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Design and implementation of an interferometer with high stability and wide dynamic range for steady-state plasmas

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A B S T R A C T

Microwave interferometry is an effective and reliable way to measure line integrated plasma electron density. An extremely low noise heterodyne interferometer has been developed for routine operation in Sino-UNIted Spherical Tokamak (SUNIST) and acts as the prototype design of a microwave inteferometer for Experimental Advanced Superconducting Tokamak (EAST) in the near future. The system has been designed with optimum frequency deduced from detailed calculation in real geometry and discharge parameters. In contrary to traditional heterodyne interferometers, the application of a single sideband modulator (SSBM) eliminates the necessity of the second millimeter wave (MMW) oscillator, which averts the intermediate frequency (IF) stability problem aroused by the two high frequency oscillators in the traditional heterodyne configuration. A pair of specially designed spot focusing antenna is also applied to boost the signal to noise ratio (SNR), whose near field scan data displays excellent focusability. The bench test data and plasma electron density measurement results from SUNIST discharges consistently show excellent performance of the interferometer, which is expected to be suitable for steady-state plasma experiments due to the high stability.

1. Introduction

Plasma electron density is one of the most important parameters in Tokamak plasma researches. Among the various approaches to measure the plasma electron density, interferometry has been long regarded to be the most reliable due to the non-intrusive feature and the operation stability. Heterodyne techniques have been widely used in interferometry nowadays since it reduces the need to deal with the amplitude or DC component of the signal, and the phase ambiguity problem no longer exists in this way [1].

A typical heterodyne interferometer for Tokamak plasma consists of two millimeter wave sources with a small frequency difference IF. The two MMW sources are mixed by a balanced mixer after one of them passes the plasma to form a phase modulated IF signal. Besides, a reference IF signal is also generated by mixing the two MMW sources directly. The two IF signals are fed into a I/Q demodulator to extract the phase difference [2]. Once the phase difference is obtained, the line integrated electron density can be directly deduced by the following equation [3].

$$\Delta\varphi = \frac{e^2}{4\pi c^2 \varepsilon_0 m_e}\lambda \int_0^L n_e dl = 2.82 \times 10^{-15}\lambda L\overline{N}, \tag{1}$$

where $\Delta\varphi$ is the total phase change induced by the plasma. m_e and e are the electron mass and charge, respectively. λ is the probing beam wavelength, L is the length of the beam path inside the plasma. c is the vacuum light speed, ε_0 is the vacuum dielectric constant, and $\overline{\mathrm{N}}$ is the line-averaged electron density in unit m^{-3}.

However, as all MMW sources have limited frequency stability, the frequency fluctuations from the two MMW sources would superpose in the mixer's output and therefore introduce frequency noise in the IF signals, which would be more pronounced since IF typically has a much smaller frequency. Such fluctuations in IF frequency would adversely affect the phase extraction and deteriorate the density evolution signal. A feasible idea to ameliorate this problem is to alter one of the two millimeter wave sources by an IF source and to generate the missing MMW signal by a SSBM [4,5]. An SSBM outputs a signal with sum frequency of its two inputs, $f_{LO} + f_{IF}$, where f_{LO} and f_{IF} are the frequency of the MMW source and IF source respectively. So the inputs of the mixer who collects the plasma induced phase signals would be

$$S_1 = A_1 \cos[2\pi(f_{LO} + f_{IF})t + \Delta\varphi], \tag{2}$$

$$S_2 = A_2 \cos(2\pi f_{LO} t), \tag{3}$$

where $\Delta\varphi$ is the phase shift induced by the plasma. Therefore, the mixer's output would be

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$$P_{plasma} = S_1 \cdot S_2 = A\cos(2\pi f_{IF}t + \Delta\varphi), \quad (4)$$

where one has neglected the sum frequency term in the product to sum formula due to its high frequency. P_{plasma} is an IF signal with phase shift induced by the plasma. On the other hand, the IF source directly gives a reference IF signal

$$P_{ref} = A'\cos(2\pi f_{IF}t), \quad (5)$$

From Eqs. (4) and (5) we can see that $\Delta\varphi$ can be extracted by an I/Q demodulator directly.

The main advantage of this approach is that, the reference IF signal directly comes from the low-frequency IF source, which has far higher frequency stability and brings in less phase noise. The main difficulty of this approach is to achieve a pure single sideband (SSB) modulation, since the existence of other harmonics also brings about phase noise. In our case, we decided to adopt the SSB modulation way because when ideally modulated, it has the potential of giving better density evolution signal than the conventional design using two MMW sources.

This paper is organized as follows: the detailed design of the system and its inherent advantages are described in Section 2. The bench test on the phase linearity and plasma electron density measurement data are displayed in Section 3. A brief summary is given in Section 4.

2. System design

2.1. Probing beam frequency optimization

The center frequency of the probing beam should be the first concern when designing an interferometer. Generally, the frequency should not be too low due to the refraction problem, which reduces the SNR, while overlarge frequency is also not preferable since it reduces the density resolution and suffers more from mechanical vibrations. To deliberate on the most optimum frequency, a ray tracing calculation is carried out under the real tokamak geometry in SUNIST[6] with plasma cross section parameters obtained from equilibrium reconstruction, and the result indicates that a frequency of about 100 GHz is the most appropriate to exhibit a comprehensively excellent performance [7].

2.2. Configuration

The schematic of the frequency modulated interferometer is shown in Fig. 1. The 17.5 GHz phase locked oscillator (PLO) provides a ~15 dBm output level with high frequency stability and accuracy. The phase noise is −102 dBc/Hz at 10 kHz and the frequency stability is ± 1 ppm. The 160 MHz oven controlled crystal oscillator (OCXO) has a phase noise of −120 dBc/Hz at 100 Hz and the frequency stability is ± 0.1 ppm. These two oscillators with high stability and extremely low phase noise lay a solid foundation for the precision of the whole system.

Both the outputs of the two oscillators are split into two and partly directed into the SSBM with an internal bandpass filter (the filter is displayed in Fig. 1 for ease of interpretation). The filtered SSBM output is a frequency modulated signal of 17.66 GHz, with carrier suppression being 54 dBc and harmonic suppression over 60 dBc. The frequency modulated signal is then pre-amplified and frequency sextupled by a multiplier to form a 105.96 GHz MMW signal, which passes through an isolator and is then emitted to the plasma by a spot focusing antenna. An identical antenna is placed at the opposite vertical window. The received MMW signal reaches the RF port of the mixer via another isolator. The LO input of the mixer is simply the output of a frequency multiplier, whose input is another portion of the 17.5 GHz signal. The preceding attenuator is applied to reduce the input level to the manufacturer prescribed value. A DC block is connected to the mixer's IF port regarding to its susceptibility to DC voltage. This IF signal with phase shifts induced by the plasma is fed into the RF port of a quadrature phase detector, whose LO input is a steady 960 MHz signal generated by the rest portion of the OCXO signal followed by a frequency multiplier. The in phase (I) and quadrature phase (Q) signals are then digitized by a data acquisition system for phase calculation.

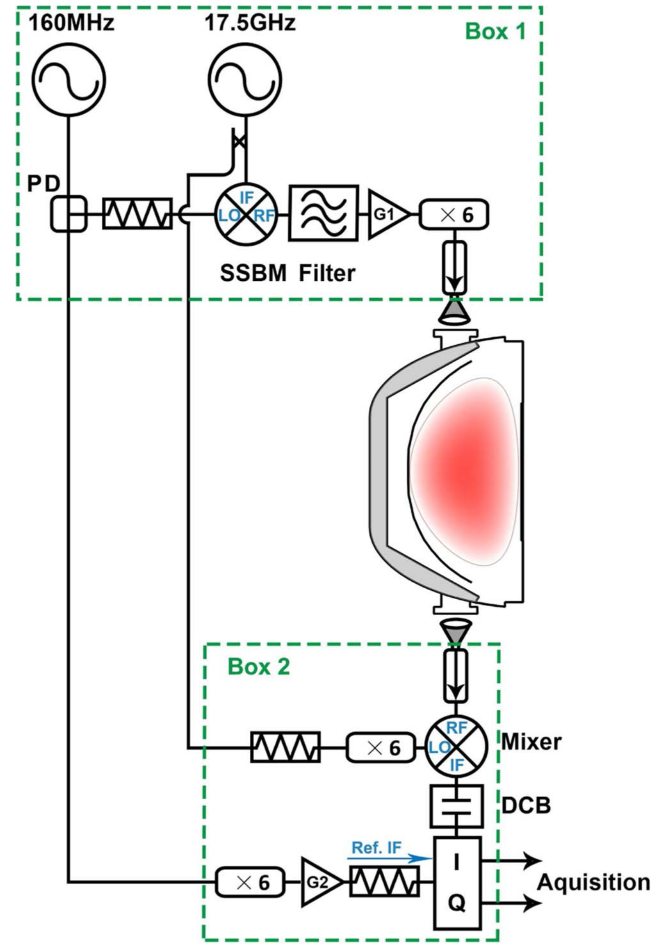

Fig. 1. Block diagram of the interferometer system. PD is the abbreviation of Power Divider and DCB refers to DC Block.

Frequency multiplication and SSB modulation features this configuration from typical heterodyne designs. These two features bring in several advantages. The application of SSB modulation eliminates the necessity of the second MMW source, which ameliorates the IF stability problem aroused by the superposition of the frequency fluctuations from the two high frequency oscillators in the traditional heterodyne configuration. This SSB modulation configuration provides the reference IF signal directly from the OCXO, which boosts the IF stability and brings in absolutely less phase noise. The application of frequency multiplication substantially reduces the two reference signal frequency transmitting between the two cases, falling into the region that is suitable for coaxial cables to do the connection. This avoids the appearance of long waveguides in the system, markedly reduces the unnecessary power loss as compared with that in Ref. 6, and further improves the system's portability. Besides, in such low frequency range (K_u band), narrower SSB modulation is available because shaper passband edges are achievable. The narrower SSB modulation with better mono frequency characteristic reduces phase noise and facilitates the phase demodulation. However, general bandpass filters in W band demands the IF frequency being at least 2% of the LO center frequency due to the poorer frequency selectivity, which is not preferable here. In addition, performing the SSB modulation in the lower frequency band, which can be covered by conventional spectrum analyzers, provides easier approach to the performance test of the SSBM. The performance of the SSBM with an internal bandpass filter is shown in Fig. 2.