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AN IMPROVED MICROWAVE INTERFEROMETER
TECHNIQUE FOR PLASMA DENSITY
MEASUREMENTS

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Abstract

An improved technique is developed for microwave interferometer measurements of plasma density, where the most useful features of previously described techniques are combined. Phase angles from a few degrees to several times 360° can be measured without ambiguity, and there are no phase angles with zero phase shift sensitivity. Reductions of the microwave power (e.g. due to absorption in the plasma) with up to a factor 100 can be taken into account in the evaluation of the measurements. With low power in the test beam, a polar display of the test beam phasor is possible. The minimization of errors due to imperfect components, and due to uncertainties in the measured quantities, are investigated theoretically and experimentally. The construction and testing of an interferometer based on this technique is described.

1. Introduction

Although microwave interferometry is a well-known and much used technique for plasma density measurements, there is still room for improvements in the practical design of interferometer circuits. For example, if one wants to study plasmas with densities up to around 10^{19} m^{-3} , one is forced to use microwaves of such short wavelength that the imperfection of microwave components becomes a serious problem, particularly if a high precision in the measurements is desired. The circuit then has to be constructed in such a way that these problems are eliminated or can be taken into account in the evaluation of the measurements.

In the present work, an improved microwave interferometry technique is described that combines the following desirable features:

1. The interferometer should be able to measure as large a range of phase shifts as possible, preferably from small angles up to several times 360° .
2. There should be no phase angles with zero phase shift sensitivity, and no ambiguity in the phase angles that requires additional information, e.g. by probes.
3. Measurements should be possible also if the power in the transmitted microwave beam varies strongly, for example due to absorption in the plasma.
4. Problems due to imperfect microwave components should be eliminated or taken into account in the evaluation of the measurements.
5. The interferometer should be easy to use; for example, a design that requires repeated careful setting of initial angles should be avoided.

The interferometer circuit proposed here combines the most useful features of the interferometer by Lindberg and Eriksson (1982) and the phase-quadrature or polar display interferometer (e.g. Hermansdorfer, 1968, pp 527, 535). Lindberg and Eriksson's interferometer is a development of the interferometer described by Hotston and Seidl (1965), which was designed for measurements of small phase shifts ($\Delta\phi \lesssim 40^\circ$). The methods of evaluation of measured signals was improved by Lindberg and Eriksson so that phase shifts up to several times 360° could be measured. They also carefully discussed the problems encountered in practice in the construction of an interferometer, particularly the problems due to imperfect components. However, the problems with ambiguity in phase angles, and with zero phase shift sensitivity at certain phase angles, remain unsolved in their interferometer.

These problems are eliminated in the phase-quadrature circuit. The main disadvantage of this design is instead that it is very difficult to take into account the effects of imperfect components, particularly a type of problems that are due to unequal power splitting in the hybrids used to combine the reference and test beam. (This problem is discussed in Section 3 below.) The phase-quadrature circuit also requires more detectors than the interferometer described in this paper.

The outline of the paper is as follows. The principle of operation and the method of evaluation is described in Section 2. In Section 3, the problem with imperfect components is discussed, and in Section 4 the initial setting of the interferometer is described. The uncertainty of measurement is investigated theoretically and experimentally; this is described in Sections 5 and 6. The possibility of polar display is briefly described in Section 7, and the overall characteristics of the interferometer are summarized in Section 8.

2. Microwave circuit and principle of operation

Microwave propagation in a plasma is treated in many textbooks. When the microwave frequency is much larger than the collision frequency, collisional damping can be neglected. The effect of the magnetic field is also negligible when the gyrofrequencies are much smaller than the microwave frequency, or when the electric vector of the microwave is arranged to be parallel to the magnetic field. The relation between the plasma density n_e and the phase shift due to the presence of the plasma is then given by (Heald and Wharton, 1965, p.120):

$$\Delta\phi(t) = \frac{2\pi}{\lambda_0} \int \left[1 - \left(1 - \frac{n_e(x,t)}{n_c} \right)^{\frac{1}{2}} \right] dx \quad (1)$$

$$\Delta\phi(t) \approx \frac{\pi}{\lambda_0 n_c} \int n_e(x,t) dx \quad \text{for } n_e \ll n_c \quad (2)$$

where λ_0 is the vacuum wavelength and $n_c = 4\pi^2 m_e / \mu_0 e^2 \lambda_0^2$ is the cut-off density. The microwave interferometer measures $\Delta\phi$.

The microwave circuit is shown in Fig.1. The microwave power delivered by the klystron is split up into two branches, the transmitted (or T) branch, which passes through the plasma, and the reference (or R) branch. The relative power in the two branches can be changed by means of attenuators in the two branches.

Both branches are split up again in HYB3 and DIR2 into the T_1 , T_2 , R_1 and R_2 branches; The T_1 and R_1 branches add in the hybrid HYB1, and together drive the detector DET1. The T_2 and R_2 branches add in a similar way in HYB2 to drive DET2. The phase angles between the branches R_1 and T_1 , and between R_2 and T_2 , can be chosen independently by means of the phase shifters PHA1 and PHA2.

Fig.2a shows the two independent phasor diagrams for the two detectors. The indices 1 and 2 on the E-field phasors denote the detector at which the electric field is drawn, and the indices R and T denote the branch from which it came. The index 0 denotes that there is no plasma in the T branch.

In Fig.2b the phasors are drawn together in a way that allows a simple geometrical interpretation of the signals; they are normalized to the amplitudes (without plasma) in the T branch, and then combined so that the normalized $\tilde{E}_T$ phasors coincide. Provided that the amplitude E_T of the T branch is small enough, the location C of the tip of the phasor $\tilde{E}_T$ (and therefore the phase shift of the transmitted branch) is uniquely defined by E_1 and E_2 . An ambiguity arises only if E_T is so large that one cannot exclude the position C_1 , shown by dotted lines in Fig.2b.

For the calculation of the phase angle ϕ in the T branch the coordinate system shown in Fig.3 is suitable. We immediately get

$$\alpha = \arctg \left(\frac{E_{2R}/E_{2TO}}{E_{1R}/E_{1TO}} \right) / \quad (3)$$

while the cosine theorem gives

$$\beta = \arccos \left[\left(\frac{E_{1R}}{E_{1TO}} \right)^2 + \left(\frac{E_{2R}}{E_{2TO}} \right)^2 + \left(\frac{E_1}{E_{1TO}} \right)^2 - \left(\frac{E_2}{E_{2TO}} \right)^2 \right] \cdot \left[\frac{2E_1}{E_{1TO}} \left(\left(\frac{E_{1R}}{E_{1TO}} \right)^2 + \left(\frac{E_{2R}}{E_{2TO}} \right)^2 \right)^{\frac{1}{2}} - 1 \right]^{-1} \quad (4)$$

With α and β known, we can construct

$$x - x_0 = \frac{E_1}{E_{1TO}} \cos \beta - \frac{E_{1R}}{E_{1TO}} \cos \alpha \quad (5)$$

and

$$Y - Y_0 = \frac{E_1}{E_{1TO}} \sin \beta - \frac{E_{1R}}{E_{1TO}} \sin \alpha, \quad (6)$$

which gives the phase angle ϕ :

$$\phi = \arctan \frac{Y - Y_0}{X - X_0} \begin{cases} + 90^\circ & \text{if } (X - X_0) > 1 \\ + 270^\circ & \text{if } (X - X_0) < 1 \end{cases} \quad (7)$$

This in principle solves the problem. The evaluation of the measured signals is best done by a computer. The program should first calculate (E_{1R}/E_{1TO}) , (E_{2R}/E_{2TO}) etc. as described below, and then successively solve Eq:ns (3)-(7) to give ϕ . The quantities (E_{1R}/E_{1TO}) etc. are easily obtained if the detectors have quadratic response, i.e. if the signals from the detectors are given by

$$u_1 = K_1 E_1^2 \quad (8)$$

and

$$u_2 = K_2 E_2^2 \quad (9)$$

where K_1 and K_2 are constants, determined by the detector-tuner assemblies. In this case we get relations of the type

$$\left(\frac{E_{1R}}{E_{1TO}} \right) = \frac{(u_{1R}/K_1)^{\frac{1}{2}}}{(u_{1TO}/K_1)^{\frac{1}{2}}} = \left(\frac{u_{1R}}{u_{1TO}} \right)^{\frac{1}{2}}$$

The measured quantities are u_{1R} , u_{2R} , u_{1TO} , u_{2TO} , u_1 and u_2 , where the indices have the same meaning as for the electric field phasors. u_1 and u_2 are the signals recorded in the use of the interferometer.

If the detector responses are not quadratic, one can correct the detector signals for the deviation from a quadratic response and then proceed as with quadratic detectors. The method of correction is described by Lindberg and Eriksson (1982).

3. Problems due to imperfect components

The interferometer of Lindberg and Eriksson is very similar to the one shown in Fig.1. The important difference is the arrangement of the detectors between the isolators ISO3 och ISO4 in Fig.1. The reader is therefore referred to their paper for the circuit that is common to the two devices, while we here limit the discussion to the new part between the two isolators. In this part of the circuit it is important to:

1. Minimize the leak between the R and the T branches through HYB1 and HYB2.
2. Make sure that the unavoidable reflections on imperfect components do not influence the measurements.

The main reason for caution is that the power splitting in the hybrids is extremely sensitive to small signals falling in through certain ports. Such unwanted signals can be due to reflections on various components, or due to insufficient attenuation in the hybrids themselves. One example is that power from the R_2 branch can leak through HYB2 and enter HYB3. After reflection on ISO3 (which reflects 6% of the power in the backward direction) and TER3, this signal mixes with the T branch microwaves in HYB3. Even if the signal is strongly attenuated by the various reflections, it can influence the power splitting between the T_1 and the T_2 branches considerably. This is illustrated by an example in Fig.4. Consider the case where we want to study the signal of power W , that falls into port 1 of a hybrid, while the unwanted signal can be regarded as a signal of power $a \cdot W$ falling into

port 3. Using $W = \text{const} \cdot E^2$, we get the phasor diagram of Fig.4b for the signals that go out through ports 2 and 4. Using the cosine theorem to find E_1^2 and E_2^2 , we get the power in the two branches:

$$W_2(\psi) = W/2 + aW/2 + 2\sqrt{a} W \cos \psi \quad (10)$$

$$W_4(\psi) = W/2 + a W/2 - 2\sqrt{a} W \cos \psi . \quad (11)$$

The power splitting between the two branches is given by $W_2(\psi)/W_4(\psi)$. The variation in power splitting when ψ is changed from 0° to 180° is, when $a \ll 1$, given by

$$\left[\frac{W_2}{W_4} (\psi=0) \right] \left[\frac{W_2}{W_4} (\psi=180^\circ) \right]^{-1} \approx \left(\frac{1 + 2\sqrt{a}}{1 - 2\sqrt{a}} \right)^2 \quad (12)$$

This quantity is surprisingly large, even for very small values of a ; for example, $a = 10^{-2}$ gives 2.25, $a = 10^{-3}$ gives 1.29, and $a = 10^{-4}$ gives 1.08. It is therefore important to adjust the tuners on the detectors so that there is a minimal leak of power between the R and the T branches through HYB1 and HYB2. Since the R branch power level is higher, it is most important to remove leak-through from the R to the T branch. This is best done by tuning the whole assemblies HYB1-TER1-TUN1-DET1 and HYB2-TER2-TUN2-DET2 by replacing the T branch connection by a detector, and adjusting the tuner for minimum leak-through. In this way, the phase and amplitude of the reflected signal on the tuner-detector assembly are such that it cancels both the small but unavoidable reflection on the terminating load, and the leak-through due to imperfections in the hybrids themselves.

Tuning in this way does not, however, minimize reflection back into the R_1 , R_2 , T_1 and T_2 branches. These reflected signals will to some extent be reflected again on imperfect components, and re-enter HYB1 och HYB2. That such signals are a significant part of the measured signals is illustrated by the fact that turning the phase shifter PHA2 (with the T branch cut off) influenced the signal level on DET1 with $\pm 15\%$. However, these additional signals only give a constant addition in phase and amplitude to the original signals, and therefore do not constitute a problem, provided that they do not come in contact with any components that are varied. The isolators ISO3 and ISO4 are therefore necessary if one shall be allowed to vary phase shifter 1 and the attenuators 1,2,3 and 4 after the initial setting of the circuit. With the isolators in place, the imperfections of the other components (the attenuators can give a phase shift with up to 100 degrees, while the phase shifters can vary the power level with typically $\pm 10\%$) are automatically taken care of in the evaluation of the measured signals by Eq:ns (3)-(7).

Frequency drift of the klystron can influence the operation of the interferometer. One reason is that the tuning of the detectors is exact for one frequency only. Another reason is that the presence of reflected waves introduces unequal path lengths, for example between the signals in the R branch that go directly to HYB1, and the signals that have followed the path DIR2-HYB2-DIR2-ISO4-DIR2-HYB1.

One might argue that even a rather large leak-through between the R and T branches through HYB1 and HYB2 can be tolerated, since these signals can be regarded as constant additions in phase and amplitude to the direct signals. This hypothesis was tested experimentally by replacing TER1 and TER2 with highly reflecting components and found to be true; however, a large mismatch complicates the initial setting of the 90° phase angle between the R_1 and R_2 branches, and also considerably increases the sensitivity of that angle to frequency drift in the klystron.

4. Initial setting of the circuit

The power in the T branch must first be chosen so low that the ambiguity in evaluation discussed in Section 2 is avoided. This was in our case made by adjusting ATT2 so that both $u_{1R}/u_{1TO} > 10$ and $u_{2R}/u_{2TO} > 10$.

The initial setting of the circuit then consists of adjusting PHA1 so that there is a phase angle of 90° between the R_1 and the R_2 branches, when the normalized T branch phasors are used as a common reference.

If the components were ideal, the setting could easily be made as shown in Fig.5: Starting at arbitrary angles (Fig.5a) one first changes PHA1 so that the angle ξ is 135° . With quadratic detectors, this is made by first measuring u_{1R} and u_{1TO} separately, and then adjusting PHA1 so that the signal from DET1 is

$$\begin{aligned} u_1 &= u_{1R} + u_{1TO} - 2(u_{1R} u_{1TO})^{1/2} \cos 135^\circ = \\ &= u_{1R} + u_{1TO} + (2u_{1R} u_{1TO})^{1/2}. \end{aligned} \quad (13)$$

This setting does not change $\xi + \eta$. Next, η is changed to 135° by setting PHA2 so that

$$u_2 = u_{2R} + u_{2TO} + (2u_{2R} u_{2TO})^{1/2}. \quad (14)$$

There are two possibilities to satisfy the relations (13) and (14), as shown in Fig.5c and d; the easiest way to ensure that the correct one has been found is to make a slight change in PHA1: One of the signals u_1 and u_2 should then increase, and the other decrease.

Due to the presence of reflected waves in the circuit, the change of PHA2 will usually influence the setting of ξ , and also u_{1R} and u_{2R} . One therefore has to use an iterative procedure, and repeat the setting procedure described above until both Eq. (13) and Eq. (14) are satisfied simultaneously. In our case, it was possible to achieve an angle between R_1 and R_2 as accurate as $90^\circ \pm 0.5^\circ$ by repeating the setting procedure typically 10 - 15 times.

A quick test of that the frequency drift of the klystron has not changed the setting, is to ascertain that it is possible to satisfy both Eq. (13) and Eq. (14) by adjusting only PHA2. In our case the drift was such that no adjustments were necessary during several weeks of operation.

Once the initial setting of 90° phase angle between the R_1 and R_2 branches is made, the operation of the interferometer is greatly simplified by the fact that there is no need to choose any particular initial relation in phase and amplitude between the R and T branches. PHA2 and all the attenuators can therefore be changed freely, provided that the power in the T branch is kept so low that the ambiguity discussed in Section 2 is avoided.

5. Theoretical estimate of the uncertainty

The phase angle ϕ is given as a function of the measured quantities by Eq:s 3-7. The uncertainty $\delta\phi$ can be obtained in terms of the uncertainties in the measured signals δu_{1R} , δu_{2R} , δu_{1TO} , δu_{2TO} , δu_1 and δu_2 by taking the total differential of the equation that is obtained by combining Eq:s 3-7. This, however, leads to a very complicated expression which is not practical to use.

The uncertainty was therefore estimated numerically by calculating the error $\delta\phi$ in ϕ that resulted when each of the parameters u_{1R} , u_{2R} , u_{1TO} , u_{2TO} , u_1 and u_2 was overestimated with 1%, 3%, 5% and 10%, while the others were kept constant. The relative power W_T/W_R between the T and the R branches was

in these calculations set equal to 0.1, 0.01 and 0.001. The result is given in Table I.

In the operation of our interferometer, W_T/W_R is kept around 0.1, and the uncertainty in the measured quantities is around 1%. This gives a theoretical uncertainty in ϕ with $\pm 2^\circ$, if the power in the T branch is unchanged, $\pm 5^\circ$ with a power reduction by a factor of 10 in the T branch, and $\pm 15^\circ$ with a power reduction by a factor of 100.

6. Experimental tests of the uncertainty

The accuracy of the interferometer has been tested experimentally by introducing flat slabs of polystyrene foam in the T branch, and measuring how the phase shifts $\Delta\phi$ vary when the initial phase angle ϕ_0 of the T branch is changed. Such slabs were found to give a phase shift of typically 1.7° per mm for our wavelength (4 mm). With a given slab, the true phase shift is independent of ϕ_0 . An uncertainty in the measurement of ϕ due to an error in one of the measured signals shows up as a variation in $\Delta\phi$, when ϕ_0 is varied. (This statement was checked numerically by varying $\Delta\phi$, ϕ_0 and the errors δu_{1R} , δu_{2R} etc. in the same way as was made in Section 5. It is also illustrated by an example in Fig.7, which shows how the error $\delta\phi$ from a 10% underestimate of E_2 varies with ϕ_0 .)

The uncertainty was tested in this way with two flat slabs of polystyrene, 10 mm and 63 mm thick, giving phase shifts around 16° and 107° . ϕ_0 was changed from 0 to 200° by PHA1, and the power ratio P_T/P_R was set equal to 0.1, 0.01 and 0.001. The obtained uncertainties in $\Delta\phi$ are given in Table II. They agree well with the corresponding theoretical estimates of Table I (calculated from 1% uncertainty in the measured quantities). Table I also shows that smaller phase shifts $\Delta\phi$ can be measured with greater accuracy than larger phase shifts, as expected.

7. Polar display of the T branch phasor

With small enough power in the T branch, a polar display of E_T is possible. This is illustrated in Fig. 7. The normalized T branch phasor $E_T = E_T/E_{T0}$ is split up in the components E_{TX} and E_{TY} . For $E_{2T0} \ll E_{2R}$, we find from Fig. 7 that

$$E_2/E_{2T0} \approx E_{2R}/E_{2T0} + E_{TY}/E_{T0} \quad (15)$$

and

$$(E_2/E_{2T0})^2 \approx (E_{2R}/E_{2T0})^2 + 2(E_{TY}/E_{T0})(E_{2R}/E_{2T0}). \quad (16)$$

With quadratic detectors, this gives

$$u_2/u_{2T0} \approx u_{2R}/u_{2T0} + E_{TY}/E_{T0} [2(u_{2R}/u_{2T0})^{1/2}]. \quad (17)$$

which shows that E_{TY} varies approximately linearly with u_2 . A similar relation holds between u_1 and E_{TX} . u_1 and u_2 can therefore be used for a polar display of E_T , if one uses a suitable choice of zero levels and sensitivities of the x and y channels of an oscilloscope. This was tested with our interferometer and found to work nicely.

8. Summary

A microwave interferometer for plasma density measurements has been designed, with the following characteristics:

1. There is no ambiguity in phase angles that requires additional information, e.g. by probes. The usual ambiguity of $n 360^\circ$ can, in an experiment with time-varying plasma density, be removed by evaluating the phase shift at closely enough spaced time intervals.

2. There are no angles with zero phase shift sensitivity.
3. The effect of amplitude variations in the transmitted branch (e.g. due to absorption in the plasma) is taken into account. The interferometer was tested to measure phase shifts with an accuracy of ± 2 degrees, if the power in the transmitted branch was unchanged, ± 3 degrees if the T branch power was reduced by a factor of 10, and ± 10 degrees if the T branch power was reduced by a factor of 100.
4. The measurements are insensitive also to rather large imperfections in the components, such as unwanted reflections, or poor attenuation and unequal power splitting in the hybrids used to combine the reference and the transmitted signals.
5. Once the basic setting of the circuit is made, there is no need for repeated careful setting of initial angles.
6. With low power in the transmitted branch, a direct polar display of the test beam electric phasor is possible (or, alternatively, a recording of the vector components of the test beam phasor on e.g. a dual beam oscilloscope).
7. Only two detectors are used, which do not have to be matched. Quadratic response of the detectors is not necessary, but simplifies the evaluation.

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Uncertainty of measured quantities W_T/W_R	1%	3%	5%	10%
0.1	$\delta\phi=2^\circ$	$\delta\phi=6^\circ$	$\delta\phi=10^\circ$	$\delta\phi=20^\circ$
0.01	$\delta\phi=5^\circ$	$\delta\phi=15^\circ$	$\delta\phi=25^\circ$	-
0.001	$\delta\phi=15^\circ$	$\delta\phi=45^\circ$	-	-

Table I. Theoretically estimated uncertainties in measured phase angles ϕ for different power ratios W_T/W_R between the T and the R branches.

W_T/W_R	uncertainty in $\Delta\phi$ for $\Delta\phi \approx 107^\circ$	uncertainty in $\Delta\phi$ for $\Delta\phi \approx 17^\circ$
0.1	$\pm 2^\circ$	$\pm 1^\circ$
0.01	$\pm 3^\circ$	$\pm 1.5^\circ$
0.001	$\pm 10^\circ$	$\pm 5^\circ$

Table II. Experimentally obtained uncertainties in measured phase shifts $\Delta\phi$ for different power ratios W_T/W_R between the T and the R branches.

Fig.1 The interferometer bridge circuit. Notations: ATT = attenuator, DET = detector, DIR = directional coupler, HYB = hybrid ("Magic T" or hybrid ring), ISO = isolator, KLY = klystron, PHA = variable phase shifter, TER = terminating load, and TUN = tuner.

Fig. 2 a

Fig 2 b

Fig.2 a: phasor diagrams for detectors 1 and 2, drawn separately. b: combined diagram with phasors normalized to the T branch phasor for each detector. Notations: E_{1R} and E_{2R} : phasors at detectors 1 and 2 from the R branch alone. E_{1TO} and E_{2TO} : phasors from the T branch alone, without plasma. E_{1T} and E_{2T} : phasors from the T branch alone, with plasma. E_1 and E_2 : combined phasors from the R and the T branches.

Fig.3 Calculation of the phase angle ϕ of the T branch.

a. Hybrid

b. Phasor diagram

Fig.4 Illustration of how the power splitting in a hybrid is strongly influenced also by a small unwanted signal.

a. Initial (arbitrary) relation between the phasors.

b. Setting $\xi = 135^\circ$ by PHA1, which leaves $\xi + \eta$ unchanged

c. Setting $\eta = 135^\circ$ by PHA2, which leaves ξ unchanged.

d. The other phasor relation satisfying Eqs: 13 and 14.

Fig.5 The phasor relations during the initial setting of the interferometer.

Fig.6 An illustration of the variation of the error $\delta\phi$ with the phase angle ϕ of the T branch (positions a, b, c and d). A: the true position of the E_1 phasor. B: the position obtained from an underestimate of E_2 with 10%. The error $\delta\phi$ is seen to be much smaller in positions a and b than in positions c and d. A phase shift $\Delta\phi$ around 90° from position a to position c would therefore give an overestimate of $\Delta\phi$ with approximately $\delta\phi_c$, while a phase shift from position b to position d would give an underestimate of $\Delta\phi$ with approximately $\delta\phi_d$. Smaller phase shifts $\Delta\phi$ would be measured with greater accuracy.

Fig.7 Illustration of polar display of the components E_{TX} and E_{TY} of the E_T phasor.

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Key words: Microwave interferometry, Plasma density measurements, Plasma diagnostics