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MICROWAVE INTERFEROMETER USING 94-GHz SOLID-STATE SOURCES

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Abstract

A 94-GHz microwave interferometer has been designed for the Tandem Mirror Experiment Upgrade and the Mirror Fusion Test Facility to replace the 140-GHz system. The new system is smaller and has modular single-channel units designed for high reliability. It is magnetically shielded and can be mounted close to the machine, which allows the use of lower power solid-state sources. Test results of the 94-GHz prototype indicate that the phase resolution is better than 1°, the Impatt FM noise is 5 MHz wide, and the Gunn FM noise is 6 kHz wide. This paper presents the antenna designs along with the test results and discusses the unique problems associated with diagnosing a high electron temperature plasma in the presence of electron cyclotron resonant heating.

Introduction

A four-channel 140-GHz microwave interferometer has operated on the Tandem Mirror Experiment Upgrade (TMX-U) for over eighteen months.[1] This system consistently provides high-resolution (6 X 10^{11} cm^{-2}) line-density measurements, but it has its limitations; changing measurement locations is difficult, and the klystrons, the extended interaction oscillators, and the high-voltage power supplies are all unreliable. These limitations have prompted us to design a new interferometer system that has already been installed on the TMX-U and eventually will be used on the Mirror Fusion Test Facility (MFTF-B). Before choosing the 94-GHz operating frequency, we considered many factors, including synchroton noise, high electron temperature nonlinearity, and plasma absorption.

The new 94-GHz interferometers are modular single-channel units designed for high reliability and portability. They are magnetically shielded and can be mounted close to the machine, which allows the use of low-power solid-state sources. In our experiments with this system, we developed a digital phase comparator that provides high-resolution linear phase measurements for carrier frequencies over 60 MHz and developed several antenns designs for the various measurement locations, including single- and double-pass configurations. We are using a ray tracing code to evaluate the antenna and retroreflector designs. Test results of the prototype 94-GHz interferometer and processing electronics indicate that the single-channel microwave interferometer clearly benefits from the reliability, small size, and low-power requirements of solid-state sources.

Criteria for Selecting Wavelength

We considered a number of competing factors when selecting the operating frequency. Spatial resolution, electron cyclotron resonant heating (ECRH) interference, and plasma refraction are all better at shorter wavelengths. At high electron temperatures, synchrotron noise and plasma absorption can be significant also, making shorter wavelengths more attractive. On the other hand, phase resolution and mechanical stability are worse at shorter wavelengths.

The index of refraction is also a function of the electron temperature T_e, which results in a nonlinearity that occurs only at a high T_e. High T_e nonlinearity is a larger percentage of the signal at shorter wavelengths.[2-4] Estimates of this nonlinearity indicate that above 50 keV the error is significant, greater than 10%. The 90 to 100-GHz operating frequency was chosen because it was the only band giving a large enough signal and having an acceptable spatial resolution, while limiting the known error terms to acceptable levels. The specific operating frequency of 94 GHz was chosen because of the availablity of well-characterized components.

The ECRH system on the TMX-U consists of four 200-kW gyrotrons operating at 28 GHz. On the MFTF-B, additional frequencies of 35 and 56 GHz will be used. These systems radiate significant power in high harmonics. The plasma also radiates synchrotron noise at the same harmonics. The 94-GHz operating frequency avoids these harmonics, but the receiver must handle the entire waveguide band as well as potential overmoded interference signals. We do not anticipate that filtering will be necessary, but we have designed the system so that overmode or single-mode filters can be added to enhance the noise immunity of the interferometer.

Microwave System

Each interferometer is magnetically shielded so that it can be mounted close to the flange on the machine (Fig 1). Two isolators and the electronic phase shifter, which use ferrites, require the magnetic shielding. Long runs of single-mode waveguides are avoided by using nonlinear tapers to make a transition to the X-band waveguides. We use 90° H-plane mitre bends exclusively to minimize propagation loses. Low-power solid-state sources can be used when propagation loses are minimized.

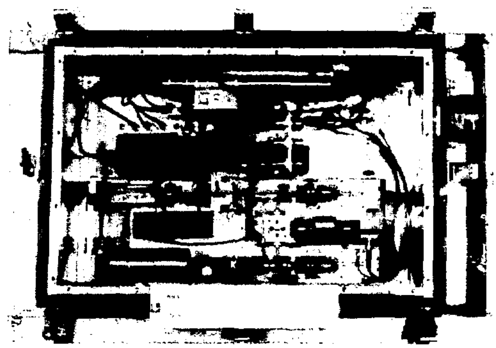

Figure 1. Microwave interferometer and RF processing system mounted in a magnetically shielded enclosure.

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The master oscillator is an Impatt oscillator with 50-mW output power (Fig 2). The local oscillator is a Gunn diode operating at 94.5 GHz with 30-mW output power, which is sufficient to drive two double-balanced microwave receivers. The electronic phase shifter allows the 94-GHz reference to be phase shifted, thereby testing the entire interferometer system in one step.

The RF processing system is packaged in the same enclosure with the microwave system. A superheterodyne tracking circuit (Fig 3) down-converts the first IF frequency of 500 MHz to 30 MHz; the circuit does not require feedback stabilization.[5] Control, power, and signal cables connect the microwave and RF processing systems to the remote power supply and control chassis. Computer control and the monitoring of key parameters enable the microwave system to operate as a stand-alone.

On the MFTF-B, the neutron radiation is expected to be 1×10^6 rads, which exceeds the lifetime of the solid-state sources, particularly the Gunn diode. The neutron fluence will have to be attenuated by a factor of 10 to meet the 10-year operational lifetime for the facility.

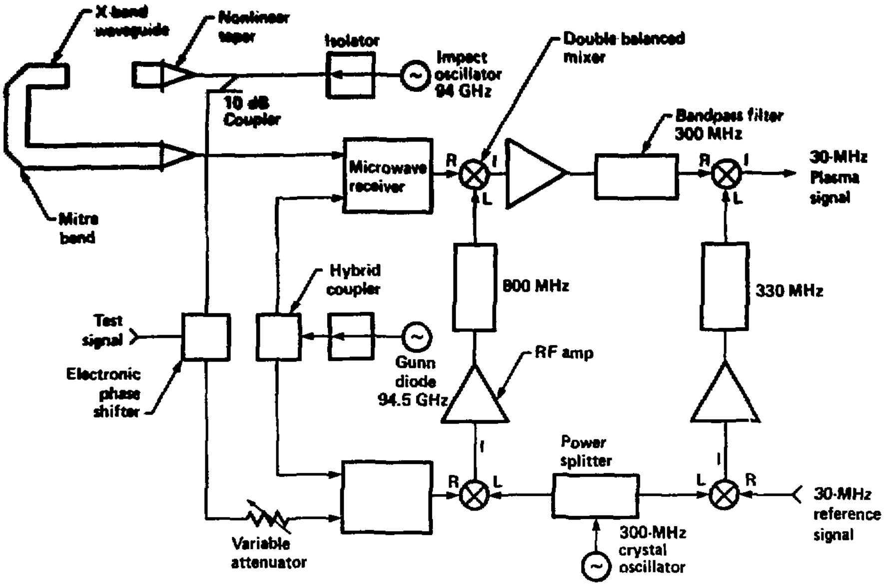


Figure 2. Block diagram of the 94-GHz microwave interferometer and RF processing system.

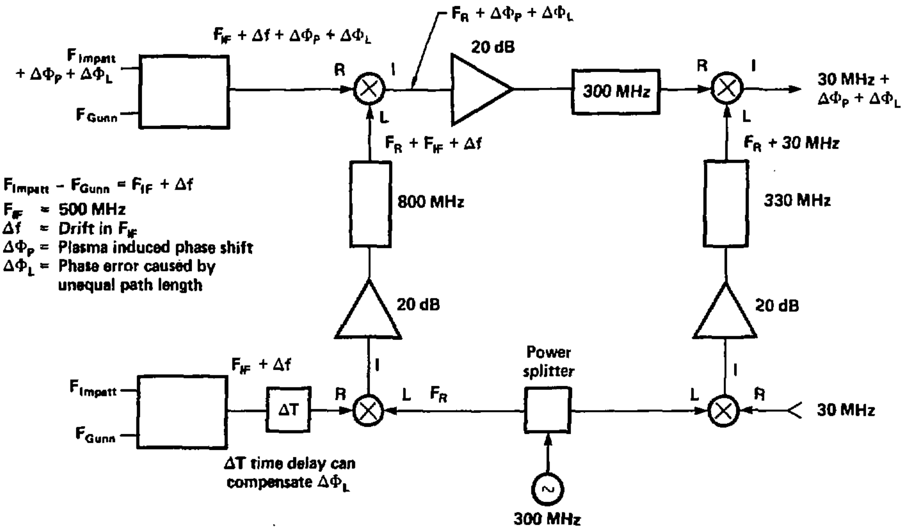
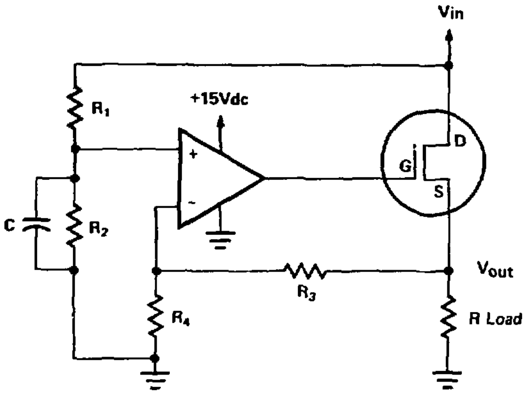


Figure 3. RF processing electronics illustrating the function of the superheterodyne tracking circuit.

Auxiliary Systems

The bias-tuned Gunn oscillator is very sensitive to power supply noise; its frequency sensitivity is approximately 1 MHz/mV. To stabilize the operating voltage, we designed an active filter (Fig 4) that allows the dc voltage to be set by the power supply while attenuating the high-frequency noise.[6] This design also limits the stored energy that might damage the Gunn in case of a fault condition. The Gunn diode requires a power supply voltage of approximately 5 V at 1.5 A; the noise at the filter output is less than 10 μV p-p.

We developed a digital phase comparator that uses prescaling to provide a wide dynamic range. It can handle phase changes of +/-32 fringes in one range and resolve phase differences of less than .1°. The limitation of this circuit is that it is a zero-crossing detector that requires a relatively high signal-to-noise ratio. Our experience with the TMX-U is that extraneous zero crossings resulting in step changes of 360° can be removed from the data provided they occur infrequently.



$$V_{out} = \left(1 + \frac{R_3}{R_4}\right)\left(\frac{R_2}{R_1 + R_2}\right) V_{in}$$

Figure 4. Simplified schematic of the capacitance multiplier filter.

Antenna Designs

We installed the first of eight channels on the TMX-U using a simple antenna design consisting of open-ended X-band waveguides. We performed tests to determine the antenna system's spatial resolution by translating a dielectric slab through the beam and monitoring the phase change as a function of position. The spatial resolution is a function of several factors including the intensity pattern of the transmitting horn, the sensitivity pattern of the receiving horn, and the phase coherence of the horn system.

The results of the tests (Fig. 5) indicate that the resolution is smaller than the beam intensity pattern. The structure apparent in the data results from interference between the shifted and unshifted parts of the beam. The asymmetries are probably from the lateral displacement of the beam by the dielectric slab. To meet spatial resolution requirements for future installations on the TMX-U and on the MFTF-B, we plan to use a focussing antenna system that has an off-axis ellipsoidal reflector and a spherical retroreflector arranged in a double-pass configuration.

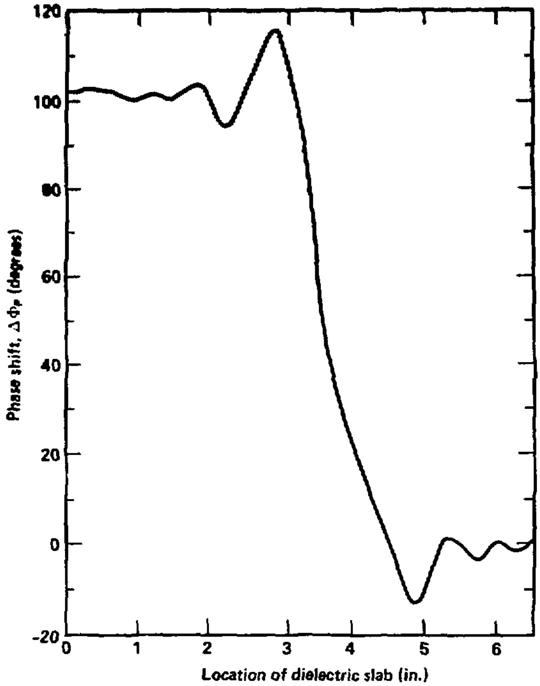


Figure 5. Test results of the measurements of the antenna system's spatial resolution.

Prototype Test Results

Performance testing of the first complete 94-GHz interferometer system indicates that the phase resolution is better than 1°, which for the 0.32-cm wavelength corresponds to a line-density resolution of approximately 2×10^{11} cm^{-2}. Measurements of the line width of the microwave sources indicate that the Impatt FM noise, which is intrinsic to the oscillator, is about 5 MHz wide, and that the Gunn FM noise, which comes from the few microvolts of residual power supply noise, is approximately 6 kHz wide. The long-term frequency drift of the 500-MHz IF is less than 10 MHz when heaters are used on both sources, but there is no active frequency stabilization.

Conclusions

We have designed a single-channel microwave interferometer that exploits the advantages of solid-state sources, namely, their reliability, small size, and low-power requirements. The performance of the new 94-GHz interferometer has been characterized in terms of both spatial and phase resolutions.

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