Unmodulated Interferometer

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Abstract

This report describes a fast, unmodulated interferometer with a bandwidth exceeding 1 MHz which delivers two separate signals for the continuously represented amplitude and phase.

1. Introduction

It is common practice in plasma physics to measure the electron density by microwave interferometry. The standard tool for obtaining separate signals for the phase and amplitude is the strip interferometer /1/. In this method the microwave generator is slightly modulated in frequency with a sawtooth voltage. All modulation methods require selective amplifiers or low-pass filters to suppress any undesired mixture products. The attainable time resolution is thus limited by the rate of the modulation frequency. In practice, however, the rate cannot be arbitrarily increased since certain requirements have to be imposed on the shape of the modulation curve. To obtain a continuous interference signal, the modulation voltage must be discontinuous (e.g. in the sawtooth case a fast back stroke whose time has to be negligible relative to the cycle). In addition, the modulation voltage has to have high amplitude linearity. Both of these requirements, namely the switching action for the point of discontinuity and the constant amplitude, create problems in practice if excessive modulation frequencies with resulting high time resolution are aimed at.

High time resolution for determining the electron density variation is required in plasma physics, particularly at the start of ignition of the discharge and before and during disruption, for measuring modes and fluctuations /2/. The fastest interferometer with the highest time resolution is the unmodulated interferometer /1/ such as was used in the early days of plasma physics. In this type the maximum time resolution depends only on the mixer diodes and the bandwidth of the following DC amplifier. Wide-band amplifiers of 200 MHz are nowadays standard in oscilloscope technique.

If there is no modulation, the amplifier used has to have good zero stability. This used to be a problem with valve units but is no longer critical since the advent of hybrid technique and integrated circuits since all elements involved in amplification are mechanically mounted on the same base and hence kept at the same temperature, thus eliminating temperature drift problems. Another reason for introducing modulation was that it is then easier to take readings of the phase shifts. In the popular sawtooth modulation technique (zebra stripe method) the phase appears as a function of time direct on the oscilloscope. This job can be done nowadays with computer modules. For reasons of time resolution there was thus an obvious case for revising the concept and reverting to the old unmodulated principle.

2. Mode of operation of the undmodulated interferometer

The information in interferometry is derived from the transit time variation of the microwave, this being caused by the plasma in the test channel relative to a constant reference channel. As it is sinusoidal quantities that are involved, a transit time variation is equivalent to a change in phase. As both the amplitude and phase angle can vary in time, this produces in the vector diagram rotating point in the Cartesian coordinate system (Fig.1).

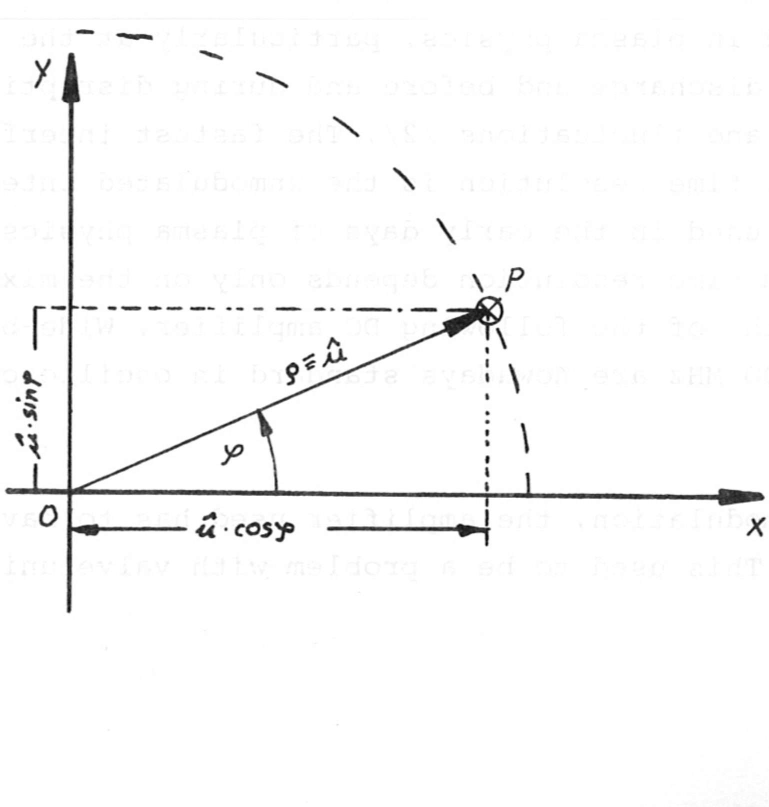


Fig.1:

The point is defined in parametric representation by the two components.

$$u_x = \hat{u}\cos\varphi \quad \text{and} \quad u_y = \hat{u}\sin\varphi$$

The angle and amplitude can then be formed with the relations

$$u = (\hat{u}^2\sin^2\varphi + \hat{u}^2\cos\varphi)^{1/2} = \hat{u}\underbrace{(\sin^2\varphi + \cos^2\varphi)}_{=\,1}{}^{1/2}$$

$$\varphi = \arctan\frac{\hat{u}\sin\varphi}{\hat{u}\cos\varphi}$$

3. Design

With an unmodulated interferometer the desired information can be obtained with a minimum of two separate mixers, the one of which receives a signal delayed by $\lambda/4$ relative to the other, this corresponding to a phase shift of $\pi/2$. The voltages obtained at the mixer output for a phase variation can be expressed by

$$u_1 = \hat{u} \times \sin\varphi$$

$$u_2 = \hat{u} \times \sin(\varphi + \pi/2) = \hat{u} \times \cos\varphi$$

This yields a polar diagram on an X-Y display in the case of density variations (Fig.2)

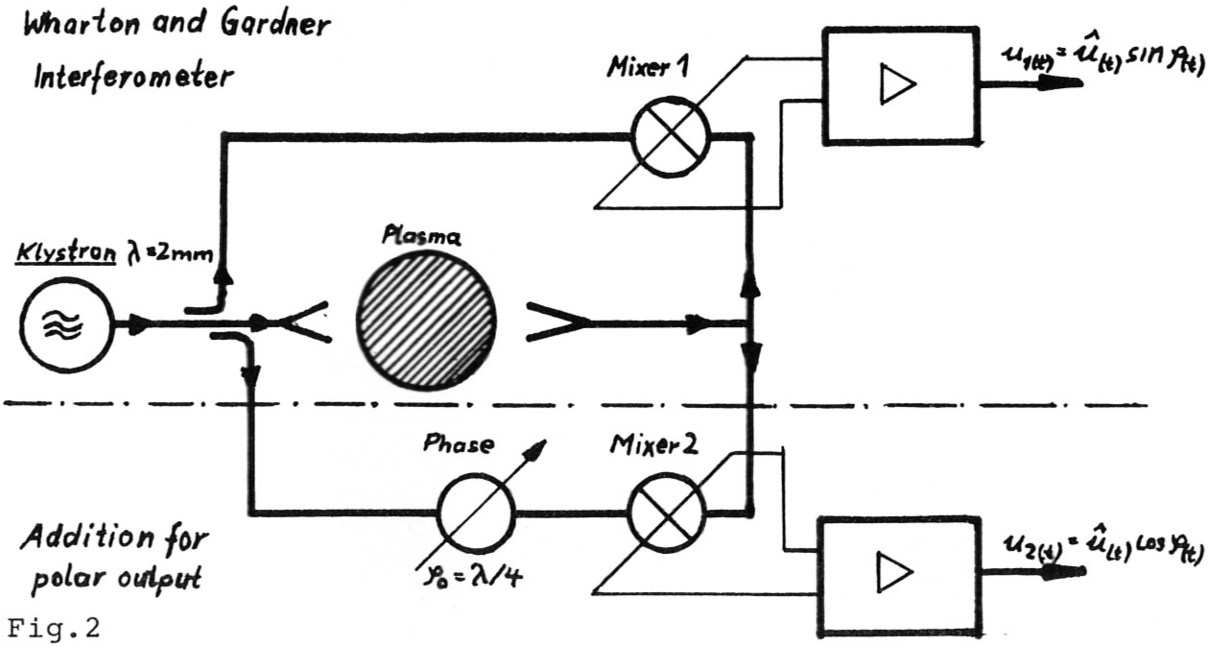


Fig.2

To include the time dependence in this representation, the centres of the circles obtained for constant amplitude were displace approx. 26°, the deflection over the entire screen lasting 200 ms. This conveys the impression of a three-dimensional plot (Fig.3)

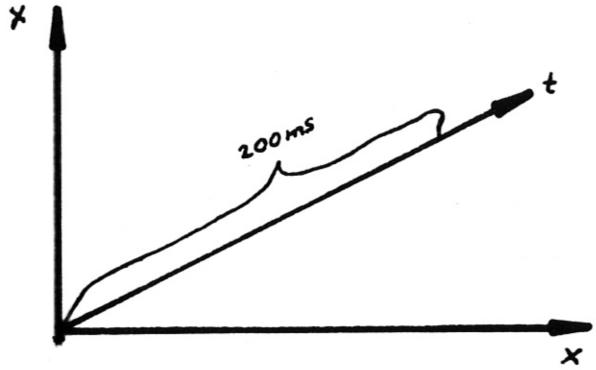


Fig.3

Figure 3awas recorded with a test bandwidth of 25 kHz.

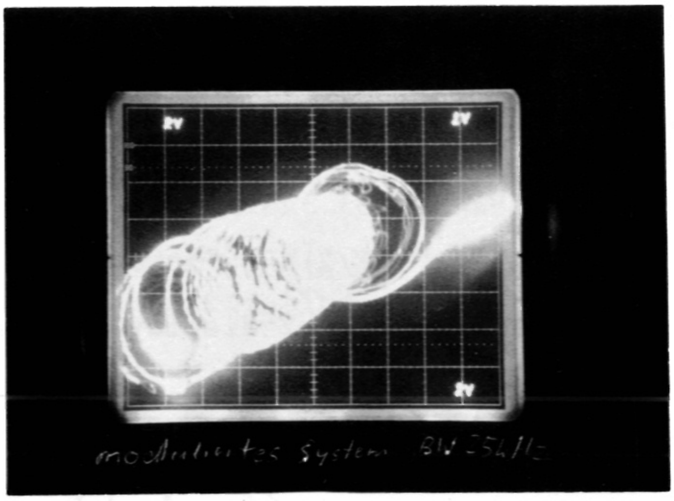


Fig.3a

Figure 3b was recorded with a test bandwidth of 1 MHz.

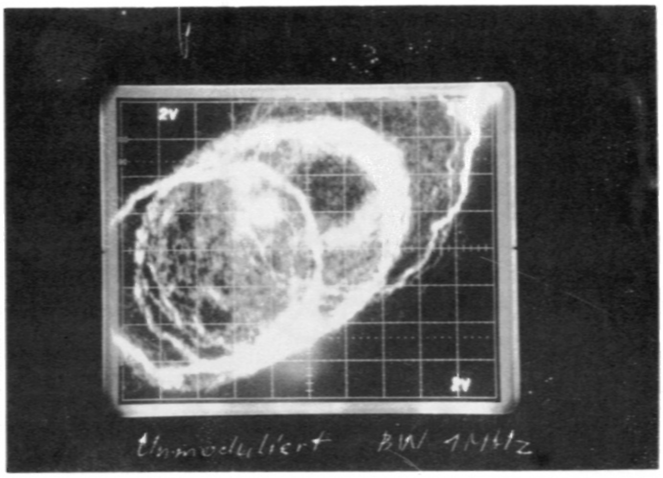
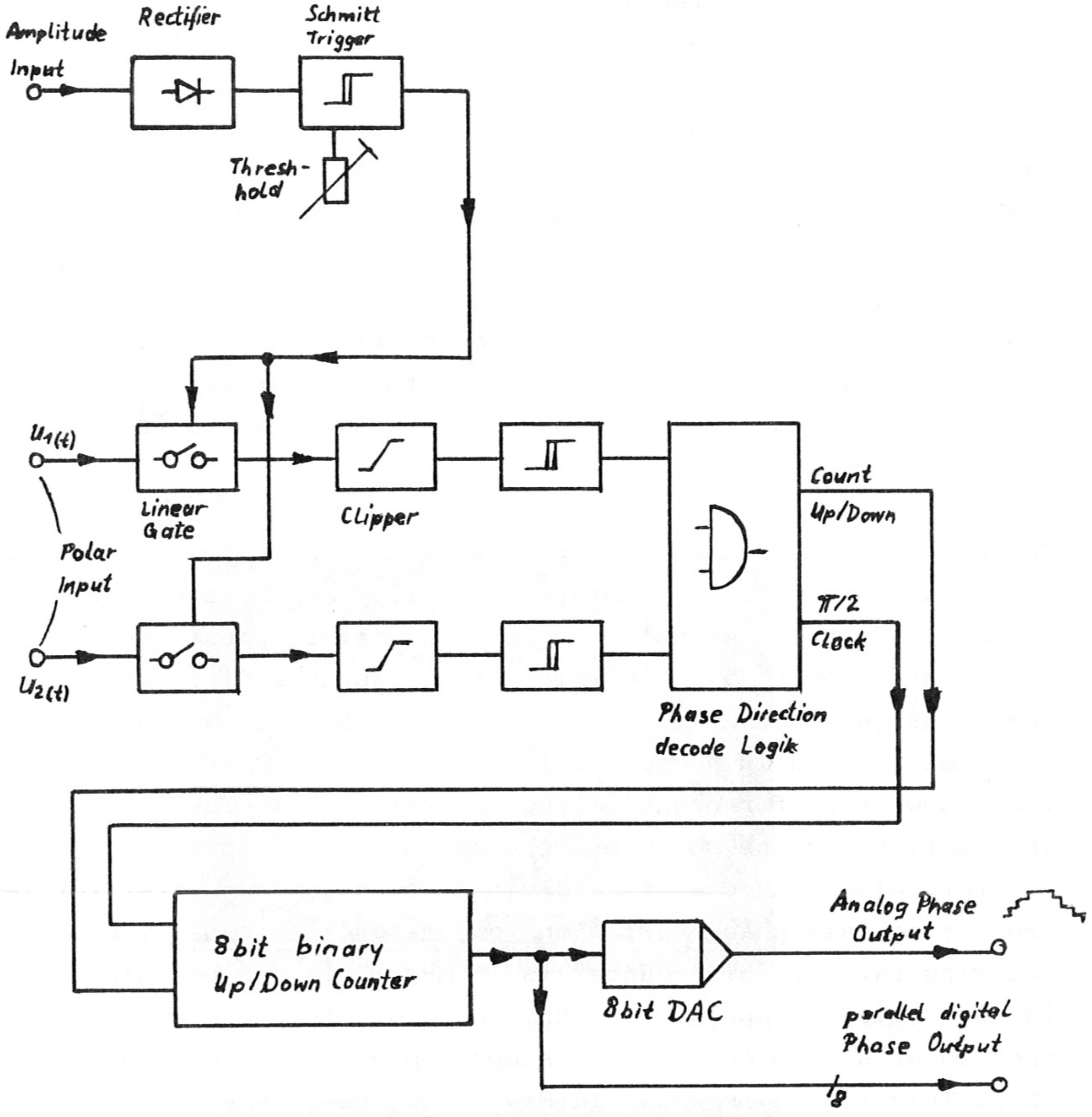


Fig.3b

The differences clearly show the high-frequency component in the signal (Fig.3b). If more information from the density yielded by the microwaves is required, higher bandwidths have to be taken. Without modulation these depend only on the mixing stage and the following wide-band amplifier and are therefore easier to attain. In order to obtain a direct, continuous representation of the phase as a function of time, the signal was split into a digital and an analog component, which were afterwards merged again. The extraction of the digital signal is shown in Fig.4. From the polar diagram the intersections with the ordinate and abscissa are counted and reproduced as a function of time /3/. The amplitude is compared with a threshold value; if the latter is larger than the value set, the two polar signals are switched to the electronic system.

The signals are limited and provided with a hysteresis. This is required to keep the last state stored if the amplitude is not reached and hence the polar signals are interrupted. The signals are transmitted to a logic which identifies the direction of the phase change. The intersections with the ordinate and abscissa are then counted in a counter (upwards for positive angular variation, downwards for negative angular variation). The 8-bit binary information for the computer is available at the output of the counter. Also connected is a digital-to-analog converter for representing fast phase variations on the oscilloscope. The upper counting rate of this counter is 15 MHz. This can be raised by faster logic to approx. 200 mHz. The digital-to-analog converter then shows a step curve whose steps represent phase changes of $\pi/2$. This signal is shown in Fig.5 for one plasma shot.

The top trace gives the output voltage of a mixer. The amplitude is a function of time and the sine of the phase. The bottom trace shows only the phase as a function of time, the amplitude being of no significance. The X axis has the scaling 5 x 2 Pi/div.



SIMPLIFIED BLOCK DIAGRAM OF A INCREMENTAL PHASE COUNTER

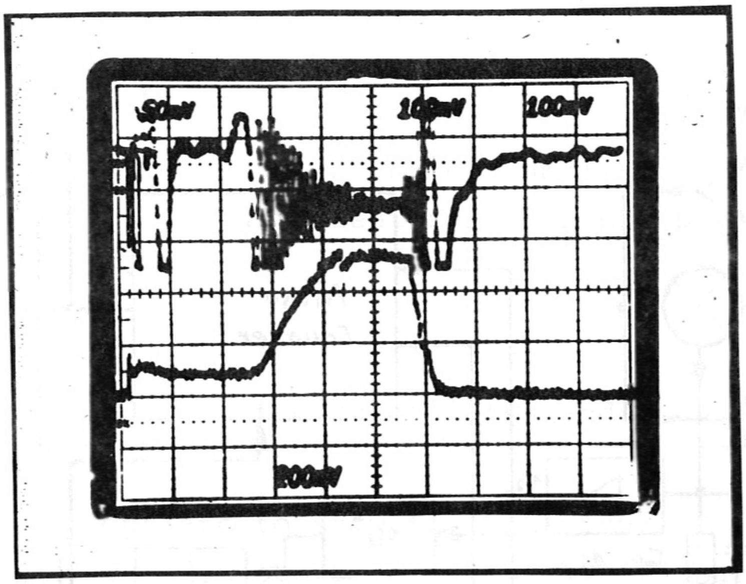
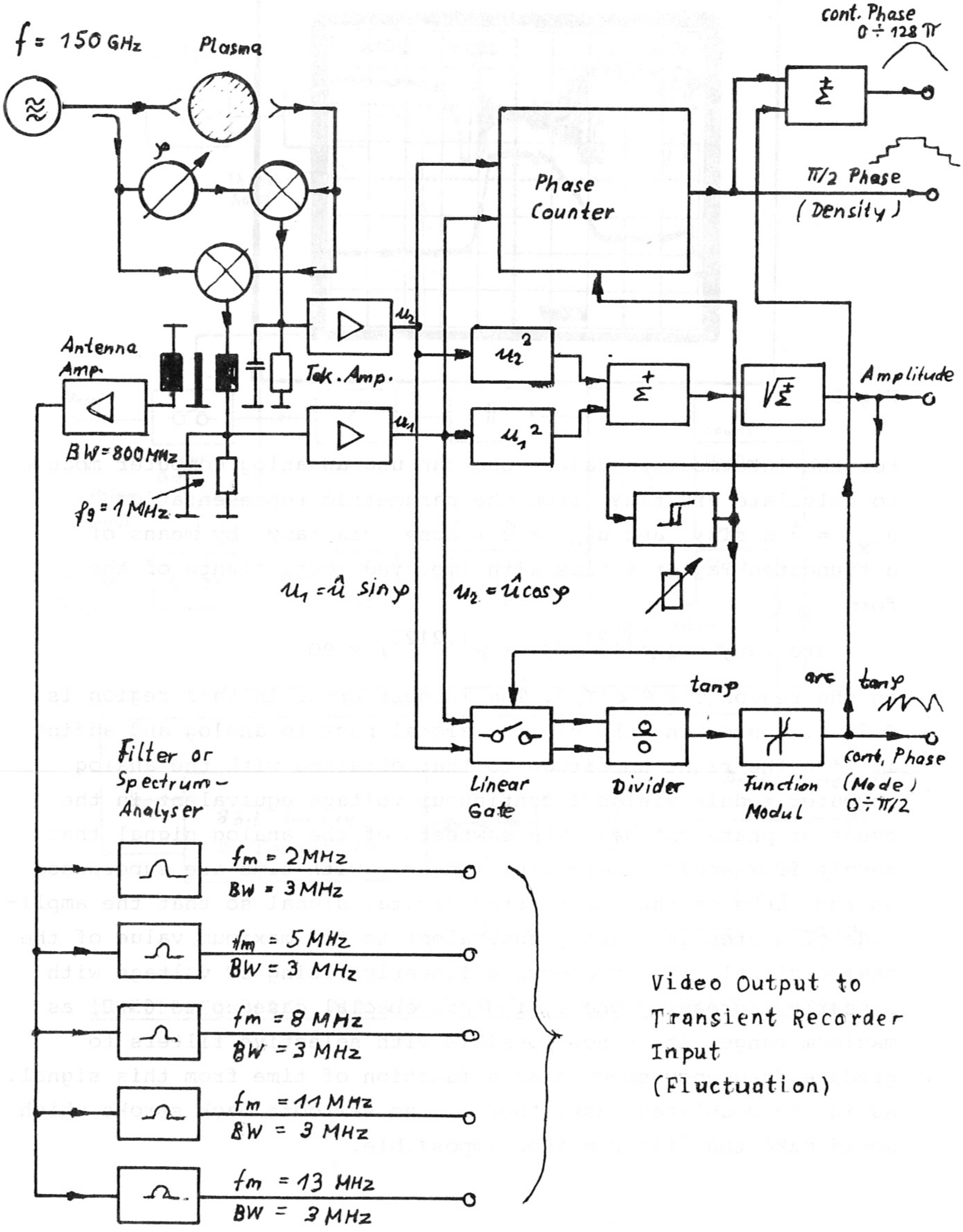


Fig.5:

For the intermediate values one can use an anlog computer module to calculate arc tanφ from the parametric representation $u_{(x)} = \hat{u} \times \sin\varphi$ and $u_{(y)} = \hat{u} \times \cos\varphi$ via tanφ by means of a truncated Taylor series with improved coefficients of the form

$$\text{arc tan}\,\varphi = (\varphi^{1,2125}/1 + \varphi^{1.2125}) \times 90^{\circ}$$

in the region $0 < \varphi < \pi/2$. The largest error in this region is 0.75 %. Converting the digital signal back to analog and adding it with the right amplitude to that obtained with the analog computer module yields a continuous voltage equivalent in the event of phase changes. The sawteeth of the analog signal that result from angles increasing linearly with time are superposed on the steps of the reconverted digital signal so that the amplitude of a step is exactly equivalent to the maximum value of the analog signal. This produces a linearly rising DC voltage with linearly increasing phase, in this special case up to 65 Pi as maximum range. It is now possible with selective filters to produce frequency spectra as a function of time from this signal. As in the modulated case, there is no sawtooth back stroke which would make the filter method impossible.



PROPOSAL FOR UNMODULATED INTERFEROMETER

The amplitude can also be calculated with the same analog computer module:

$$A = \left(u_{(x)}^{2} + u_{(y)}^{2}\right)^{\frac{1}{2}}$$

The two signals thus obtained have a small-signal bandwidth of 600 kHz, which is sufficient for, for example, mode analysis (Fig.6).

4. Comparison between the unmodulated and modulated interferometers

It is also appropriate to show the behaviour of the modulated and unmodulated systems in operation with several parallel channels (Fig.7).

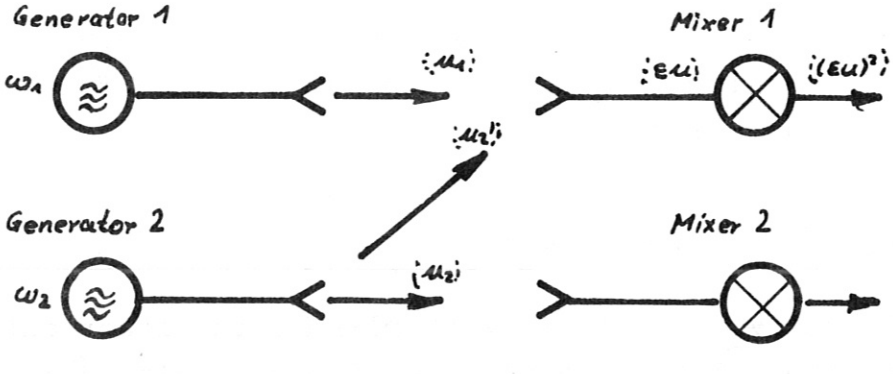


Fig.7:

The voltage at mixer 1 is obtained by superposing two signals:

$$u = u_1 \sin(\omega_1 t + \varphi_1) + u_2' \sin(\omega_2 t + \varphi_2)$$

where u_2' represents the component at mixer 1 deriving from generator 2. Assuming a square-wave characteristic of the mixer diode, the following mixture products are obtained at the output:

$$
\begin{aligned}
u^2 = {} & \frac{u_1^2}{2} - \frac{u_1^2}{2} \cos 2\,\omega_1 t \cos 2\,\varphi_1 \\
& + \frac{u_1^2}{2} \sin 2\,\omega_1 t \sin 2\,\varphi_1 \\
& + \frac{u_2'^2}{2} - \frac{u_2'^2}{2} \cos 2\,\omega_2 t \cos 2\,\varphi_2 \\
& + \frac{u_2'^2}{2} \sin 2\,\omega_2 t \sin 2\,\varphi_2 \\
& + u_1\, u_2' \Big[\cos(\omega_1-\omega_2) t \cos(\varphi_1-\varphi_2) \\
& \qquad -\sin(\omega_1-\omega_2) t \cos(\varphi_1-\varphi_2) \\
& \qquad -\cos(\omega_1+\omega_2 6 \cos(\varphi_1+\varphi_2) \\
& \qquad +\sin(\omega_1+\omega_2) t \sin(\varphi_1+\varphi_2)\Big]
\end{aligned}
$$

a) If $\omega_1 = \omega_2$, i.e. if the two antennae are supplied from the same generator, it follows that $\omega_1 - \omega_2 = 0$, and only two components in the low-frequency range are obtained from the neighbouring channel:

$$\frac{u_2'^2}{2} + u_1\, u_2' \cos(\varphi_1 - \varphi_2)$$

As $u_2' = f(t)$ and $\varphi_2 = f(t)$ are with plasma, the lower cut-off frequency of the selective amplifier in the modulated system has to be higher than its maximum bandwidth to exclude this cross-talk. This constitutes limitation in the time behaviour.

b) If $\omega_1 \neq \omega_2$, i.e. if the two antennae are supplied by two generators and $|\omega_1 - \omega_2| > \omega_E$, where ω_E denotes the cut-off frequency up to which the amplifier transmits, the neighbouring generator delivers only the component.

$$\frac{u_2'^2}{2} \; -$$

If this component is not constant in time, it acts as a disturbance in the unmodulated system. In the modulated system it is a) that applieds. In the unmodulated system special attention should be paid to good directional characteristics of the mechanical structure of the antennae to keep this disturbing component small.

To summarize, it can be stated that it is possible in the modulated system to achieve a certain channel separation by choosing various modulation frequencies and the respective selective amplifiers. In the unmodulated system channel separation can only be done if the antennae have very good directional characteristics.

Comparative Table

Characteristics	modulated	unmodulated
Frequency stability	sensitive	insensitive
Modulation linearity	highly linear	uncritical
Generator noise	sensitive	insensitive
Resolution	governed by width of intensity modulation	governed by noise
Time behaviour	dependent of amplitude of modulation frequency	only dependent on amplifier bandwidth
Correlation with other measurements	with another signal if two-beam oscilloscope	with all other measurements
Evaluation by computer	not possible	very good, data being digital
Recording	photo	magnetic tape
Ambiguity due to mixture products	very likely	not so likely
Channel separation	by various modulation frequencies and selective amplifiers	only by means of mechanical design

The advantages of the unmodulated system over the modulated one are insensitivity to generator frequency fluctuations for equal conductor lengths in the test and reference channels and the resulting insensitivity to generator noise. Furthermore, the unmodulated system does not need a linear modulation characteristic, and so a transit-time tube with its higher output power is used as generator. The resolution of the system is governed only by the signal-to-noise ratio. The time behaviour depends only on the mixer and amplifier bandwidths. The analog and digital output signals can be correlated with all other measurements on any oscilloscope, UV recorder or ADC. Data acquisition by computer is very good since the data are digital. Recording can be done on magnetic tape. As mixing is done with a discrete frequency and not with a frequency spectrum, ambiguity due to undesired mixture products (back stroke) is not so likely to arie. The system is suitable for filtering out amplitude frequency spectra for fluctuation measurement since if affords continuous representation of amplitude and phase.

Disadvantages are the somewhat greater outlay for tuning of the second mixer and, in multi-channel operation, the greater outlay for focusing the microwaves to reduce cross-talk.

4. Summary

The unmodulated system is very suitable for obtaining more information from microwave diagnostics. It yields the entire bandwidth without any disturbing modulation signals and therefore facours measurement of frequency spectra. It gives the electron density better than a modulated system and allows fast processes in the plasma to be investigated.

Acknowledgements

The author has to express his gratitude to Dr.N.Gottardi and E.Rossetti for the helpful collaboration.

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