

The Ammonia Maser as an Atomic Frequency and Time Standard*

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THE essential qualities of an atomic frequency and time standard are high signal-to-noise ratio, high frequency stability, high operating frequency—within the region of existing microwave techniques—and reproducibility. The maser^{1,2} distinguishes itself in the first three of these requirements. The present signal-to-noise ratio of our instruments is about 10^4 as compared to about 100 for atomic beam machines, and the frequency stability is approximately 1×10^{-11} or better for periods of a few minutes. It is expected that the period of this stability can be extended. The frequency of the maser is about two and one-half times that of cesium beam standards. The maser has, however, the basic shortcoming that its output frequency is not easily reproduced. It is here that the maser's competitor, the atomic beam machine,³ excels.

There are a number of effects that introduce frequency shifts in the maser² and make reproducing a particular frequency difficult. The least well understood of these is probably the Doppler shift that may be expected to occur because of the variation of molecular emission with position inside the resonant cavity. As a result of this nonuniform emission there will be a net flow of power along the length of the cavity either in the direction of the molecular velocity or opposed to it, i.e., a traveling wave will exist in the cavity in addition to the standing wave. Associated with the traveling wave, the average molecular velocity, and the losses in the cavity, a Doppler shift in frequency is expected. The shift can be either positive or negative relative to the Bohr frequency and the magnitude of the shift will depend upon the beam flux, the cavity Q , the molecular velocity—properly averaged—and the position of the coupling iris. The frequency shift arising from power flow to the coupling iris has been treated in some detail by Shimoda, *et al.*

There is a way of reducing this Doppler effect, and perhaps even eliminating it. This can be done by projecting two identical beams into the cavity²—the beams entering opposite ends—and locating the coupling hole at the center. An almost zero Doppler shift should result

depending upon how symmetrical the apparatus can be made. The main features of our double beam maser are shown in Fig. 1. Rather simple tests determine the degree of symmetry, but it remains to be demonstrated experimentally just how symmetric the apparatus can be constructed. If the symmetry is perfect, then the maser should be expected to oscillate at the Bohr frequency, provided that other effects mentioned later are adequately reduced. It is perhaps interesting to note that experimentally we observe a shift in frequency of about 2×10^{-9} from double-beam operation to single-beam operation. This is not a fixed shift but presumably depends upon the values of the parameters already mentioned. From this figure we estimate the measured ammonia frequency to be within 2×10^{-9} of the Bohr frequency.

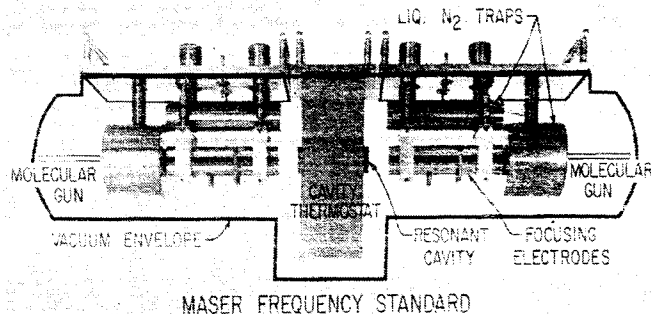


Fig. 1—A double-beam ammonia maser.

Other effects introducing frequency shifts in the maser can be reduced adequately for reproducibility to within 2×10^{-10} by careful adjustment. Some of them can be avoided.

The most important of these effects are the shifts incurred by cavity "pulling." This frequency shift is approximately given by

$$\Delta f_{\text{NH}_3} = \frac{Q_{\text{cavity}}}{Q_{\text{line}}} \Delta f_{\text{cavity}}$$

where Δf_{NH_3} is the shift in frequency of the maser signal from the frequency it would have if the cavity were tuned to the maser frequency, Q_{cavity} is the loaded Q of the cavity, Q_{line} is the Q of the spectral line, and Δf_{cavity} is the difference frequency between the peak of the cavity resonance and the peak of the ammonia resonance. The loaded Q of our cavity is about 5000 and the Q of the spectral line is about 5×10^6 . Then if we wish

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¹ J. P. Gordon, H. J. Zeiger, and C. H. Townes, "The maser—new type of microwave amplifier, frequency standard, and spectrometer," *Phys. Rev.*, vol. 99, pp. 1264–1274; August, 1955.

² K. Shimoda, T. C. Wang, and C. H. Townes, "Further aspects of the theory of the maser," *Phys. Rev.*, vol. 102, pp. 1308–1321; June, 1956.

³ L. Essen and J. V. L. Parry, "The caesium resonator as a standard of frequency and time," *Phil. Trans. Roy. Soc. (London)*, A, vol. 250, pp. 45–69; August, 1957.

our maser frequency to be "pulled" by not more than 1×10^{-10} or 2.4 cps, the cavity must be tuned within 2.4 kc. of the ammonia line; *i.e.*, $\Delta f_{\text{cavity}} = 2.4$ kc. In this piece of arithmetic it is important to choose Q_{line} as the Q of the spectral line for non-interacting ammonia molecules, *i.e.*, under conditions of no feedback in the molecular amplifier. Since the maser is a regenerative amplifier the line width or the amplifier bandwidth is not a fixed quantity. Indeed, this is actually observed experimentally. We can easily observe molecular bandwidths from less than 100 cps to over 7 kc. Fig. 2 shows a typical trace of a line shape or response curve for a particular set of conditions. It is somewhat difficult to set the cavity within the required limits. We have found that setting the cavity for a symmetrical line shape on the recorder permits the setting of the maser signal with a reproducibility within 2×10^{-10} . This requires sweeping over the line shape several times with the maser adjusted for line widths of about 700 cps. Actually for N^{14} ammonia the line shape is not expected to be symmetric because of hyperfine structure. Under these circumstances a small frequency shift is introduced by symmetrizing the line shape. This shift could be avoided by using N^{15} ammonia without loss in signal-to-noise ratio.

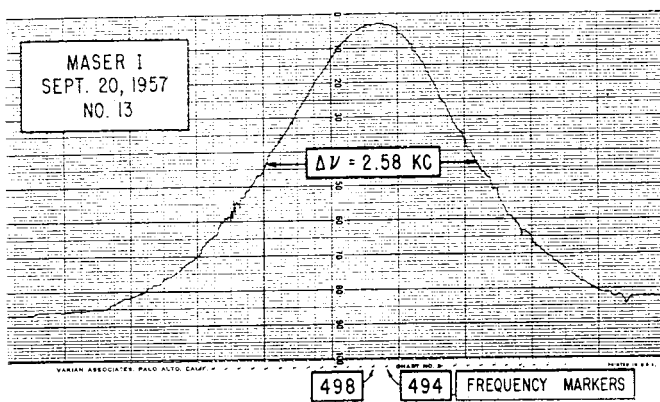


Fig. 2—A recording of the ammonia line shape or amplifier response curve for particular conditions of beam flux, external excitation, and resonant cavity characteristics.

To prevent cavity detuning that occurs with a change in cavity temperature, the temperature must be controlled within 0.01°C in order that the maser frequency does not vary more than 1×10^{-11} . Also our experiments indicate that frequency shifts produced by magnetic fields, pressure fluctuations, and voltage fluctuations, can be easily reduced to within 1×10^{-10} .

In order to measure the high frequency of the maser,

a multiplier chain must be used. The power spectrum of the chain has a finite bandwidth depending upon the quartz crystal from which the primary frequency is derived and the introduction of new signal and noise components by the chain itself. If the envelope of the spectrum is not symmetrical, the multiplier chain frequency cannot be assumed to be an integral multiple of the primary frequency. This assumption is usually a good one, but we thought it best to make some appropriate measurements, considering the kind of precisions that are involved. Using the maser as a spectrum analyzer, we were able to determine that the bandwidth of the power spectrum of our chain was about 5 cps at 23,900 mc, and that it was symmetrical.

It is evident from observing the beat note between two masers that temperature variations of the waveguide structure introduce significant changes in the match between the maser cavity and the waveguide. This causes a frequency shift that could presumably be avoided by undercoupling the cavity to the waveguide structure.

In conclusion, experiment indicates that masers could be constructed according to a recipe such that different machines would oscillate within an estimated 3×10^{-10} . This recipe could be considerably simplified by constructing double beam masers as symmetrical as possible. If it can be shown that a degree of symmetry could be attained that would allow frequencies of different machines to be consistent within 1 or 2×10^{-10} , then this method of construction would probably be preferred because the maser would, so far as the authors can see, oscillate at the Bohr frequency. In either case, the maser has application as a standard of frequency and time. Measurements show the maser to be the most stable oscillator so far devised, at least for short periods, and there seems to be no insurmountable reason why this stability cannot be sustained for long periods.

Our measured frequency for the $J=3, K=3$ transition is

$$23,870,129.007 \pm 10 \text{ cps precision } \pm 100 \text{ cps accuracy.}$$

The measurement is reproducible to ± 5 cps. We estimate that this measurement is within 100 cps of the Bohr frequency. This frequency is based on a comparison with a cesium beam standard assuming that the cesium transition has the frequency 9,192,631,840 cps. Comparison with other measurements⁴ requires reduction to a common time base.

⁴ J. Bonanomi and J. Herrmann, "Determination of the ammonia inversion frequency," *Helv. Phys. Acta*, vol. 29, pp. 451-452; 1956.