Parametric Diodes in a Maser Phase-Locked Frequency Divider*

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Summary—The use of an ammonia-beam maser in a portable frequency standard requires a frequency divider which can be transistorized. A divider which uses no microwave tubes and hence one that can be transistorized is described. An ammonia-maser-controlled signal generator used to tune up the divider is also described. It is found that the use of a parametric diode frequency multiplier substantially improves the lock-in performance of the divider. Some data are given for comparing the performance of the maser frequency divider with and without the parametric diode frequency multiplier.

Frequency Divider

In order to divide the ammonia-beam maser[1,2] (hereafter called the maser) frequency down to a useful frequency for standards work, a phase-locked frequency divider has been designed and built. This divider, which does not use any microwave tubes (other than planar triodes), was designed as the first step toward a completely transistorized divider.

The circuit diagram is shown in Fig. 1. The system uses a phase-locked servo loop. A simplified explanation of the operation is as follows: The frequency of the voltage-controlled oscillator, which is approximately 1 mc, is multiplied approximately 24,000 times and beat with the maser output. The resulting IF at a value of several megacycles is fed into a phase-sensitive detector. The reference voltage for this detector is derived from the voltage-controlled oscillator. The error voltage output from the phase-sensitive detector is fed through a suitable integrator and phase-correction circuit to the VCO.

To prevent accidental locks to frequencies derived from the VCO, double heterodyning and frequency division of VCO frequency by a rational fraction are used to secure the phase-detector reference frequency and the translation frequency for the second IF. The VCO is locked with zero error when the frequencies and phases at the two inputs of the phase-sensitive detector are

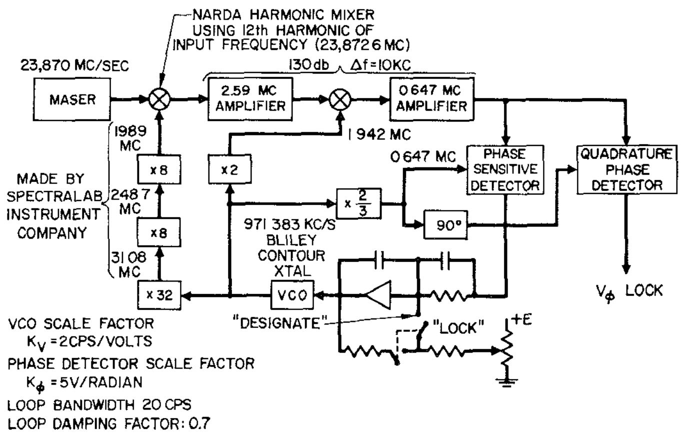

Fig. 1—Block diagram of phase-locked frequency divider.

equal. The frequency condition is then

$$[(Nf_0 - f_m) - Mf_0] = Df_0 \tag{1}$$

where

f_m = maser frequency = 23,870 mc,
f_0 = VCO frequency = 971,383 kc,
$N = 32 \times 8 \times 8 \times 12 = 24,576$,
$M = 2$,
$D = 2/3$.

Hence, $f_0 = f_m/(24,573 + 1/3)$. The loop bandwidth is 20 cps; the loop damping factor is 0.7.

Maser-Controlled Signal Generator

Of great utility in "tuning up" the divider for initial lock as well as for optimizing parameters and making the measurements described below is a means of obtaining maser frequency and stability at much greater power than maser signal power. An obvious way of amplifying at frequencies at which stable, high-gain amplifiers are not presently available is by the use of double conversion; *i.e.*, one translates to a frequency where amplification is convenient and then translates back to the desired frequency. This technique uses a common local oscillator for both translations and thus subtracts out to first order the drifts and swings of the local oscillator from the desired amplified signal. In the present case an additional difficulty is encountered because of the extremely low power output of the ammonia

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[1] J. P. Gordon, H. J. Zeiger, and C. H. Townes, "The maser—new type of microwave, frequency standard, and spectrometer," *Phys. Rev.*, vol. 99, p. 1264; August, 1955.

[2] J. Bonanomi, J. dePrins, J. Hermann, and P. Kartoshoff, "Améliorations d'un maser à NH_3," *Helv. Phys. Acta.*, vol. 30, p. 492; 1952. (In French).

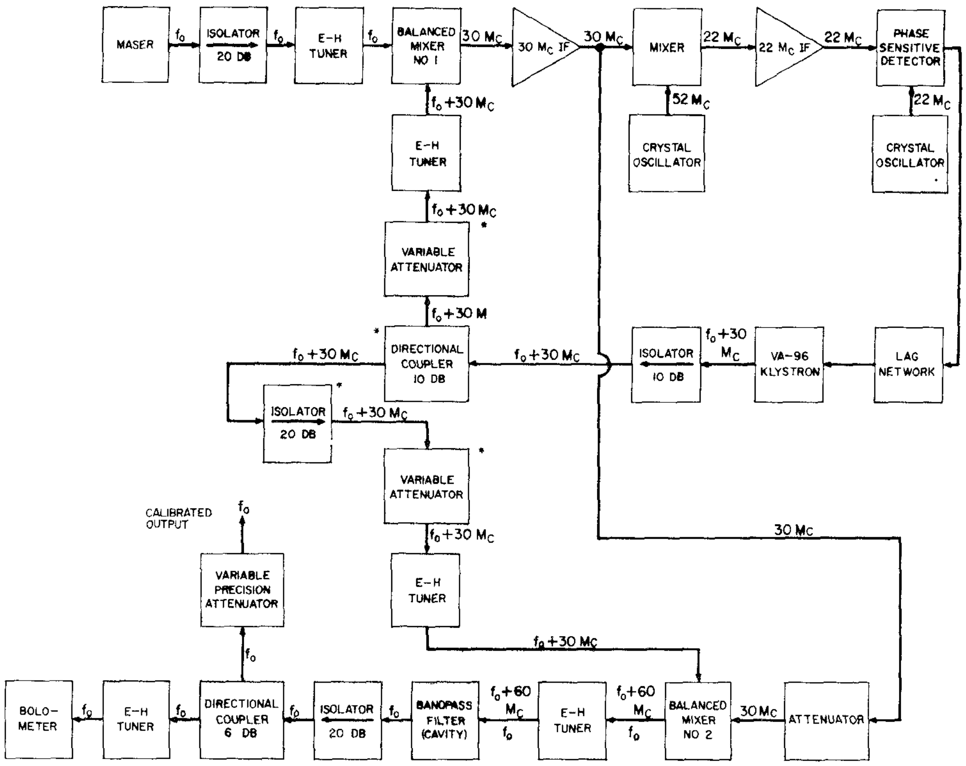

Fig. 2—Maser signal generator. For proper operation, leakage signals at frequency f_0 going from balanced mixer No. 2 to balanced mixer No. 1 must be kept at a lower level than the maser signal. This is accomplished by judicious use of isolators, attenuators, and the directivity of the directional couplers (shown with asterisks).

maser ($\sim 10^{-10}$ watt), the comparatively high conversion loss of K-band mixer diodes ($\sim$8 db), and the poor stability of K-band klystrons. Amplified power in the milliwatt region requires IF amplification of the order of 90 db. The resulting narrow bandwidth of this high-gain IF amplifier and the consequent rapid phase shift of output with frequency give rise to phase modulation as the local oscillator jitters. This is overcome in the following way. Since it is the maser frequency that we wish to amplify, we can make use of the IF offset phase-locked klystron[3] mixed with its IF. In effect, we have substituted the stability of a stable, low-frequency crystal oscillator for that of a klystron as our local oscillator in the double conversion amplifier and have thus eliminated the phase modulation referred to above. The circuit diagram is shown in Fig. 2. Dual conversion from 30 mc to 22 mc is used in the phase-lock loop to alleviate the shielding problem by keeping low-level amplifiers and oscillators at different frequencies. No "ghost locks" were observed. Further comments are contained in the caption for Fig. 2. A power output of approximately 0.2 mw coherent with the maser and at the same frequency has been obtained with this maser signal generator.

[3] M. Peter and M. W. P. Strandberg, "Phase stabilization of microwave oscillators," Proc. IRE, vol. 43, pp. 869–873; July, 1955.

Locking the Divider

The frequency divider is connected to the maser signal generator, which is set to supply power several orders of magnitude higher than that of the maser. The divider is put into operation by switching to "Designate" (see Fig. 1) and tuning the VCO into the correct frequency while one watches the beat frequency output of the quadrature phase detector. When the beat frequency decreases to a sufficiently low value, the switch is put on "Lock" and one can observe a further decrease in beat frequency as the VCO frequency drifts and finally comes to a halt at a dc level of quadrature voltage output. It is clear that when the phase-detector output (which is the error signal) is null, the output of the quadrature phase detector is a dc maximum. Further, the value of this dc is, before the onset of saturation, a monotonically increasing function of the input signal, the linearity of which is modified by AGC action in the IF. The AGC acts to compress the range of quadrature phase-detector output. This output can be used as an indicator while the system is being tuned and peaked. As the maser-controlled signal generator power is decreased, the quadrature phase-detector dc output voltage V_q decreases and the increase in gain caused by AGC action increases the noise modulation of V_q. Since this noise is significantly higher in frequency than 20 cps, the loop bandwidth frequency, the VCO frequency, is unperturbed. The dc value of V_q remains constant for each value of maser-signal generator power down to very low signal-to-noise ratios. This indicates that the long-term VCO frequency remains a fixed fraction of the maser frequency. The divider can be switched from the maser signal generator directly to the maser.

Parametric Diode Frequency Multiplier

Operation at low signal-to-noise ratios does not, as pointed out above, result in decreased stability, but it does increase the probability of an accidental break of lock. As is evident from Fig. 1, the chief cause of poor signal-to-noise ratio is the use of a mixer which must perform two operations: 1) harmonic multiplication (from 1989 mc to its twelfth harmonic at 23,872 mc) and 2) mixing. The result seems to be inefficient operation for both applications. Previous measurements had indicated that a marked improvement in conversion efficiency of the mixer had resulted when the driving frequency for the harmonic mixer was increased to any integral submultiple of 23,872.6 mc. For example, at appropriate frequencies near 1 kmc, 2 kmc, and 3 kmc, the signal-to-noise ratio remained constant providing the driving power was in the ratio of 40 (for 1 kmc) to 8 (for 2 kmc) to 1 (for 3 kmc). With eventual transistorization of the divider in mind, the highest tube freqeuncy used was 1989 mc. There is enough power available at this frequency to degrade the performance of the IN26A mixer diode so that one operates at a rectified current which gives maximum locking. In the typical run cited below, this was at 1 ma, which corresponds to 9.8-mw drive. Even when higher driving frequencies were used, the mixer-diode rectified current was kept constant.

The availability of the new parametric diodes with their possibilities for efficient frequency multiplication[4,5] raises the question of whether the performance of the divider (in terms of signal-to-noise ratio) will improve if such a diode is inserted in the multiplying circuit between the harmonic mixer and the last multiplying stage. In particular, will the loss in power caused by harmonic-conversion loss be more than offset by the introduction of a higher frequency into the harmonic mixer?

For this purpose, a very crude multiplier was constructed that employed a Hughes Type 2810 parametric diode in a detector mount at the junction of a coaxial T. The system was driven at 1989 mc through a low-pass filter and terminated by a coax-to-waveguide transition leading to an RG 49/U waveguide, which served as a high-pass filter to the output. The third arm of the T was terminated by a tuner and short, and tuners were inserted at judiciously chosen points. The microwave driving power was adjusted so as to drive the diode beyond its zener point; then the dc bias was set to a value which balanced the dc component of the diode current to zero. Typically, the second harmonic output, which is at 3978 mc, is 7 db down from the input, although, with some critical adjustments, 6 db have been obtained. At these efficiencies, power outputs from 8 to 32 mw have been observed. An attempt was made to measure harmonic outputs higher than the second with the present multiplier. Even the third, at 5967 mc, was more than 15 db down. At these low levels, no attempt was made to determine the relative harmonic content (as between 2, 3, 4, etc.) of the signal driving the harmonic mixer under operating conditions. However, pronounced variations in the sensitivity of the system corresponding to a nearly fixed rectified current from the harmonic mixer diode have been observed when a stub tuner in the line between the diode multiplier and the harmonic mixer was slightly varied. One may infer from this that, since the tuner will vary the relative intensity of harmonic components entering the harmonic mixer, this system is very sensitive to the relative intensity of even extremely low-level harmonic components.

Experimental Procedure

A series of comparative runs was taken both with 1989-mc drive to the harmonic mixer and with the output of the parametric diode frequency multiplier driving the harmonic mixer. The amount of power from the maser signal generator was varied and the dc level of output voltage from the quadrature phase detector, V_q, was noted. The point at which lock-break occurred was also noted. In every case, an attempt was made to obtain optimum conditions of "sensitivity" as evidenced by maximizing V_q. It was found that the IN26A was superior to the IN26 for the harmonic mixer diode. Runs with three IN26A's indicated a wide (approximately 3 to 1) variation in the crystal current giving maximum V_q.

The power available to the harmonic mixer of the frequency divider from the maser signal generator was measured by monitoring the power output of the maser signal generator with a power bridge, tapping some off with a calibrated directional coupler, and then inserting calibrated microwave attenuators. In order to minimize the possibility of obtaining an erroneously high sensitivity figure because of high-level microwave leakage which bypasses the attenuators, readings were obtained by lowering the 30-mc drive into the last mixer of the maser signal generator. This reduced the amount of power at maser frequency which was generated. The new power level was measured with the power bridge,

[4] A. Uhlir, Jr., "The potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, pp. 1099–1115; June, 1958.

[5] D. B. Leeson and S. Weinreb, "Frequency multiplication with nonlinear capacitors—a circuit analysis," Proc. IRE, vol. 47, pp. 2076–2084; December, 1959.

and the microwave attenuation was reduced by the appropriate amount. The resulting V_q agreed with the previous value within the error in reading the power bridge; this indicated that the leakage was negligible. Finally, the direct maser power output was measured by comparison with the output of the calibrated maser signal generator by using V_q as the indicator. At this relatively high drive, it was demonstrated by the technique described above that the error caused by leakage was negligible.

In all subsequent runs the maser alone, with output level controlled by a calibrated attenuator, was used to drive the divider.

Conclusion

In Fig. 3, the curves marked (A) and (B) indicate V_q vs attenuation of the maser alone for the frequency divider with 1989-mc drive and with the parametric diode multiplier (3978-mc drive), respectively. These curves were based on a typical run. Curve (C), from a run in which the parametric diode multiplier was used, represents the best performance obtained. The abscissa, which is the attenuation in the maser output, is scaled to the square root of power. This scaling would normally give a straight-line response for a linear detector. Zero db at the right, which is the full maser output, corresponds to −73 dbm. Corresponding values of V_q are obtained at 11 db less maser power with the parametric diode multiplier than with 1989-mc drive. In the respective cases, the power for the harmonic mixer was 3.8 mw with the diode multiplier and 9.8 mw with the 1989-mc drive. The driving powers were obtained by calibrating the harmonic mixer crystal current at 1989 mc, and its second harmonic. Mixer crystal currents were approximately 1 ma for both fundamental and second harmonics. These values gave the best V_q. Lock-break occurs at correspondingly lower maser power with the parametric diode multiplier.

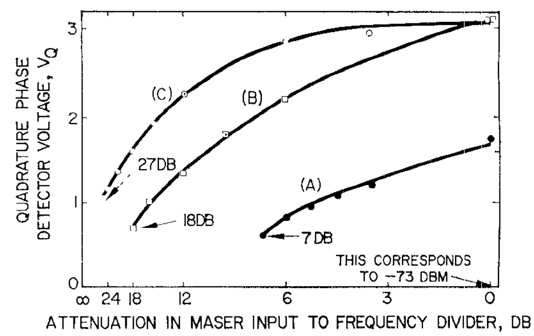

Fig. 3—Response of frequency divider to maser power input. Curve (A) is for 1989-mc drive to harmonic mixer as illustrated in Fig. 1. Curves (B) and (C) are for the case where the Hughes Type 2810 parametric diode is used as a frequency multiplier to drive the harmonic mixer. (Arrows indicate value of maser attenuation at which the divider broke lock.)

It should be noted that whereas the techniques discussed in this paper have enhanced our ability to lock a low-frequency crystal oscillator (the VCO) to a high-frequency reference, conversely, the locking of a high-frequency oscillator to a low-frequency reference can also be enhanced.

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