Multifrequency channel microwave reflectometer with frequency hopping operation for density fluctuation measurements in Large Helical Device[a)]

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In order to measure the internal structure of density fluctuations using a microwave reflectometer, the broadband frequency tunable system, which has the ability of fast and stable hopping operation, has been improved in the Large Helical Device. Simultaneous multipoint measurement is the key issue of this development. For accurate phase measurement, the system utilizes a single sideband modulation technique. Currently, a dual channel heterodyne frequency hopping reflectometer system has been constructed and applied to the Alfvén eigenmode measurements. © *2010 American Institute of Physics.* [doi:10.1063/1.3478747]

I. INTRODUCTION

Simultaneous multipoint measurement of fluctuations provides knowledge of the nature of a magnetic confinement plasma, such as magnetohydrodynamics, turbulence, and so on. For constructing the multipoint measurement system of microwave reflectometry, there are several techniques. One technique utilizes number of different fixed frequency sources.[1–3] Each frequency component provides the local information of the plasma at the corresponding cutoff surface. However, measurable points are limited by the number of sources. Another technique utilizes an impulse which has broadband frequency components.[4,5] The frequency component of the impulse is continuous and we can select and use the desired frequency component. However, the temporal resolution is limited by the pulse repetition rate and therefore the application of fluctuation measurements is concentrated on low frequency phenomena. Recently, a new operation technique has been developed, that is called frequency hopping.[6–8] It is a sort of frequency scanning operation. The source frequency is swept step by step in the whole frequency range. This technique allows the frequency selection widely in the desired frequency range on the assumption that the plasma condition is steady during a frequency scanning period. However, this technique is not a strictly simultaneous measurement and further development is needed. One example of the simultaneous measurement system is a compound system which is constructed with two or more frequency hopping systems.[9] Another example is the frequency modulation system.[10]

We have been developing a multifrequency channel microwave reflectometer system in the Large Helical Device (LHD).[11] The system includes a broadband frequency-tunable source, which has the ability of fast and stable hopping operation. For constructing a multichannel system, the system is upgraded from the previous one channel V-band frequency hopping system.[12] This one channel system utilized a single sideband (SSB) modulation technique which was applied for accurate heterodyne phase detection. The system with SSB modulation technique becomes simple because it requires only one microwave source. Recently, high performance SSB modulators are available in the wide-band frequency range and its sideband rejection achieved around −20 dB.[13] The concept of a simultaneous multichannel system is shown in Fig. 1. When the carrier frequency (f_0) is changed in the hopping operation, the probe frequency of f_0-f_{m1} [in the case of lower sideband (LSB) modulation with a modulation frequency of f_{m1}] is followed as HOP1 shown in the right of Fig. 1 The additional modulation sources (f_{m2} and f_{m3}) generate the corresponding shifted frequency components and then each frequency component can be synchronized during the hopping operation. Currently, dual separate modulation sources have been applied in LHD and we try to measure the fluctuation amplitude of the Alfvén eigenmode. In this paper, we describe the dual channel frequency hopping reflectometer system and present some characteristics of the SSB modulation technique in Sec. II, and preliminary LHD plasma experimental results in Sec. III, and then summarize the present results in Sec. IV.

II. DUAL SINGLE SIDEBAND MODULATION FREQUENCY HOPPING REFLECTOMETER SYSTEM

The schematic of a dual channel frequency hopping V-band reflectometer system is shown in Fig. 2. A microwave synthesizer (Anritsu Co. Ltd., model MG3692B) is used as a source with a low phase noise. The utilized frequency range is from 12.5 to 18 GHz and its output frequency is easily changed by external general purpose interface bus remote control. For direct phase measurement, SSB modulation is utilized. The source output is split into probe

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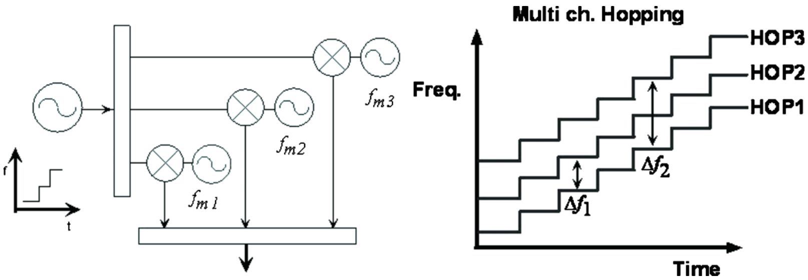

FIG. 1. (Color online) Concept of simultaneous multi-frequency channel frequency hopping operation. Schematic of system design (left) and operation frequency (right). Here, $\Delta f_1 = f_{m2} - f_{m1}$ and $\Delta f_2 = f_{m3} - f_{m1}$.

and reference signals. Two SSB modulators are used for two spatial position measurements. Each SSB modulator driven by 220 (f_{m1}) and 2.5 (f_{m2}) MHz quartz oscillators shifts the frequency of the probe signal for the heterodyne I-Q detection. The combined frequency component of both modulator outputs is shown in Fig. 3. Here, the carrier frequency is 14.0 GHz. The LSB components of $(f_0 - f_{m1})$ and $(f_0 - f_{m2})$ are used. The suppression levels of the carrier frequency (f_0) and image sidebands of $(f_0 + f_{m1})$ and $(f_0 + f_{m2})$ are less than −20, −17, and −10 dB, respectively. These suppression levels are similar to those of the previous one channel system. The combined signal is quadruple followed by an active multiplier to bring the launching frequency up to 50–72 GHz (V-band). Then, the frequency difference (Δf) between two probing microwaves is about 0.9 GHz. The modulated microwaves launch from the outboard side opposite the major radius direction on the equatorial plane. The polarization of the launched wave is set to the extraordinary mode and the right-hand cutoff layer is used as the reflecting surface. Each reflected wave is received and mixed with a reference wave and each intermediate frequency (IF) signal is amplified and discriminated by each bandpass filter (BPF). The pass frequency component of each BPF is 880 ± 20 and 10 ± 2 MHz, respectively, and the rejection level is less than −40 dB. Thus, the BPF can eliminate additional sidebands and also the carrier frequency component. Each frequency spectrum of the BPF output signal is shown in Fig. 4. These signal amplitudes are sufficient to detect the fluctuation phase. Then, these signals are led to I-Q detection. The output signals of the I-Q demodulator, which are described by $A \cos \phi$ and $A \sin \phi$, are acquired by a real-time data acquisition system[14] based on a compact peripheral component interconnect digitizer and the sampling rate is usually 1 MHz during the whole plasma discharge. Therefore, we can obtain a high signal-to-noise ratio for accurate phase measurements.

III. EXPERIMENTAL RESULTS

An example of a preliminary LHD experiment utilizing this dual channel hopping reflectometer system for the radial distribution measurement of Alfvén eigenmodes is shown in Fig. 5. The experiment is carried out on a discharge where the axial magnetic field strength is 2.0 T, the averaged electron density is under 0.2×10^{19} m^{-3}, and three tangential neutral beams are injected with constant power. While the plasma condition is mostly steady-state and the fluctuation frequency stays constant, the probe frequency is swept from 48 to 60 GHz in 1 GHz step sizes with 20 ms duration. Figure 5 shows the reflectometer output, the hopping carrier frequency, and the frequency spectrogram of two IF components. We can see a coherent frequency component of around 90 kHz in both channels. The amplitude of this coherent frequency component is plotted as a function of the launching microwave frequency shown in Fig. 6. Here, the amplitude is estimated by using a digital bandpass filter whose frequency is set from 80 to 100 kHz. Also, the amplitudes are normalized by the maximum value of each channel to compare each profile. Since the density fluctuation level is not completely steady in the plasma discharge, there are still small differences. However, we think that both distributions of the fluctuation power are almost similar and simultaneous dual channel operation is useful. It consequently results that the frequency hopping step number in one sweep period and the sweep time itself can be reduced for the radial distribution measurements.

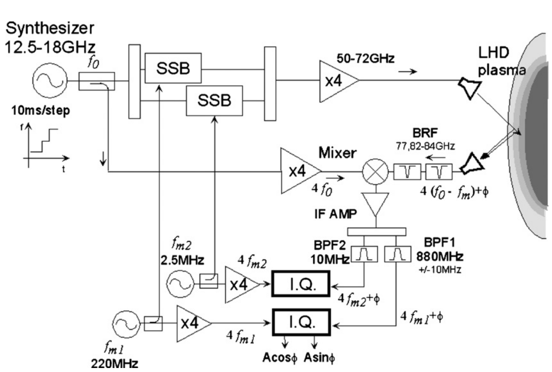

FIG. 2. Schematic of two channel V-band frequency hopping microwave reflectometer. f_0 is carrier frequency (12.5–18 GHz), f_{m1} and f_{m2} are modulation frequencies (220 and 2.5 MHz), and ϕ is the phase difference of the plasma fluctuation component.

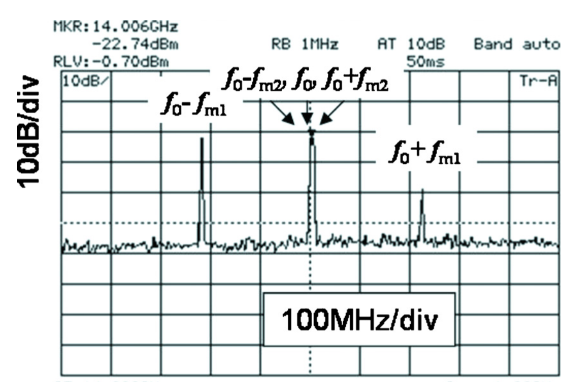

FIG. 3. (Color online) Frequency spectrum of the combined signal of two SSB modulator outputs in the LSB operation. The carrier frequency (f_0) is 14.0 GHz and the modulated frequencies are 220 MHz (f_{m1}) and 2.5 MHz (f_{m2}).

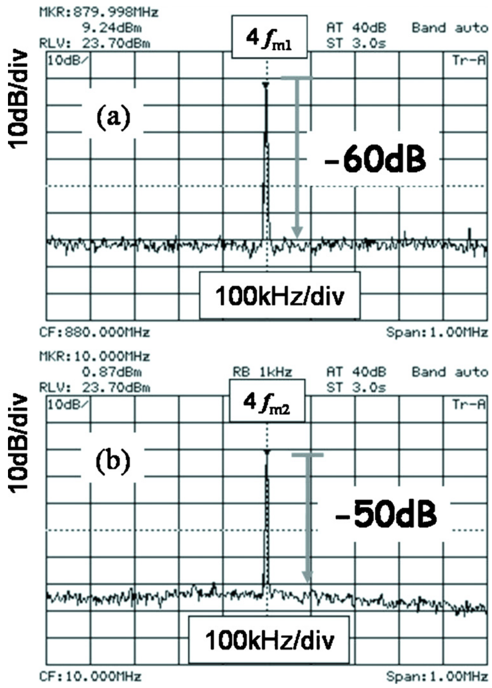

FIG. 4. (Color online) Frequency spectrum of IF signals. Each center frequency is (a) 880 MHz ($4f_{m1}$) and (b) 10 MHz ($4f_{m2}$), respectively.

IV. SUMMARY AND FUTURE WORKS

A multifrequency microwave hopping reflectometer system has been developing in the LHD and currently a dual channel system is constructed for the electron density fluctuation profile measurement. The system uses a SSB modulator for accurate direct phase measurement. In the system test, the signal-to-noise ratio is high enough for fluctuation measurements. In the preliminary LHD plasma experiment, energetic particle driven Alfvén eigenmodes can be observed and similar distributions can be obtained by both channels.

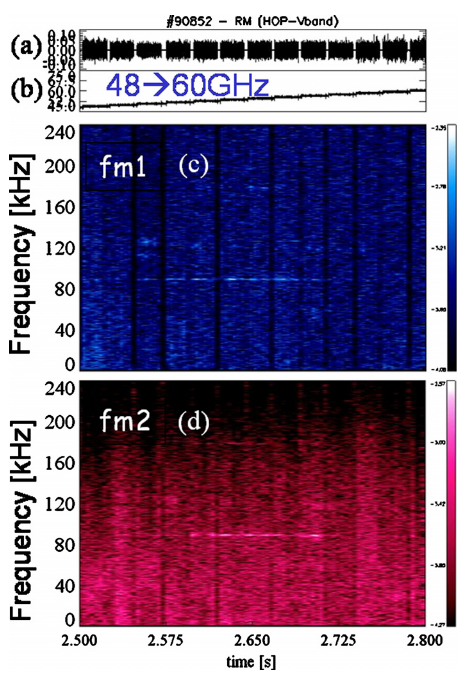

FIG. 5. (Color online) Example of the plasma experiment. Temporal behavior of (a) reflectometer signal, (b) launching carrier frequency, and frequency power spectrogram of both detector outputs of (c) f_{m1} signal and (d) f_{m2} signal.

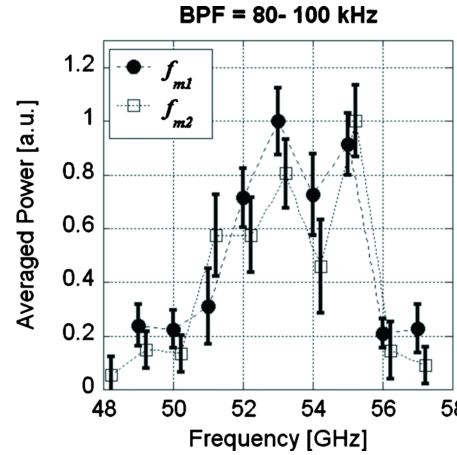

FIG. 6. (Color online) Fluctuation amplitude as a function of the launching microwave frequency. Here, the frequency component of the fluctuations, which is from 80 to 100 kHz, is plotted. Circles are f_{m1} signal and squares are f_{m2} signal.

For more improvements, we have started to develop and construct some other techniques. One is a frequency modulation system,[10] another is a comb frequency generator system. These new techniques can be used to obtain wide multifrequency components. For the present, the output power is fairly small for LHD plasma experiments. Therefore, it will contribute to physics studies in the near future.

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