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A SIMPLE 4mm MICROWAVE RECEIVER FOR PLASMA SCATTERING EXPERIMENTS

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A SIMPLE 4 mm MICROWAVE RECEIVER FOR PLASMA SCATTERING EXPERIMENTS

by

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A B S T R A C T

A microwave receiver working in the 4 mm band has been developed for use in plasma scattering experiments. The receiver has a bandwidth of 6 Mc/s and an integrating time of 1 μsec. The measured sensitivity (unity signal-to-noise ratio) was 2×10^{-10} W. This sensitivity could be improved by a factor of 1200 as the result of component development. The receiver is simple in construction and does not require a separate local oscillator.

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CONTENTS

INTRODUCTION

The scattering of microwave radiation by a plasma is a well known method of investigating the presence of density inhomogeneities (Wort 1966, Wort and Heald 1965, Heald and Wharton 1965). Owing to the mass motion of the plasma, the frequency of the scattered radiation is often Doppler shifted away from the frequency of the incident radiation by a few megacycles.

Theoretical analysis (Fosterling and Wuster 1951, Ginzburg 1964, Gil'denberg 1964) suggests that it should be possible, in such an experiment, to generate radiation at a harmonic frequency of the incident power for relatively low power levels ($\lesssim 1\ W/cm^2$) in the incident beam of radiation. Another possible effect is that of cross modulation if two microwave beams in the same frequency band are incident on the plasma. Verification of the predictions of the theory could lead to the development of more refined diagnostic techniques and to the development of possible ways of heating a plasma by microwave radiation.

In order to detect the cross modulation of two microwave beams it is necessary to use a sharply tuned receiver, so that one beam can be detected and the other rejected. A superheterodyne receiver meets this requirement and also has the advantage of high sensitivity.

A major disadvantage of the superheterodyne receiver is the need to lock the frequency of its local oscillator at a fixed frequency difference from that of the oscillator producing the beam it is desired to detect. The receiver to be described does not use a separate local oscillator but draws an equivalent amount of power from the oscillator generating the microwave beam whose scattering it is desired to detect. This results in a considerable saving in complexity and an increase in the flexibility of the receiver.

The receiver could also be used in experiments in harmonic generation, if it were possible to produce sufficient power at the harmonic frequency of the incident beam for this to act as the local oscillator signal. This could possibly be done by the use of an oscillator tube such as the 4TFK3 which produces 4 mm power by harmonic generation of 8 mm power and has waveguide outputs for both the 8 mm and 4mm bands. If this were so the use of the receiver to be described would be a great advantage since, in harmonic generation experiments, a local oscillator of suitable frequency might not be readily available.

The receiver which has been constructed for use in the 4 mm band has a band width of 6 Mc/s and its detector an integration time of 1 μsec. The minimum detectable signal is 2×10^{-10} W, a figure which could be improved upon. By comparison, the simplest type of microwave receiver (which consists of a microwave detector diode whose output is amplified by a wide band amplifier) would not appear to be capable of detecting signals of less than 3×10^{-9} W with a time resolution of 1 μsec even under favourable circumstances. Recent reviews of the subject (Harvey 1963, Warner 1966) suggest that the present receiver has not been described before. Some solid state physics experiments in electron paramagnetic resonance have made use of a single klystron to provide both the power incident in the speciman under examination and the power of the local oscillator of the receiver, (Buckmaster and Dering 1965, 1966; Brown et al 1965, 1966). In the solid state experiments the signal transmitted by the cavity containing the speciman under examination is offset in frequency from the power incident on the cavity by the frequency at which the magnetic field applied to the speciman is swept. This frequency is often in the audio range and frequencies in excess of 100 kc/s do not appear to have been used. This means that the bandwidth of the amplifier circuits used can be made small and the detector circuits made with a long time constant.

In the plasma physics experiments the frequency shift between the scattered and incident signals might be as great as several megacycles and the scattered signal itself might have a frequency spectrum of the order of a megacycle in width. Thus a receiver for use in plasma physics experiments requires much greater bandwidth amplifiers than one for use in solid state experiments and should be readily tuneable. Also the microwave frequency at which plasma physics experiments are usually performed is higher than in a solid state experiment, so that the components have usually a poorer performance.

THEORY OF THE RECEIVER

Fig. 1 shows a simple form of scattering experiment using a receiver of the new type. Microwave power from the oscillator O at frequency f is beamed onto the plasma. A small amount of power, of the order of milliwatts, is drawn from the oscillator and passed to the mixer C of the receiver by means of a waveguide; the wave entering the mixer by this path is represented by $A \cos(2\pi ft + \varphi)$ where φ is an arbitrary phase angle. Some of the power scattered from the plasma at frequency $f + \Delta f$ enters the receiving horn H_2 and passes to the modulator M by means of a waveguide; the amplitude of the wave entering M is a_1. The modulator amplitude modulates the wave at a frequency p, much less than the microwave frequency; the wave entering the mixer C from the modulator is represented by $a_0 (1 - \xi \cos 2\pi pt) \cos 2\pi (f + \Delta f)t$, where ξ is some constant less than unity.

The output of the mixer is passed to an intermediate frequency (I.F.) amplifier whose mid-band frequency is close to one of the frequencies $p \pm \Delta f$ and the output of the amplifier is detected by a linear detector connected to a circuit of time constant τ. If a balanced mixer is used with square law detectors of equal efficiency the voltages produced at the outputs of the mixer are (Harvey 1963),

$$\left[A \cos(2\pi ft + \varphi) \pm a_0 (1 - \xi \cos 2\pi pt) \cos(2\pi (f + \Delta f)t) \right]^2 .$$

Expanding this expression and assuming that $A \gg a_0$, and retaining only those large terms whose frequency is such that they might be amplified by the I.F. amplifier, the output of the mixer is found to be

$$\pm A a_0 \left[\cos(2\pi (\Delta f)t - \varphi) - \frac{\xi}{2} \cos(2\pi (p + \Delta f)t - \varphi) - \frac{\xi}{2} \cos(2\pi (p - \Delta f)t + \varphi) \right] .$$

In order to obtain a receiver of low noise it is usual to choose the operating frequency of the I.F. amplifier to be in excess of 40 Mc/s. In the experiments projected for this type of receiver the frequency change of the scattered radiation will be less than this, so that first of terms in the expansion can be neglected.

The signal which is passed to the I.F. amplifier is then

$$\pm A a_o \xi \left[\text{Cos } (2\pi (p + \Delta f)t - \varphi) + \text{Cos } (2\pi (p - \Delta f)t + \varphi) \right] .$$

If only one of the frequencies $p \pm \Delta f$ lies within the range of the amplifier, the output of the detector is proportional to $A a_o \xi$; this result assumes that τ the time constant of the detector circuit is such that $\tau p \gg 1$. If both of the side band frequencies are amplified by the same factor the output of the detector is proportional to $2 A a_o \xi |\text{Cos } (2\pi (\Delta f)t - \varphi)|$ if τ is small compared with the time variation of the cosine term. In a laboratory plasma, however, the geometrical configuration is rarely static so that Δf is not zero and φ changes with time. If the time constant τ is long compared with the time scale of the variation of the cosine term the detector circuit will register the mean value of the cosine term which is $2/\pi$. The results are summarised in Table I.

TABLE I

OUTPUT OF DETECTOR CIRCUIT ($\tau p \gg 1$)

No. of side bands in range of I.F. amplifier	one	two	two
$\tau (\Delta f - \frac{d\varphi}{dt})$	-	$\gg 1$	$\ll 1$
Detected signal arbitrary units	$A a_o \xi$	$\frac{4}{\pi} A a_o \xi$	$2 A a_o \xi |\text{Cos}(2\pi(\Delta f)t - \varphi)|$

An alternative method of building the receiver, which appears at first sight to be very attractive since it avoids the power losses inherent in the modulator, is to use the arrangement of Fig.1, but to omit the modulator and then change the frequency of the high level signal entering the mixer by such an amount that the output of the mixer would be accepted by the I.F. amplifier.

Ernst and Skislak (1963) have described such a frequency changer; in this device microwave power enters at a frequency f and emerges at a frequency $f + p$ ($f \gg p$), together with small amounts of power at frequencies f, $f-p$. Even if the conversion efficiency of the device were high enough not to place a serious power drain on the oscillator, the receiver is open to the following objection. If the conversion efficiencies of the mixer crystals are not quite equal the output of the frequency converter at frequencies f, f + p would be mixed and amplified by the I.F. amplifier and mask the low level scattered signal. As an example if the mixer is unbalanced by 10% and the power level falling on the mixer at frequency f + p is 3 mW and there is 8 μW of power at frequency f, the signal supplied to the I.F. amplifier is the same as that due to a scattered signal of 8×10^{-9} W. This spurious signal will be mixed with the amplifier noise by the non-linear characteristic of the detector, producing excess noise at the output of the receiver. For a square law detector the amplitude of this noise is proportional to that of the signal if this is large (Robinson 1962). The receiver of Brown, et al (1965) appears to be open to this objection.

EXPERIMENTAL

A test was carried out on a receiver assembled from components that were readily available in the laboratory; the apparatus is shown in Fig.2. Power from a 70 Gc/s oscillator after passing through the level setting attenuator A was fed to a balanced mixer containing two crystal diodes type IN 2792, the power being adjusted so that the rectified crystal currents were 0.5 mA. The power simulating the radiation scattered from the plasma was obtained by sampling some of the high level power by means of the directional coupler and passing it to the modulator M by way of the resistive vane and rotating vane attenuators. The modulator, which had an operating frequency of 45 Mc/s, is described in more detail below. The power then passed to the mixer by way of the ferrite isolators. In order to facilitate observations a mechanical chopper was used to give 100% modulation of the wave at a frequency of a few hundred cycles per second. In this case $\Delta f = 0$ and the relative phase φ of the wave entering the mixer was important, so that the phase shifter was adjusted to give maximum amplitude of the chopped signal displayed on the cathode ray oscilloscope. Subsequent variation of the attenuation in the arm QFM was by means of the rotating vane attenuator which introduced no observable phase shift. The 3 db points of the I.F. amplifier were at frequencies of 42.7 and 48.6 Mc/s, and the integrating time of the post detector circuit was 1 μsec.

The power level of the wave entering the modulator was adjusted and it was found that the amplitude V of the signal displayed on the cathode ray oscilloscope was related to the amplitude a_1 of the wave by $V \propto a_1^n$, with $n = 0.93$. This relation was accurate to better than ± 10% over the power range 6.8×10^{-7} W to 3.4×10^{-9} W. If $a_0 \propto a_1$ the theory given above predicts that $n = 1$. The apparatus was then adjusted so that low level power falling on the modulator was 5×10^{-7} W. The level setting attenuator A was altered so that the amplitudes A, a_1 of both high and low power waves varied. It was found that $V \propto A\, a_1$ to an accuracy of ± 3%, as the power falling on one of the mixer crystals varied from 1.1 mW to 0.4 mW, the usual operating condition being 1.0 mW. These results are taken as showing that a true mixing of the signals took place and the analysis given above is approximately correct.

The sensitivity of the receiver was measured by observing the chopped waveform on the oscilloscope screen and increasing the attenuation in the arm QFM until the amplitude of the waveform was equal to that of the noise. When this occurred the power passing through the waveguide chopper was 8.5 db above the power required to give unity signal-to-noise ratio (Williams 1947, Barlow and Cullen 1950). This power is usually taken as the minimum detectable signal. Disconnecting the waveguide run at X caused the chopped waveform to disappear from the oscilloscope screen. The power falling on the modulator which lifted the noise output of the detector by its own height was calculated from the known attenuations and insertion losses of the waveguide components and the output of the oscillator, which was measured with a calorimeter; this power level was 5.9×10^{-10} W with a probable error of ± 20%. The minimum detectable signal was then 8.3×10^{-11} W. The test arrangement was unusual in that the phase angle was adjusted to give maximum sensitivity. The experiments in which it is proposed to use the receiver are such that $(\Delta f - d\varphi/dt) \gg 1$; reference to Table I shows that this reduces the sensitivity of the receiver by a factor of $\pi^2/4$ to 2.1×10^{-10} W.

Fig.3 is a diagram of the modulator which consists of a selected IN 2792 diode connected to one arm of a hybrid tee, the opposite arm being terminated by a matched load. The power was incident on the tee through the shunt arm and the modulated signal emerged through the series arm. The crystal was biased as shown and connected to a laboratory signal generator producing a 45 Mc/s signal of nominal amplitude 0.2 V r.m.s.

The characteristic of the modulator was measured to zero modulating frequency and a microwave power level of 400 μW. The amplitude a_0 of the emergent wave was related to a_1, that of the incident wave, and the bias voltage V applied to the diode by the following empirical expression:-

$$a = 0.170\, a_1 \left[1 + 0.644 \tanh 2.68\,(V - 0.32)\right] .$$

The accuracy of the expression is ±4% for V in the range 0.6 to 0.06 V. The phase shift through the modulator was not measured. An ideal modulator, that is one whose characteristic is that the output wave has an amplitude $\frac{1}{2} a_1(1-\mathrm{Cos}\, 2\pi pt)$, when used in a receiver of the type described above would produce a sensitivity $\pi^2/4$ worse than that which would be obtained from the same mixer and I.F. amplifier used in a conventional superheterodyne receiver.

An exceptionally good superheterodyne receiver working in the 4 mm band with a similar band width and integration time would have a sensitivity of 1.7×10^{-13} W (Warner 1966), so that it should be possible to obtain an improvement in the sensitivity of the present receiver of 1200. Most of this, a factor of 280, could be obtained by improvements in the design of the modulator, the remainder being due to imperfect coupling between the mixer and the I.F. amplifier and to noise in the amplifier itself.

It is interesting to note in this respect that waveguide switches which would form ideal modulators are already commercially available for use at frequencies up to 18,000 Mc/s, with switching times of the order of 5×10^{-9} sec.

CONCLUSIONS

A new type of microwave receiver, working in the 4 mm band, has been constructed for use in plasma scattering experiments. Theoretical analysis has shown that the sensitivity of such a receiver could be 2.5 times worse than that of a superheterodyne receiver. The present receiver has not obtained this sensitivity by a factor of 1200, the main cause of the discrepancy being in the lack of efficient waveguide switches for use at this frequency. Such switches are available for use at longer wavelengths.

In its present state the receiver has the advantages of simplicity and cheapness as it requires no separate local oscillator or frequency stabilisation. It also has the advantages of a narrow bandwidth, giving good selectivity, and a higher sensitivity than that of a simple crystal video receiver.

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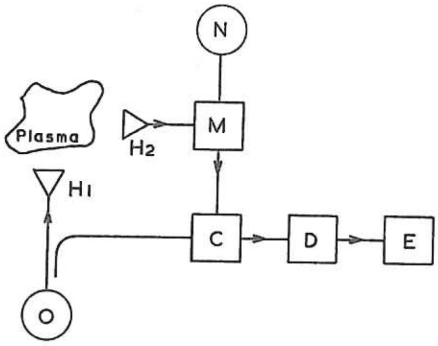

Fig. 1

(CLM-P 112)

Block schematic diagram of the receiver and associated equipment C - microwave mixer; D - intermediate frequency amplifier operating at frequency p; E - detector circuit, time constant τ; O - microwave oscillator; H_1 - transmitting horn; H_2 - receiving horn; M - modulator; N - oscillator of frequency p

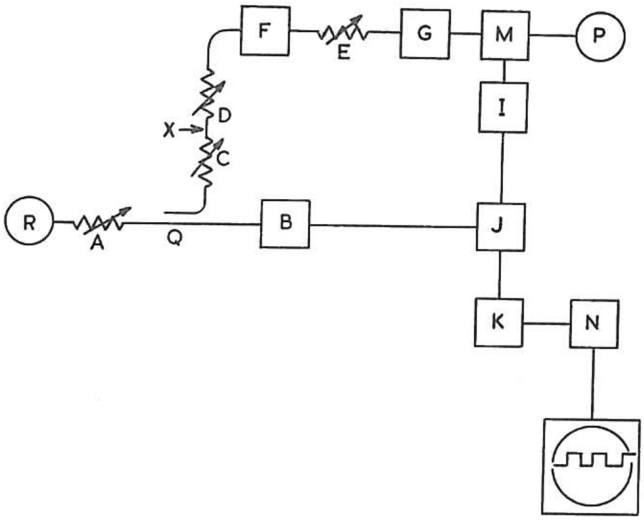

Fig. 2

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Schematic diagram of laboratory test of receiver: A - level setting attenuator; B-phase shifter; C-resistive pad attenuator; D - resistive pad attenuator; E - resistive pad attentuator; F - mechanical chopper G - rotating vane attenuator; I - ferrite isolator; J - balanced mixer; K - I.F. amplifier; M - modulator; N - detector; P - oscillator (45 Mc/s); Q - directional coupler; R - microwave oscillator (70 Gc/s)

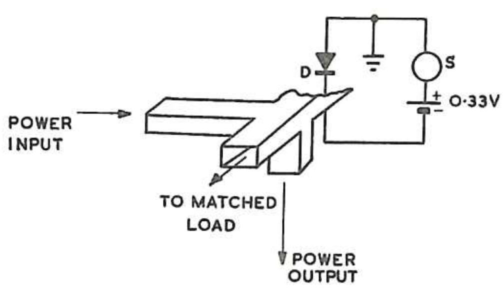

Fig. 3

(CLM-P 112)

Schematic diagram of modulator using a hybrid tee: D - diode type IM 2791; S - signal generator (0.20 V rms at 45 Mc/s)