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A 2-mm MICROWAVE INTERFEROMETER

Archer H. Futch
W. Keith Mortensen

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Abstract

A 2-mm microwave interferometer has been developed, and phase shift measurements have been made on the Baseball II experiment. The interferometer system employs a 140-GHz receiver for double down conversion of the plasma signal to a 60-MHz, IF frequency. The 140-GHz references signal is also down-converted and compared with the plasma signal to provide the desired phase change of the signal passing through the plasma. A feedback voltage from a 60-MHz discriminator to a voltage-controlled oscillator in the receiver provides frequency stability of the 60-MHz IF signals.

Introduction

This report describes a microwave interferometer system designed to follow the density decay of a laser-produced plasma. Measurements at the higher densities expected during the early decay require millimetre wavelengths to avoid the dissipative and nonlinear region near the critical cutoff density. Therefore, the operating frequency was chosen to be 140 GHz.

The interferometer design is similar to one suggested by W. F. Cummins for the 2X experiment and was based on earlier experience with a stabilized 70-GHz system.[1] The design was modified to take advantage of commercial components and the different operating conditions of the Baseball II facility. The lower output power of klystrons operating in this frequency range and the greater attenuation of the signal in the waveguide made a sensitive detector desirable. A superheterodyne receiver with double down conversion provided the necessary sensitivity.

Interferometer Description

Microwave power is supplied by two water-cooled reflex klystrons each having a nominal output power of 100 mW at 140 GHz. Figure 1 is a schematic diagram of the interferometer. Microwave power from the source klystron operating at 140 GHz passes through an isolator to a

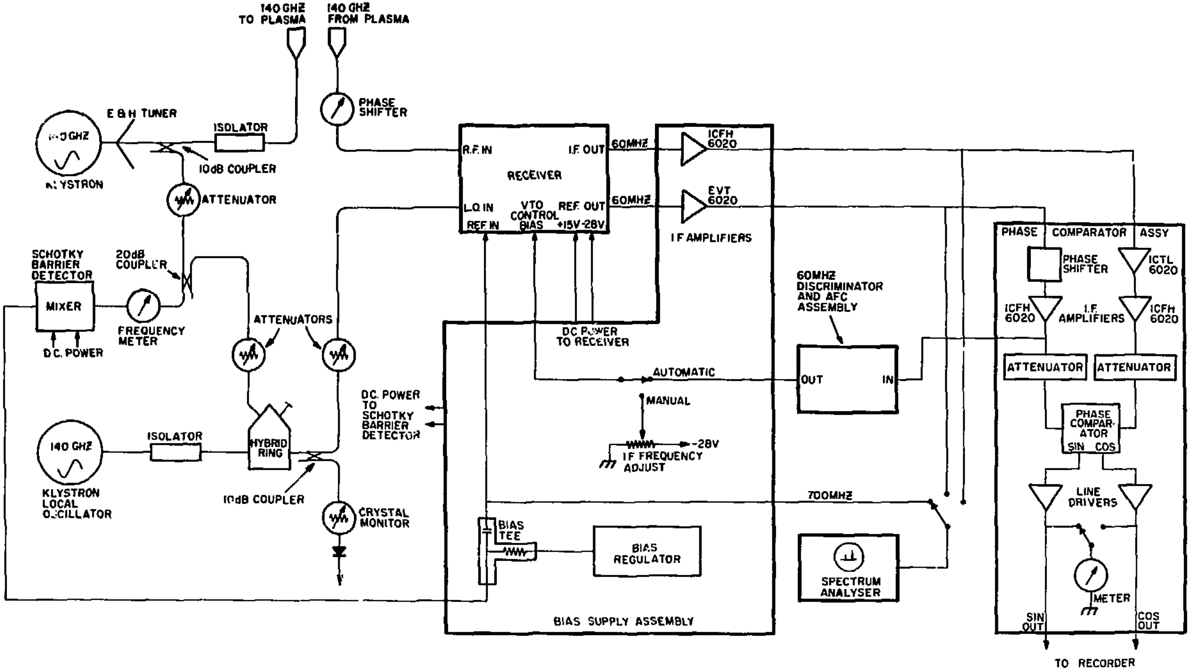


Fig. 1. Microwave interferometer phase detection circuits (Dwg. No. LEA 77-250164-00).

tapered waveguide transition section, which converts the fundamental TE_{10} rectangular mode to the circular TE_{11} mode propagating in 2.057-cm copper water pipe. This oversize waveguide is used for transmitting the microwave power to and from the plasma with relatively low attenuation at 140 GHz.

Quartz windows are used to provide the transition from air to the vacuum in the Baseball II facility. Transition around 90-deg corners is made by reflecting the microwave power off copper plates at an angle of 45 deg to the circular waveguide. Some rotation of the E vector is observed in the circular waveguide. The polarization rotation is compensated for by rotating the circular to rectangular transition section to maximize the plasma signal fed into the receiver. The rotation can be eliminated by the use of elliptical waveguides.[2] The open ends of the circular waveguide serve as the transmitting and receiving horn. That part of the circular waveguide within the vacuum system is made of silver-plated stainless steel to reduce the heat leakage into the 4 K environment of the Baseball II facility.

A 10-dB coupler diverts part of the signal from the source klystron through a 20-dB coupler where it combines with a local oscillator (LO) signal at 140.7 GHz. Both frequencies then pass through a frequency meter to a Schottky Barrier mixer diode, which generates a 700-MHz reference signal. The reference signal passes through a bias tee to the reference input of a 2-mm superheterodyne receiver.

A second klystron operating at 140.7 GHz provides the LO power. Microwave power from the LO after passing through an isolator is split into two paths by a hybird ring. One path goes to the LO input of the receiver after passing through a 10-dB coupler. One arm of the coupler provides a signal to a crystal detector for monitoring the LO input power. The second path provides LO power to the Schottky Barrier mixer diode as described previously.

Microwave power passing through the plasma to the receiving horn enters a superheterodyne receiver, which is a 140-GHz balanced double-down-conversion receiver. The first stage, which down-converts the signal to 700 MHz by mixing the plasma signal with the LO signal, consists of a 3-dB microwave coupler, two diode mixers and bias tee assemblies, a 3-dB IF hybrid junction, and a 43-dB IF amplifier. The diode mixers are equipped with GaAs Schottky Barrier diodes optimized for 140.0-GHz operation.

The second stage down-converts both the plasma signal and the 700-MHz reference signal to 60 MHz. A voltage-controlled oscillator (VCO) serves as the LO for the second down conversion. Band-pass and high-pass filters reduce spurious responses to a minimum.

Also shown in Fig. 1 is a block diagram of the receiver, amplifier, and phase detection circuits. Direct current power is supplied to the receiver and the Schottky Barrier detector by a bias supply circuit as indicated. The VCO control bias is also supplied from the same chassis. Both the DC bias and the output from the 60-MHz discriminator are fed into the input of a summation amplifier. The output of the summation amplifier provides both the operating voltage and the feedback voltage required to stabilize the IF frequency at 60 MHz. Figure 2 is a detailed circuit of the bias supply chassis.

The bias supply chassis of Fig. 2 also contains two IF amplifiers. The 60-MHz IF output from the receiver is amplified by a 20-MHz band-pass amplifier (ICFH6020) having a gain of 25 dB. The reference signal is amplified by a 20-MHz band-pass amplifier (EVT6020) with a gain of 60 dB. The different gains adjust the plasma signal and the reference signal to approximately the same level. Both signals then go to the phase comparator circuit.

Details of the phase comparator circuit are shown in Fig. 3. The reference signal passes through a phase shifter before being amplified 25 dB by a second band-pass amplifier (ICFH6020). The plasma signal is fed into an IF limiting amplifier (ICTL6020) to eliminate the amplitude variations of the plasma signal and to make possible a more accurate determination of the phase difference between the reference path and the plasma path.

Both signals then pass through attenuators, which adjust the amplitudes to the power level required by the phase comparator (6-dB). The phase comparator is a commercial assembly consisting of a power divider, two balanced mixers, and a quadrature (90-deg) hybrid with associated circuitry. Two outputs provide signals proportional to both the sine and the cosine of the phase difference between the reference and the plasma signal. The sine and cosine output signals feed into line driver amplifiers, which provide appropriate signals for recording.

A 60-MHz reference IF output from the phase comparator circuit provides the input to the discriminator circuit (see Fig. 4). Output voltage from the discriminator that is proportional to the difference

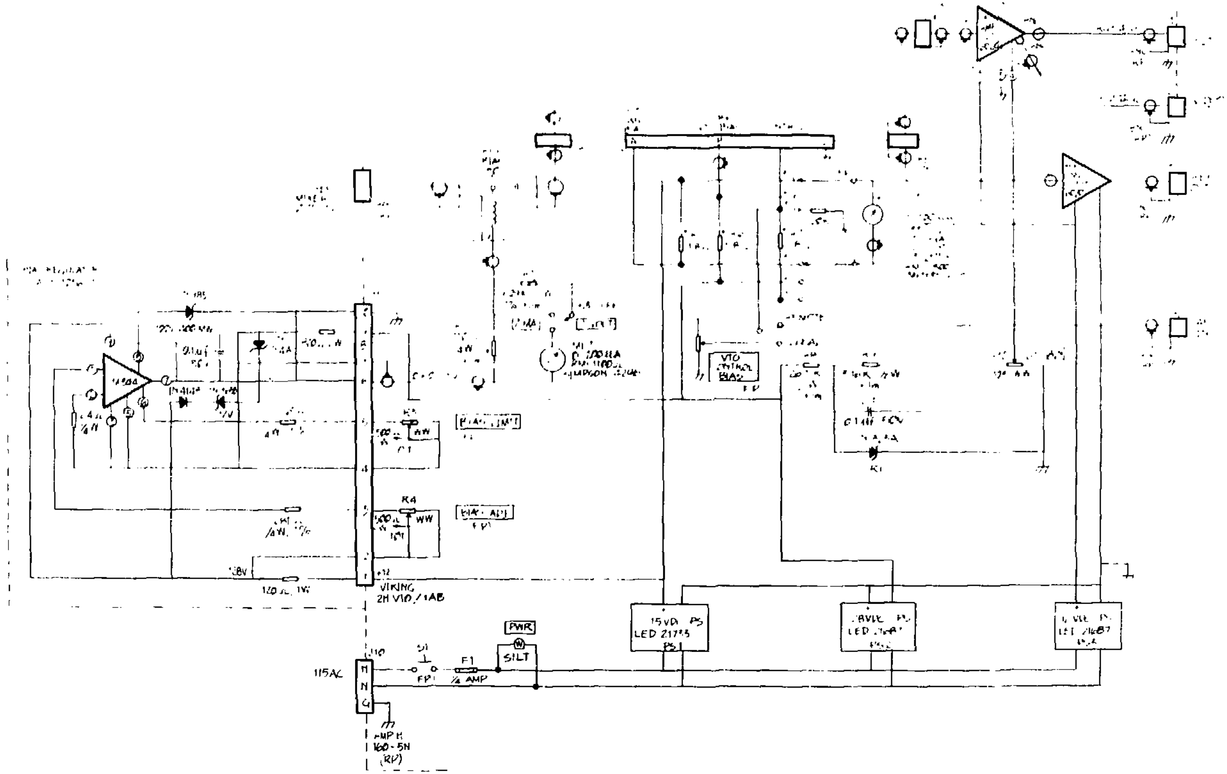


Fig. 2. Circuit diagram of bias supply chassis (Dwg. No. LEA 75-105601-SA).

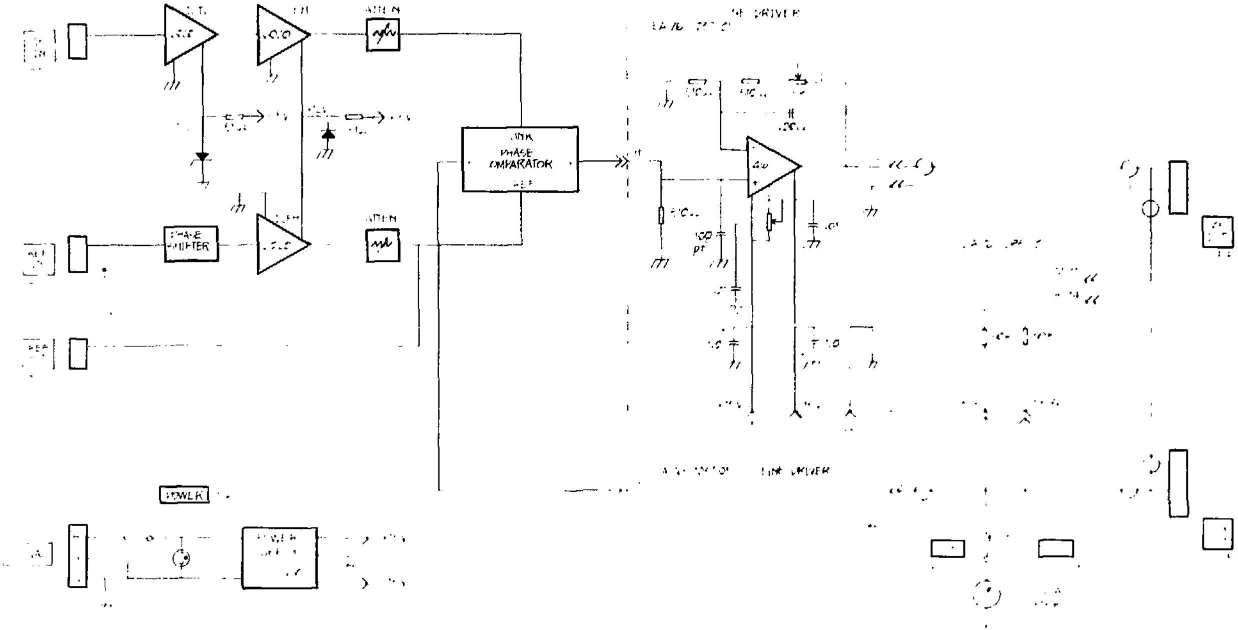


Fig. 3. Circuit diagram of phase comparator (Dwg. No. LEA 76-108501-L0).

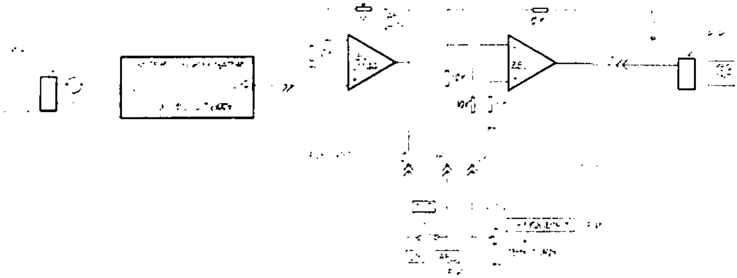


Fig. 4. Discriminator and automatic frequency control (Dwg. No. LEA 70-400311-LO).

between 60 MHz, and the IF frequency is fed to the summation amplifier. The output of the summation amplifier provides the voltage-controlled oscillator bias as discussed previously. A spectrum analyzer proves invaluable for tuneup of the interferometer and for monitoring of both IF frequencies and the second LO frequency (760 MHz).

A number of precautions are followed to prevent damage to the klystron during operation. A flowmeter installed in the water cooling circuit provides a visual indication that adequate coolant is being supplied to the tube. The design of the klystron power supply includes several protective devices (as shown in Fig. 5) to insure the correct application of voltages to the tube. Diodes between the reflector and the cathode prevent positive excursions of the reflector voltage. Relays insure that a number of conditions must be satisfied before the resonator voltage is applied. These conditions are as follows: the filament must be on, the filament voltage must have been on for a minimum of 2 min, and the reflector must be at least 20 V negative with respect to the cathode.

The reflector power supply could provide 5 mA of current over the voltage range from 0 to 1600 V. The rms voltage ripple is less than 2 mV. The power supply for the resonator is a 50-mA, 0 to 4-kV supply with a rms ripple of 1 mV.

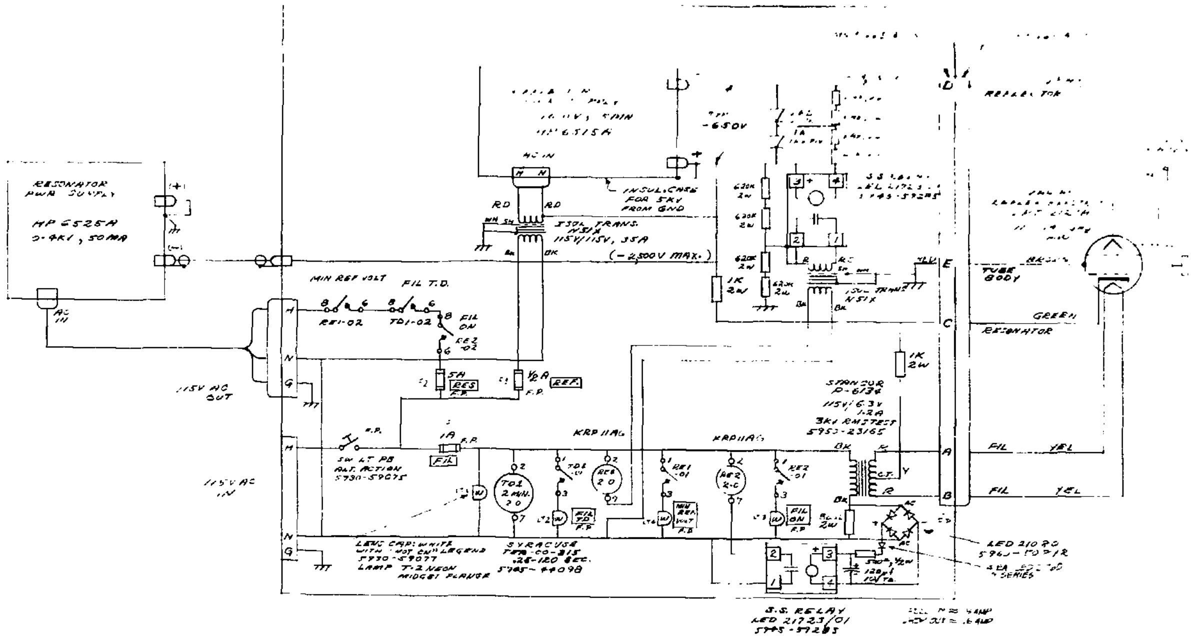


Fig. 5. Klystron power supply circuit (LEA-75-103101-SA).

Operating Procedure

The following procedure is followed in the tuning of the interferometer for phase measurements:

1. Coolant water is turned on.

2. Alternating current power is applied to klystron power supplies and other electronic chassis.

3. Resonator voltages of both klystrons are adjusted to specified values.

4. Schottky Barrier bias voltage is adjusted to 0.80 V as recommended by the manufacturer

5. Operating frequency of the source klystron is mechanically adjusted to 140.0 GHz, and the frequency of the LO is adjusted to 140.7 GHz by use of a frequency meter.

6. The LO input power is adjusted to 8 mW.

7. The first IF frequency is observed to be 700 MHz on the spectrum analyzer by teeing off the output from the bias tee. The VCO frequency is also visible on the output signal from the bias tee.

8. The VCO bias is adjusted to provide a local oscillator frequency of 760 MHz.

9. The second IF frequency is monitored by the spectrum analyzer and adjusted to exactly 60 MHz by varying the bias voltage of the VCO.

10. The 60-MHz IF frequency is stabilized by switching in the feedback voltage from the discriminator to the summation amplifier.

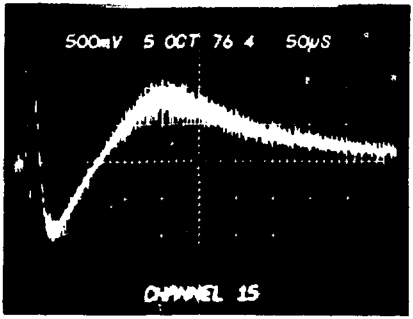
11. The amplitude of the IF and reference IF is adjusted to 6 dBm as required by the phase comparator. The attenuators prior to the phase comparator are used for this adjustment.

12. The phase shifter is varied such that the output of $\sin\theta$ is zero and the output of $\cos\theta$ is a maximum.

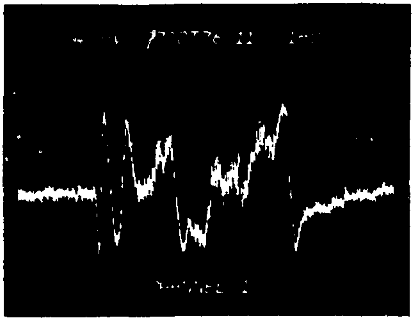
Performance

The 140-GHz interferometer has been used on the Baseball II facility for plasma density measurements. Measurements were made (1) on plasmas produced by laser irradiation of a frozen NH_3 pellet with 10.6μ radiation from a 25-J CO^2 laser[3] and (2) on target plasmas produced by the trapping of a plasma stream from a deuterium-loaded titanium washer gun.[4] Figures 6(a) and 6(b) are typical oscilloscope traces of the interferometer output for the laser-produced plasma and the streaming plasma, respectively.

The decay of the laser-produced plasma was strongly dependent on the focus of the laser and the accuracy



(a) Output during decay of laser-produced plasma.



(b) Output produced by the streaming plasma from deuterium-loaded titanium washer gun.

Fig. 6. Typical oscilloscope traces of interferometer sinθ output.

of the hit by the laser light; the interferometer output reflected this variation. Little variation was observed in the streaming plasma for different shots. Consequently, the interferometer output for the streaming plasma was very reproducible.

One source of systematic error in the interferometer measurement of phase shift resulted from the effect of the skewed magnetic field produced by the Baseball coil on the refractive index of the plasma. The dispersion relation for propagation at an arbitrary angle, θ, relative to the magnetic field is given by Appleton's equation,[5] which we simplify here by neglecting collisions and making the low density approximation:

$$\mu^2 = 1 - \frac{\omega_p^2/\omega^2}{\left(1 - \frac{\Omega_b^2 \sin^2\theta}{2}\right) \pm \left(\frac{\Omega_b^4 \sin^4\theta}{4} + \Omega_b^2 \cos^2\theta\right)^{1/2}} ,$$

where Ω_b is the ratio of the electron cyclotron frequency to the microwave frequency, ω_p is the plasma frequency, and ω is the microwave frequency. The effect of the skewed magnetic field was minimized by propagating the microwaves with the E vector parallel to the z axis of the Baseball coil ($\cos\theta$ equals zero at the magnet center) and by choosing the microwave frequency such that $\Omega_b \ll 1$. We estimate the systematic error in the measured density due to the skewed magnetic field to be less than 10% for a magnetic field of 1 tesla.

A slow phase drift of the interferometer made it desirable to rezero the phase prior to each shot. This phase drift could be eliminated between pulses by a feedback of the d.c. output of the phase detector to an electronic phase shifter in the reference arm. Cummins has described a track-and-hold circuit that keeps the interferometer balanced between shots and holds the feedback voltage constant during a shot.[6]

Acknowledgments

The authors would like to acknowledge the previous work of W. F. Cummins that established the basis for the present interferometer. Their thanks are due to Al Waugh for the design of the klystron power supplies and their protective circuits. They are also grateful for the assistance of Bert Derheimer and P. A. Housel for the considerable modification and debugging of the electronic circuits required.

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