DESIGN AND DEVELOPMENT OF 140 GHZ D-BAND PHASE LOCKED HETERODYNE INTERFEROMETER SYSTEM FOR REAL TIME DENSITY MEASUREMENT

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Abstract

A design and development of a 140 GHz phase locked heterodyne interferometer system in which transmitter and receiver are phase-locked by a reference crystal oscillator of 100 MHz has been presented in the paper. This phase locking provides a highly stabilised intermediate frequency (IF) of 2 GHz. The IF signal is further down converted by IQ mixer to generate I & Q signals in form of sine and cosine waves each of frequency 100 KHz. These 100 KHz signals are digitized by 12-bits ADC. The controller uses these signals to generate real time density signal. The interferometer system has a time phase analysis of 2.5 µs and phase error measurement capability of 0.07 radian. The performance of the developed microwave and RF electronics at various stages has been examined in the paper. Also, the overall performance of the phase locking interferometer system with AGC signal is shown. Laboratory tests results and actual results after installation of the system in ADITYA Tokomak at the Institute for Plasma Research, India has been presented.

1. INTRODUCTION

In a Tokomak, plasma density is measured using an electromagnetic wave which experiences a phase shift \( \varphi(t) \) with respect to a reference signal while passing through the plasma column. In millimetre wave spectrum, usually homodyne or heterodyne circuits are used to determine \( \varphi(t) \). In a simple homodyne system, an EM wave with a constant amplitude and angular frequency \( \omega_0 \) is launched onto the plasma by transmitter system. The EM wave transmits through the chord length of the plasma column. The transmitted wave is received by the receiver. The reference and transmitted signals are mixed in a frequency mixer which produces phase signal at its output. This phase signal is the difference of both the input signals at the mixer input and is represented by \( s(t) = a(t) \cos[\omega_0 t + \varphi(t)] \), with the amplitude \( a(t) \) and phase \( \varphi(t) \) that is function of time on the scale \( \omega_0^{-1} \). The frequency \( \omega_r = \frac{d\varphi}{dt} \) is defined as beat frequency or instantaneous Doppler shift of the received signal on the scale \( \omega_0 \). The major problem with a homodyne system is that its dynamic range may be limited by the transmitted AM noise and by the mixer 1/f noise. In heterodyne scheme output of the probing microwave oscillator with frequency \( \omega_1 \approx \omega_0 \) is used as local oscillator (LO) for down shifting the frequency of both the received and the reference signals. Frequency jitters and drifts in the microwave source causes unestablished IF signal. To overcome this problem probing frequency of the source is locked by highly stabilized crystal oscillator to improve the phase noise of the source and overall performance of the system. Phase information of the received signal can then be obtained without any ambiguity with standard numerical techniques using the Quadrature (IQ) phase detection with sine and cosine signals.

At ISSTOK \(^3\) a 100GHz probing frequency is down converted to the 850 MHz IF signal. After that I and Q signals
and phase are obtained by the Quadrature detection scheme. Similarly at MIT [5] in LDX system a 60 GHz frequency is down converted to 70 MHz IF signal and this 70 MHz signal is given to the IQ demodulator and these IQ signal is processed by the same Quadrature detection scheme. Another scheme of phase determination is comparing the zero cross points of the two signals like in K-STAR [7] and at TCBAR [6], with and without plasma, from the time delay of two signals phase can be obtained without any ambiguity.

At Korean Super Conducting Tokomak Advance Research (KSTAR) Tokomak, a 280 GHz signal is down converted to two 60 MHz IF signals and it is further down converted to two 5 MHz signals which is converted to TTL pulses with the help of phase comparator by comparing the time delay between the two signals. So, for determining the phase of plasma signal with the help of the heterodyne system one can use the Quadrature phase detection or time delay method.

The heterodyne interferometer system at IPR is a PLL system and is using the time delay method for phase calculation. A single channel 140 GHz heterodyne interferometer is developed and is discussed in the paper and some primary result of the system with Aditya Tokomak plasma shots are presented.

2. HETERODYNE WORKING PRINCIPLE

The dispersion relation for the ordinary mode of propagation i.e., wave propagation perpendicular to magnetic field of the plasma with its electric field parallel to the same magnetic field is given by [2][3],

\[ w^2 = w_{pe}^2 + c^2 k^2 \]

‘k’ is the wave vector and ‘c’ is speed of light in vacuum. Refractive index can be written as:

\[ n_f = \frac{c}{v_{ph}} = \frac{k c}{w} \]

From equation (1) and (2) Refractive index for ordinary wave can be written as

\[ n_{f0} = \sqrt{1 - \frac{w_{pe}^2}{w^2}} = \sqrt{1 - \frac{n_e e^2}{w^2 \epsilon_0 m_e}} \]

This refractive index measurement can give the electron density of plasma. When an electromagnetic wave travels in vacuum for a distance ‘l’, its instant phase is given by

\[ \Phi_v(t) = wt - k_0 l \]

Where \( k_0 = \frac{2 \pi}{\lambda} \). If the wave passing through the plasma column as shown in the Fig.1, with chord length ‘l’, its instant phase is given by [3].

\[ \Phi_p(t) = wt - k_0 \int_{-Z_0}^{Z_0} n_f(z, t) dZ \]

Now the phase difference introduced by the plasma path relative to the vacuum path for the wave travelling the same column is

\[ \Delta \Phi_p(t) = \Phi_p(t) - \Phi_v(t) = k_0 \int_{-Z_0}^{Z_0} \left(1 - n_f(z, t) \right) dz \]
Now using Eq. No 3 in Eq. No 6, phase in terms of refractive index of the plasma is given by Eq. No.7.

\[ \Delta \Phi_p(t) = k_0 \int_{-Z_0}^{Z_0} \left( 1 - \sqrt{1 - \frac{n_e(z,t)e^2}{w^2\varepsilon_0 m_e}} \right) dz \]  

(7)

For symmetric density profile we have

\[ \int_{-Z_0}^{Z_0} dZ = 2 \int_{0}^{Z_0} dZ \]  

(8)

If the probing frequency ‘w’ is much larger than the plasma frequency the following approximation can be used

\[ \sqrt{1 - \frac{w^2 \rho_e}{w^2}} = 1 - \frac{w^2 \rho_e}{2w^2} \]  

(9)

Using this result in Eq.No. 7

\[ \Delta \Phi_p(t) = k_0 \varepsilon_0^2 \epsilon_0 m_e w^2 \int_{0}^{Z_0} n_e(z,t) dZ \]  

(10)

Integral in the equation can be replaced by the average electron density over a certain distance ‘l’.

\[ \bar{n}_e(t) = \frac{1}{Z_0} \int_{0}^{Z_0} n_e(z,t) dZ \]  

(11)

Using this equation in Eq.No 10, we have final equation for the average electron density in terms of phase

\[ \bar{n}_e(t) = \frac{2\pi f_c \varepsilon_0 m_e}{Z_0 e^2} \Delta \Phi_p(t) \]  

(12)

3. CIRCUIT DESIGN AND DESCRIPTION

The basic principle of operation of interferometer system is an effect of change of phase of electromagnetic waves in plasma depending on its density. The electrical specifications of the designed and developed system are given Table I. A Block diagram of D-Band interferometer system is shown in Fig.2. The system consists of a transmitter and a receiver circuit. In the transmitter a 7 GHz DRO has been used. This frequency is coupled to the receiver circuit through a 10 dB directional coupler. A doubler is used after the coupler which doubles this frequency to 14 GHz. Further this frequency is multiplied 10 times by an IMPATT Multiplier, and a stable frequency of 140 GHz has been achieved. This frequency is fed to the band pass filter (BPF) after which it is radiated by a D-band horn antenna in the plasma column through the transmitting end.

Fig.2. D-Band Heterodyne System
TABLE 1. ELECTRICAL SPECIFICATIONS

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF Frequency</td>
<td>138 GHz</td>
</tr>
<tr>
<td>LO Frequency</td>
<td>140 GHz</td>
</tr>
<tr>
<td>Frequency Stability</td>
<td>10 ppm</td>
</tr>
<tr>
<td>Time Phase Analyze</td>
<td>5 µs</td>
</tr>
<tr>
<td>Time collection</td>
<td>1 s</td>
</tr>
<tr>
<td>Phase error measurement</td>
<td>0.07 radian</td>
</tr>
<tr>
<td>Data rate of real time density</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Output RF Power</td>
<td>+20 dBm</td>
</tr>
<tr>
<td>IQ Detector Frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>RF to IF Gain</td>
<td>70 dB with AGC system</td>
</tr>
<tr>
<td>Conversion Loss of Mixer</td>
<td>9 dB</td>
</tr>
<tr>
<td>Noise Figure</td>
<td>12 dB</td>
</tr>
<tr>
<td>Gain of Horn</td>
<td>30 dB</td>
</tr>
<tr>
<td>Waveguide</td>
<td>WR-06</td>
</tr>
<tr>
<td>Data interface</td>
<td>TCP/IP Ethernet</td>
</tr>
<tr>
<td>External trigger</td>
<td>TTL</td>
</tr>
<tr>
<td>Input impedance of trigger input</td>
<td>50 Ohm</td>
</tr>
<tr>
<td>Extension waveguides</td>
<td>WR-90</td>
</tr>
</tbody>
</table>

In the Receiver we have a similar circuit. Instead of a DRO, a Voltage Controlled Oscillator (VCO) has been used. The output of the VCO is centred about 6.9 GHz. The VCO is Phase Locked with a 100 MHz Crystal Oscillator through a phase detector. The phase detector receives Intermediate Frequency (IF) of 100 MHz from a balanced mixer. If there is any phase error between stable Crystal oscillator frequency and balanced mixer IF, the phase detector sends voltage signal to the VCO and the VCO adjusts its output frequency accordingly and keeps the loop phase locked with a stable output frequency. Similar to the transmitter circuit, the receiver circuit is also provided with a directional coupler, doubler and an IMPATT Multiplier which converts the VCO frequency of 6.9 GHz to 138 GHz. A 140 GHz Signal from the Transmitter travels through the plasma column. After passing through the plasma column, it is received from the receiving horn antenna situated on the other end of plasma column. Here, the phase shifted transmitter 140 GHz signal is mixed with receiver 138 GHz signal with the help of a balanced mixer. The balanced mixer generates an Intermediate Frequency (IF) of 2 GHz. The 2 GHz frequency signal is further amplified by a Low Noise Amplifier (LNA). This signal is then fed to a power amplifier (PA) with Automatic Gain Controller (AGC). The power amplifier has been used to convert a low-power radio-frequency signal into a signal of significant power, typically for driving the circuit ahead. AGC is an adaptive system used for gain control in this circuit. Here the average output signal level is fed back to adjust the gain to an appropriate level for a range of input signal levels. The AGC effectively reduces the signal strength if the signal is strong and raises it when it is weaker.

The output of the above stage is fed to the IQ Detector Stage. The IQ Detector splits the incoming signal into two parts which are in Quadrature Phase Difference with each other. IF signal of 2 GHz is further down converted 100 KHz I and Q signal with 2.0001 GHz synthesizer and IQ demodulator. Thus the outputs of the IQ Detector are two purely sinusoidal signals having a phase difference of 90 degrees between them. These signals of 100 KHz are digitized by a 12 bit analog to Digital Converter (ADC). The converter converts digital data in Ethernet Pockets and transfers them through TCP / IP Interface to PC Station. TCP/IP provides end-to-end connectivity specifying how data should be formatted, addressed, transmitted and received at the destination. PC Station collects data from the Interferometer and calculates absolute phase change during Plasma Discharge.
The electrical specifications of the interferometer system have been shown in Table-1 and discussed below.

(a) The plasma frequency for a density of \((2 \times 10^{19})/\text{m}^3\) is about 40 GHz. The probing frequency is chosen 3.5 times larger than the plasma frequency so that the waves can completely penetrate through the plasma column.

(b) The frequency of I & Q signals are 100 KHz each. This corresponds to a time period of \(1 / (100 \times 10^3) = 10\ \mu\text{s}\) for each cycle. Each cycle has 2 zero crossing points occurring at duration of 5 \(\mu\text{s}\) each.

(c) The maximum achieved plasma pulse duration in Aditya Tokomak is 250 ms. Based on this fact the ‘Time Collection’ has been kept as 1 second so that plasma pulses of duration up to this duration can be captured.

(d) Output power of the transmitter is kept at 20 dBm (100 mW) to overcome the total path loss of about 40 dB and ensure linear operation in receiver’s dynamic range whose minimum sensitivity is about -60 dBm.

4. SETUP AND OTHER PARAMETERS

A 140 GHz, D-band, Heterodyne Interferometer system has been installed in ADITYA Tokomak at vertical port No 7, Top and Bottom port at channel (-7) which is 7 cm inwards from the central channel. This is shown in the Fig. 3. The chord length of the centre channel (XX’) is 50 cm. The chord length of the (-7) channel is 48 cm.

As shown in Fig.2 there are two output signals of the system. The first output signal is the real time density signal which appears in terms of voltage and can be seen on oscilloscope. This signal is used for density feedback control. The other output signal goes to the PC which has inbuilt software for density calculation and it generates density profile immediately after a plasma shot.

4.1 Sensitivity of the receiver

Noise Power (\(P_{\text{noise}}\)) at room temperature \(T\) and at a given bandwidth (\(\Delta f\)) is defined as [5]

\[
P_{\text{noise}} = KT\Delta f
\]

Where \(K\) is Boltzmann constant, taking: \(T = 300\ \text{K}, \ \Delta f = 2\ \text{GHz}\). \(P_{\text{noise}} = -80.81\ \text{dBm}\)

By adding the conversion loss (CL) of mixer and the noise figure (NF) of the receiver, we get the final Noise Power of the receiver.

\[
P_{\text{noise}} = -80.81\ \text{dBm} + \text{CL} + \text{NF} \quad \text{Taking CL} = 9\ \text{dB}, \quad \text{NF} = 12\ \text{dB}, \quad P_{\text{noise}} = -59.81\ \text{dBm} \approx -60\ \text{dBm}
\]

This is ‘Minimum Sensitivity’ of the receiver system.
Now let us calculate the signal being received at the receiver end. The total path loss including the 20 m waveguides and vacuum path between the two antennas is around 40 dB. Power of the transmitter system is about +20 dBm.

Power at the receiver end \(P_{\text{Receiver}}\) is \(P_{\text{Receiver}} = +20 \text{ dBm} - 40 \text{ dB} = -20 \text{ dBm}\).

So, \(P_{\text{Receiver}} > P_{\text{noise}}\)

Hence, the receiver can easily detect the transmitter’s signal coming from the plasma path.

4.2 Phase calculation

The IQ detector generates two 100 KHz I and Q signals at its output which are phase shifted by 90° with respect to each other. Since the signals are of 100 KHz, we will have two zero crossings per cycle each at an interval of 5µs and we get a zero crossing point from either of the signals every 2.5 µs.

I and Q signals are stored in terms of voltage values. A zero crossing is detected whenever voltage values change polarity, i.e. change from positive to negative and vice versa. Occurrence time of a zero crossing point is determined by interpolation between two known timings corresponding to two different voltage values. In this way all zero crossing points are determined along with their timing information.

Phase difference between two zero crossing points remains constant. By comparing the time duration between two different zero crossing points, we can know how phase has evolved between these two points with respect to time. Similarly phase change between each individual pair of zero crossing points is known. Finally all the individual phases are added and we get the total phase introduced during the entire discharge. This can be calculated below by the following formula.

\[
\sum_{0}^{N} (\varphi_{n} + \varphi(n - 1) - \varphi(n))
\]

Where,

\(n\) - Number of current zero crossing points from the beginning of discharge.

\(N\) – Total quantity zero crossing points during of discharge

5. LAB CALIBRATION

5.1 Phase measurement

Initial testing and calibration of D-band heterodyne system has been done in laboratory. To monitor the increase or decrease in phase, a wedge shaped Teflon material as shown in the Fig. 4 was used.

![Wedge shape Teflon material](image)
The wedge shape Teflon material has been used for two reasons:

1. Symmetry: Due to its wedge shaped shape
2. To observe smooth change in phase.

When the Teflon material is initially inserted / pushed inside between the transmitting and receiving antennae, the slope increases. We deduct that phase is increasing. When the Teflon wedge is removed / pulled back, the slope decreases and accordingly phase also decreases. This happens due to wedged shaped material whose thickness increases during insertion and decreases during removal. The path difference changes accordingly with respect to the reference path and we get the phase change. This is shown in the Fig 5.

![Fig.5. Increases and then decreases of the phase](image-url)

### 5.2 Measurement of Real Time Density Signal

The following experiment was done for a real time signal generated by the system. A test setup is shown in Fig.6. A metal reflector plate containing solenoid has been used. It works on the principle of electromagnetic pulse. A trigger is applied to the solenoid and the solenoid generates an electromagnetic pulse. As per the electromagnet principle, the metal reflector moves back and forth linearly. This displacement is measured by the micrometre scale. This movement causes a change of phase and accordingly a voltage is generated on oscilloscope. This is shown in Fig.7.

![Fig.6. Test setup for real time phase measurement](image-url)

![Fig.7. Real time phase signal on oscilloscope](image-url)
The displacement measured by micrometre was 8.8 mm that corresponds to a phase difference of 25.8 rad by the following equation.

\[ \Delta \phi = \left( \frac{2\pi}{\lambda} \right) (\Delta x) \]

Where \( \Delta x \) - path difference, \( \lambda \) - the wavelength.

The oscilloscope gave the voltage pulse of 1.684 V which corresponded to 25.93 radian phase.

7. INSTALLATION ON TOKAMAK AND RESULTS:

Real time density signals in terms of voltage and actual density signal has been measured for plasma shots. 1 V of real time density signal corresponds to a phase of 15.4 radians or a density of \( 6 \times 10^{12} \) /cm\(^3\). Results from different types of plasma shots with and without gas puff with their effects on density signal has been shown in the Fig.8 and 9.

8 CONCLUSION:

Real time and actual density measurements have been carried out by the D-band interferometer system in laboratory and Tokomak Plasma density has been measured in Aditya Tokomak at IPR. The effects of gas puffing has been seen on real time density signal for different plasma shots of the Aditya tokomak. The D-band heterodyne interferometer system can be used for density feedback control with the help of real time density signal at ADITYA Tokomak.

References