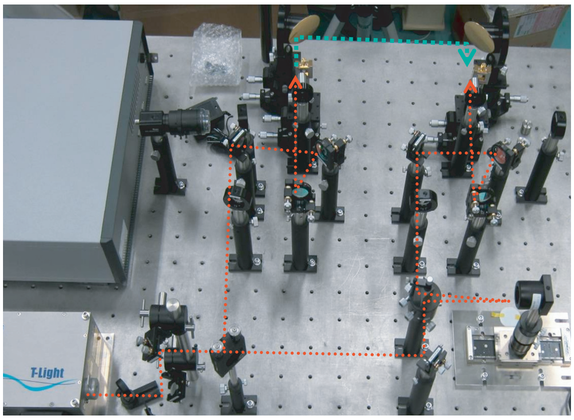

Fig. 4 Photograph of THz-TDS test system.

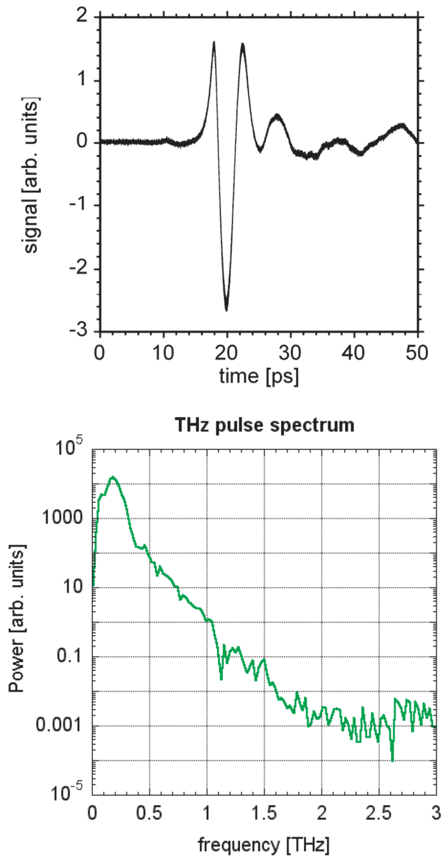

Fig. 5 Detector output signal (upper) and its frequency spectrum (bottom).

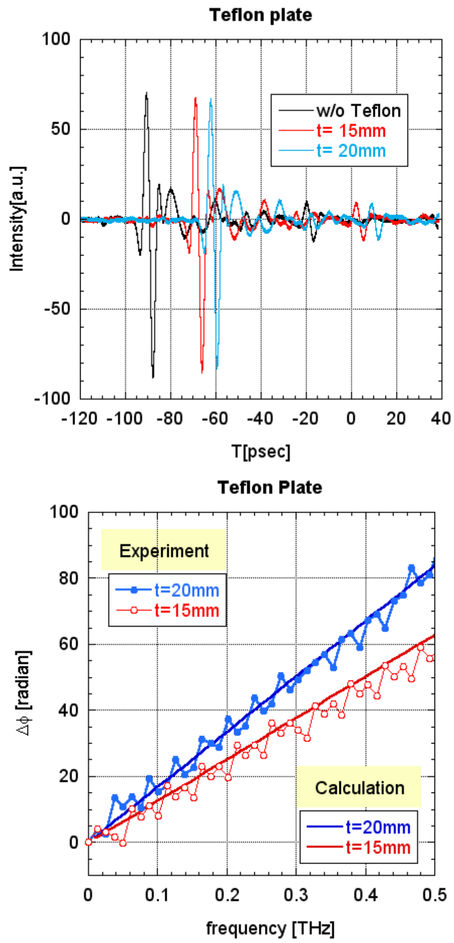

Fig. 6 Waveform of THz pulse penetrating through the Teflon plate (upper). The phase difference ($\Delta\phi$) as a function of the frequency (bottom).

the silicon hemisphere lens and emitted from an off-axis parabolic mirror. The same design of a parabolic mirror is focused on the receiving PC antenna, which is also a bow-tie type. The output of the detector antenna is amplified by a current amplifier (NI LI-76, gain of 10^6 V/A, frequency range of 20 kHz). The signal is directed to a lock-in amplifier to improve sensitivity, and then the time trace of the signal is acquired by a PCI-based analog-to-digital converter.

An example of the THz pulse wave is shown in Fig. 5. Here the femtosecond laser output is around 40 mW, the bias voltage of the emitting antenna is 10 V, and the lock-in amplifier sensitivity is 10 mV. The shape of the frequency spectrum is that of a typical bow-tie antenna. The output frequency components are up to 2 THz in this example.

When a Teflon plate is placed between the emitter and detector parabolic mirrors, the shape of THz pulse is modified and delayed, as shown in Fig. 6. The phase shifts, as a function of the emitted frequency, are obtained for two plate widths. These values show good agreement with calculated values, which assume a refractive index of 1.4. Therefore, this THz-TDS can measure refractive index, and it can be used to perform an electron density measurement in plasma.

3. Dispersion Test of Optical Fiber

For the proof-of-principle, a high-temperature plasma experiment should be performed. For the experiment, the pumped femtosecond pulse should be delivered via an optical fiber. We tested an optical fiber designed for the telecom band (~1.5 μm wavelength). Recently, studies showed

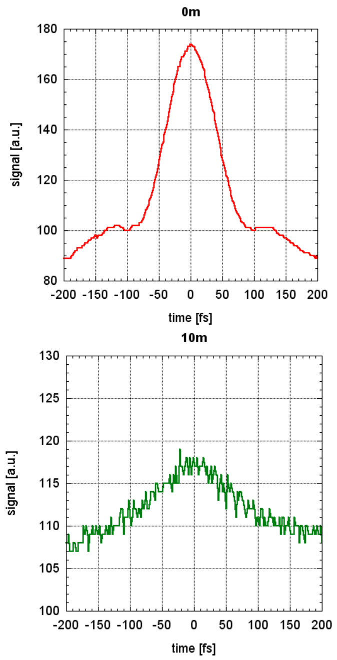

Fig. 7 Waveform of auto-correlated signal w/o fiber (top) and with 10 m fiber (bottom).

that this telecom band pulsed light can be used for the THz-TDS system [10,11]. However, the general purpose single-mode fiber (categorized in ITU-T G.652 B) for telecommunication has quite a large level of dispersion—around 20 ps/nm/km at a wavelength of 1.5 µm. It leads to a large frequency chirp, and the fiber cannot be used for the transmission of the pumped light. The dispersion-shifted single-mode fiber (ITU-T G.653 category) is one solution because the dispersion value of this fiber at 1.5 µm is almost zero, and transmission losses are less than 0.22 dB/km.

Several lengths of the dispersion-shifted optical fiber (Fujikura FutureGuide DS), with dispersion of less than 3.5 ps/nm/km and a dispersion slope of less than 0.085 ps/nm^2/km, as per the catalog, were tested to observe the dispersion effect. For these tests, the pumped laser pulse width was around 100 fs at a wavelength of 1.5 µm. This corresponds to a wavelength broadening of around 200 nm. The laser light is forced to chirp regardless of the dispersion-shifted fiber. Figure 7 shows the waveform measured by an autocorrelator before and after passing through the fiber. The shape of the femtosecond laser pulse becomes broader. The pulse width is plotted as a function of the fiber length in Fig. 8. The experimental value almost agrees with the estimate of around 400 fs at 100 m. Here we used the dispersion listed in the catalog. It should be noted that the catalog value was measured by a CW wave. We can conclude that the dispersion effect can be calculated, and some methods of dispersion compensation, such as using an optical grating, can be designed. We will apply such a method to the LHD plasma experiment in the near future.

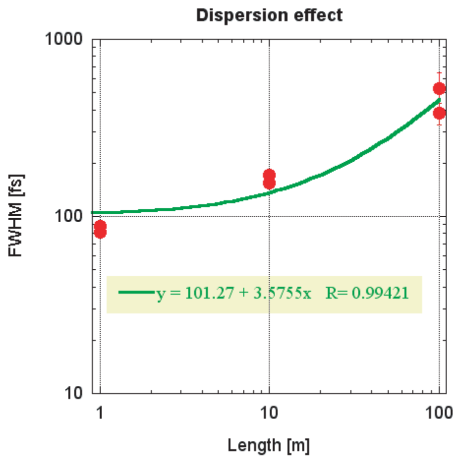

Fig. 8 Pulse width via the optical fiber which lengths are 1, 10, and 100 m.

4. Summary

For future fusion plasma studies, a THz region diagnostic system is needed. We determine that a modified THz-TDS system is a useful tool as a combination of reflectometer/delayometer for electron density measurements. A THz-TDS test system has been constructed at NIFS, and THz radiation can be obtained. Material and optical fiber transmission characteristics tests have been carried out using this TDS system. The dispersion effect of a pulsed wave has been found for the first time. After demonstrating this THz-TDS system in LHD plasma, it will be available for a DEMO reactor.

Acknowledgments

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