THE INVESTIGATION OF AN ELECTRON RESONANCE SPECTROMETER UTILIZING A GENERALIZED FEEDBACK MICROWAVE OSCILLATOR

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The purpose of this investigation was to determine the technical feasibility and the attainable sensitivity of a "self-stabilized" oscillator-spectrometer system in terms of a generalized sample-carrying feedback element to replace the conventional spectrometer systems. This new "self-stabilized" oscillator-spectrometer has a microwave amplifier with a generalized network element in the positive feedback loop causing oscillation to occur at the network's central resonant frequency, with essentially instantaneous frequency stability. This eliminates the need for electronic frequency stabilizing equipment. With the paramagnetic test sample located in the H field of the generalized feedback element, the network's attenuation and phase characteristics are altered when paramagnetic resonance occurs. The resultant problem is to determine the effect this change has on the oscillator's amplitude and frequency of oscillation. From this, the system's ultimate sensitivity is determined from a consideration of the noise within the oscillator loop.

The oscillator-spectrometer is similar in principle to the autodyne detector. Little work has been done toward analyzing the autodynes theoretical sensitivity. Furthermore, no attempt has been made to extend the autodyne's use into the microwave region where it can be used for EPR work. With such a system for EPR detection, we are able to discard the conventional electronically stabilized low power klystron and superheterodyne detection systems and replace them with this "all microwave" device. A block diagram of the "self-stabilized"

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Microwave Oscillator-Spectrometer is shown in Figure 1. The amplifier is assumed to have a power gain of G_P and a noise figure of F_1.

Although the feedback network may take on any configuration desired, it must contain a resonant cavity in one form or another. This cavity must: (1) be the frequency determining element of the network; (2) contain the paramagnetic sample. When the proper loop phase and amplitude conditions are met, oscillation will occur at the resonant cavity frequency. This provides a built-in frequency stabilized system. A directional coupler at the amplifier output is used to sample the microwave power. The amplitude change is monitored by a crystal detector. To detect the frequency shift, the coupled energy is passed through a frequency discriminator and then detected.

When electron paramagnetic resonance occurs, both the cavities Q and resonant frequency are affected by the sample susceptibility χ . Any change in the sample cavity, at magnetic resonance, causes a change in the feedback network. The cavities resonant frequency will change by $\Delta\omega_r$, introducing a reactive component into the feedback network. The amplitude of the frequency variation due to magnetic resonance is

$$\Delta\omega_r = \frac{\partial\omega_r}{\partial\chi}\Delta\chi , \qquad (1)$$

where $\partial\omega_r/\partial\chi$ is a characteristic of the generalized feedback network.

The change in the sample carrying cavity Q is reflected as a change in the feedback attenuation N_V. The expression for changes in oscillation amplitude at the amplifiers output terminal when paramagnetic resonance occurs becomes

$$P_s = K_p G_p P_i \left[\frac{\partial\,(1/N_V)}{\partial\chi}\Delta\chi\right]^2 \qquad (2)$$

G_p is the amplifier power gain; the resonance signal is seen to be proportioned to networks input power. K_p is referred to as the "regenerative amplification" and can be as high as 10^6. It is given by the expression

$$K_p = \frac{\partial P_o}{\partial G_p} \frac{G_p}{P_o} \qquad (3)$$

Here the term $\partial P_o / \partial G_p$ is the slope of the amplifiers gain versus input signal characteristic curve. As the amplifier become more linear, K_p, increases the overall detection sensitivity. This explains why the resonance signal is stronger for low levels of oscillations where the amplifier is linear.

In order to calculate the minimum detectable change in power level or frequency of oscillation, the noise in the system must be determined. The problem reduces to the fact that if an amplifier with noise figure F_1 is connected as an oscillator, then, what will be the resultant noise fluctuations of the oscillator's frequency and output amplitude?

If we represent the amplifiers characteristic curve by

$$V_1 = \alpha V_{in} - \gamma V_{in}^3, \qquad (4)$$

and let the amplifier noise, e_n, be a driving source as shown in Figure 1, then, by the methods of Rice and Bennett the noise fluctuations of the oscillator's output amplitude becomes

$$P_N = \frac{F_1 k T_o(\alpha - 3/2 \gamma P_o R_o)}{3 \gamma P_o R_o} \Delta \omega_{Det}, \qquad (5)$$

and the oscillator's frequency variation due to noise becomes

$$\Delta \omega_N = \frac{F_1 K T_o \omega_o}{P_o Q_n} \Delta \omega_{Det}, \qquad (6)$$

Here, k is Boltzman's Constant, T_o room temperature in degrees Kelvin, Q_n the feedback networks Q, and $\Delta \omega_{Det}$ is the detection systems bandwidth.

From equation (4) the regenerative amplification as defined by (3) can be expressed in terms of amplifier parameters. That is, K_p becomes

$$K_p = \frac{-(\alpha - 3/2 \gamma P_o R_o).}{3 \gamma P_o R_o} \qquad (7)$$

It is important to note that the amplitude noise in the system is simply the thermal noise $F_1 k T_o \Delta \omega_{Det}$ amplified by the regenerative amplification.

Equations (2), (3), and (5) fit into place like a puzzle to form the magnetic resonance spectrometer. Figure 2 can be drawn to represent the system for detection of the amplitude variations. Here, the feedback network is driven from an ideal noiseless generator whose output is set equal to the amplifier power output P_i. Since there are essentially two noiseless amplifiers preceding the detector, its noise becomes negligible thus eliminating the need for superheterodyne detection. A similar system diagram can be drawn from (1) and (6) to represent the system for frequency detection.

Amplitude detection: if we divide the signal by the noise from equations (2) and (5) and set the resulting signal to noise ratio equal to unity, the minimum detectable change in susceptibility χ, becomes

$$\chi_{min} = \frac{\partial(1/N_v)}{\partial\chi} \sqrt{\frac{P_i}{F_i K T_o \Delta\omega_{Det}}} \qquad (8)$$

In order to demonstrate the technical feasibility and to experimentally verify the attainable sensitivity, an electron paramagnetic resonance oscillator-spectrometer was designed and constructed. The spectrometer utilized a 100 mw travelling wave tube with a noise figure of 20 db operated at a power level of 6 mw and frequency of 9.7 kMc. Theoretical calculations indicated a minimum detectable susceptibility of $\chi'' = 1.2 \times 10^{-11}$ for this system. A test sample of Bruceton Coal diluted in silica containing 1.5×10^{14} spins was used to verify the system sensitivity. This corresponded to a sample susceptibility of 4.7×10^{-11}. The recorded derivative signal to noise ratio was approximately 3.5. Thus, the minimum detectable susceptibility becomes

$$\chi'' = 1.35 \times 10^{-11}$$

If an amplifier with a noise figure of 10 db were used with a level of oscillation of one watt the minimum detectable susceptibility would be $\chi'' = 7.8 \times 10^{-14}$. Thus, the microwave oscillator-spectrometer resultant sensitivity is seen to be in agreement with the theoretically calculated sensitivity.

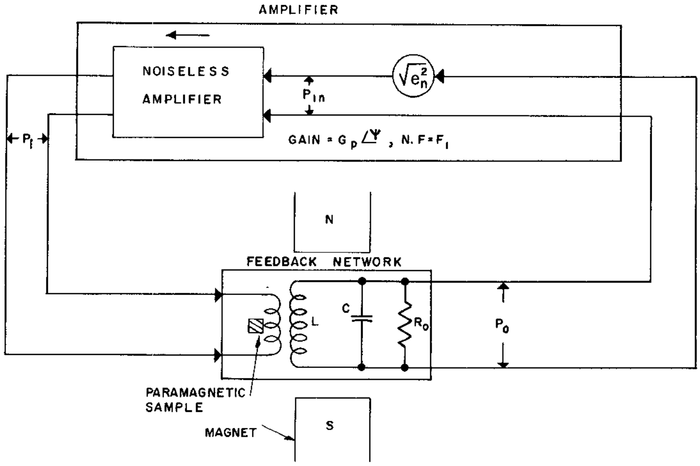

Fig. 1. Block diagram of oscillator spectrometer system.

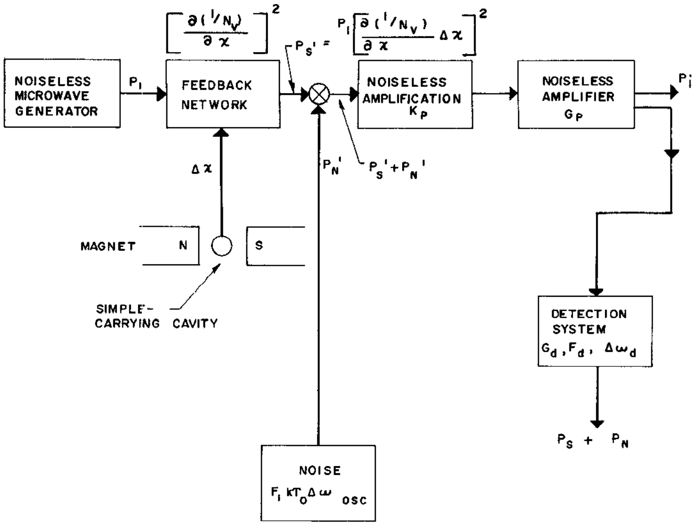

Fig. 2. Equivalent diagram of the oscillator-spectrometer for amplitude detection.

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