Design of a Superconducting Cavity Stabilized Maser Oscillator

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The pioneering works of W. H. Hartwig (Ref. 1), S. R. Stein and J. Turneaure (Ref. 2), J. J. Jimenez and A. Septier (Ref. 3), and others (Ref. 4) have shown the possibility of using a superconducting cavity to stabilize a microwave oscillator. The achievement of cavity Qs of the order of 10^{10} has made possible the realization of frequency standards with performance which could surpass that of the hydrogen maser.

The present study explores the possibility of integrating a superconducting cavity with a traveling wave maser to obtain a frequency standard with very high spectral purity.

I. Introduction

There are two basic methods for using a high Q resonator to stabilize a microwave oscillator. In one method, a voltage controlled oscillator (VCO) is used in a FM detector loop, as shown in Fig. 1, to stabilize the oscillator frequency. The second method, shown in Fig. 2, utilizes the high Q resonator as a transmission filter and stabilizes a microwave oscillator to the cavity/frequency. Both methods have been used by the investigators mentioned in Refs. 1–4.

The motivation for the present program was the long experience with traveling wave masers (TWMs) and closed-cycle refrigerators (CCRs), which technologies appeared to blend in very naturally with the requirements for a good superconducting cavity stabilized maser oscillator (SCSMO).

In the present article, a discussion is presented of the microwave electronics problems related to the SCSMO. In future articles, the cryogenics problems will be discussed and the statistical properties of the output signal from a SCSMO will be described.

II. Design of a SCSMO

The low-noise performance of a TWM would appear to make it a good device for integrating with a superconducting cavity to achieve a stable oscillator.[1] In such an application the TWM would operate at high signal levels

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[1] S. R. Stein is investigating the use of parametric amplifiers for reasons similar to ours (Ref. 5).

and in partial gain saturation in order to provide amplitude stabilization. Thus, it is apparent that the application of the TWM here is completely different from the usual linear-unsaturated mode in a receiving system.

In the usual electron tube or semiconductor oscillator, the mechanism for amplitude stabilization is contained in the Van der Pol equation (Ref. 6), which introduces damping terms proportional to the square of an exciting voltage or current. Whereas the Van der Pol equation was derived through phenomenological arguments to explain experimental observations in electronic oscillators, the same saturation effects were already inherent in the equations for the solid state maser as originally proposed by Bloembergen (Ref. 7). Subsequently, it was observed that power saturation in a maser was necessarily accompanied by a rise in the spin temperature of the amplifying medium, and that the spin temperature determined the noise performance of a maser.

Siegman (Ref. 8) has postulated an equation to account for saturation in a TWM; however, for present purposes a graphical approach will be adequate. Figure 3 shows a typical response for a TWM as a function of distance along an amplifying structure of great length; typical operating points a and b for an amplifier of length L cm are shown. The small signal gain G of the TWM is given by the slope for small values of x, while the oscillator gain G_o is given by P_b/P_a and is, of course, less than G. The response shown in Fig. 3 is for fixed conditions on certain parameters, such as pump power, operating temperature, and the static magnetic field. Variations in these parameters will cause corresponding power fluctuations in the oscillator output. Moreover, to the extent that these variations also cause frequency and phase fluctuations, they will need to be examined in greater detail in a later study.

An important observation can, however, be made at this point: the low-noise performance of a TWM can be realized in an oscillator provided the input section of the maser operates in the linear-unsaturated mode. The signal-to-noise ratio then can be made sufficiently high by the time the signal suffers amplitude saturation, toward the end of the TWM, that the spectral purity is not degraded. In other words, the high spin temperature (which implies high noise temperature) toward the end of the structure, due to saturation, will not degrade a properly designed SCSMO.

The microwave design problem is then to provide the proper coupling coefficients to the superconducting cavity so as to achieve the desired gain G_o while maximizing the loaded Q.

Figure 4 shows the equivalent circuit for the SCSMO. The transmission cavity has been analyzed in great detail by Montgomery, Dicke and Purcell (Ref. 9) and only the results need to be given here.

The transmission loss through the cavity at resonance is given by

$$T(\omega_0) = (4\beta_1\beta_2)/(1 + \beta_1 + \beta_2)$$

and the loaded Q is given by

$$Q_L = Q_u/(1 + \beta_1 + \beta_2)$$

In the above equations,

$T(\omega_0)$ = transmission loss at resonance

β_1 = coupling coefficient at input

β_2 = coupling coefficient at output

Q_L = loaded Q of cavity

Q_u = unloaded Q of cavity

An X-band TWM can easily have a gain in excess of 40 dB; hence, an oscillator gain of 30 dB is reasonable. Thus the transmission loss through the cavity should be around 10^{-3}. Assuming the input coupling can be made equal to the output coupling,

$$\beta_1 = \beta_2 = \beta$$

one has, finally,

$$T(\omega_0) = 4\beta^2/(1 + 2\beta)$$

and

$$Q_L = Q_u/(1 + 2\beta)$$

Using the numbers quoted above,

$$Q_L \approx (1/1.03)Q_u$$

Thus, the high gain in a TWM makes possible a loaded Q which approaches the unloaded Q.

One of the advantages of the servoed oscillator shown in Fig. 1 is that the time constant of the loop may be made sufficiently long to smooth out the noise in the system. With the SCSMO the noise is negligible, and the cavity performs a smoothing of any phase instabilities which may be inherent in the TWM. For Qs of the order of 10^{10} and

oscillations at a frequency of 10^{10} Hz, the time constant of the cavity is around 1 second. The transit time through a TWM is something less than a microsecond, and the superconducting cavity thus averages a signal which makes over a million round trips through the TWM. Small phase fluctuations through the TWM are nullified, and a highly monochromatic signal should be realizable.

Turneaure and Stein (Ref. 2) have shown that the Q of a superconducting cavity can increase by as much as an order of magnitude per Kelvin in the region of 4 to 1.5 K. It is essential, therefore, to operate the cavity at around 1.5 K; the TWM may be operated at 4.2 K. It is apparent then that the difficult problem to be solved for a continuously operating SCSMO is that of cryogenic refrigeration. Not only is it necessary to maintain the cavity at around 1.5 K with high temperature stability but the cavity also needs to be kept free of any mechanical

motion. These problems will be discussed in a future study.

III. Conclusions

The superconducting cavity appears to be compatible with a traveling wave maser. The real advantage of the superconducting cavity stabilized maser oscillator is that the cavity can be integrated with the TWM in such a way that rigid microwave connections can be made. Second-order perturbations resulting from fluctuations in transmission line joints are thus eliminated. However, the more serious problem is that of the mechanical (dimensional) stability of the cavity itself.

A special closed-cycle refrigerator needs to be developed for the SCSMO, and it will be discussed in the next report.

References

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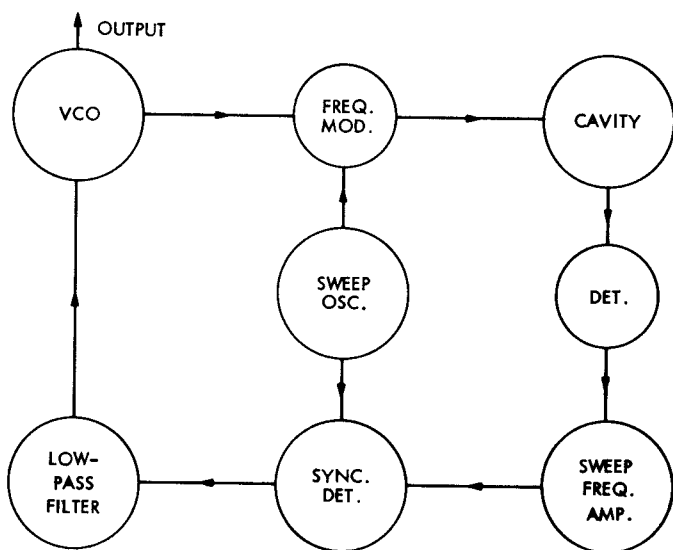
Fig. 1. Frequency modulation servoed oscillator. (The supercon-
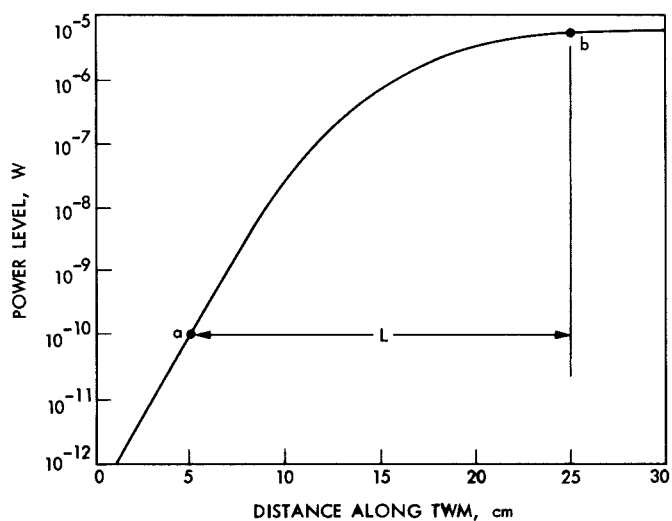ducting cavity is used as a frequency discriminator.)

Fig. 2. Regenerative microwave os-
cillator (The cavity is used as a
transmission filter.)

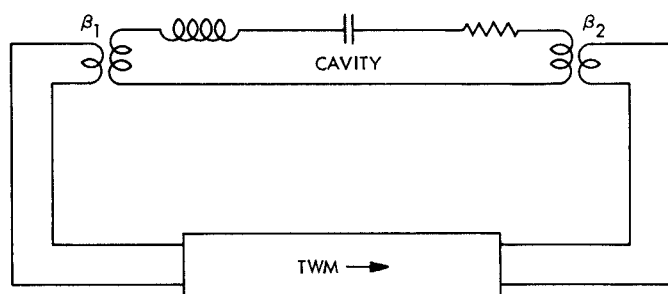Fig. 3. Typical power saturation curve for a TWM (see text)

Fig. 4. Equivalent circuit for a SCSMO (A small part of output
signal would be used as the stable oscillator output.)