FREQUENCY STABILITY OF He-Ne MASERS AND MEASUREMENTS OF LENGTH*

T. S. Jaseja, A. Javan, and C. H. Townes
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 11 February 1963)

Frequency stability of the oscillations of He-Ne masers at 1.153 μ has been examined under more controlled conditions than was previously the case.[1,2] Frequency spread of the oscillation (stability over very short times) has been reduced to about 20 cps, or about eight parts in 10^{14}; frequency drifts as slow as a few tens of cycles per second per second were obtained; and the frequency resettability for a given maser over long periods of time was found to be somewhat less than 0.5 megacycle, or about one part in 10^9. While these results may still be improved, at least the short-term stability is within about one order of magnitude of the theoretical limit expected for these particular masers, and each of these results are important measures of the masers' ability to determine lengths with great precision.

Spontaneous emissions into the oscillating mode of the maser, having random phases and a frequency spread, produce an irreducible fluctuation in the maser frequency which is given in the optical and infrared regions, when $h\nu \gg kT$, by[3,4]

$$\Delta\nu_{\text{osc}} = (4\pi h\nu/P)(\Delta\nu)^2, \qquad (1)$$

where $\Delta\nu_{\text{osc}}$ is the half-width at half-maximum of the spectrum of the oscillation of frequency ν; h, k, and T are, respectively, Planck's constant, Boltzmann's constant, and the temperature of the electromagnetic field present at frequency ν and not due to the maser action; P is the power produced by the maser oscillation. $\Delta\nu$ is typically the half-width at half-maximum of the cavity resonance at frequency ν. For the masers used, the calculated value of $\Delta\nu_{\text{osc}}$ is 0.02 cps for a power output somewhat less than one milliwatt.

Another limit on frequency fluctuations is set by thermal oscillations of the separation between mirrors of the maser. If the relative position of the mirrors is fixed by spacers of uniform cross section and material, their fractional change in length due to thermal vibrations in the lowest mode, and hence the fractional change in maser frequency, can be shown to be

$$\delta\nu_T/\nu = (2kT/YV)^{1/2}, \qquad (2)$$

where V is the total volume of the spacers, Y is Young's modulus for the spacer material, and T their temperature. For the masers used, expression (2) gives $\delta\nu_T = 2$ cps. Additional thermal oscillations of the mirror position other than the lowest extensional mode of the spacers are relatively unimportant, although with some types of construction they can be significant. This lowest mode has, in our case, a frequency of about 1.5 kc/sec and could give discrete side bands on the oscillation frequency if it were not damped, as it is because of contact with a table on which the masers rest.

Since the theoretical fluctuation given by (2) corresponds to a relative motion of the two maser mirrors of only 5×10^{-13} cm, extreme care must be taken to prevent extraneous acoustic vibration. The masers were hence supported on a massive shock-mounted table with resonant frequencies of many seconds and in a cellar room of an isolated building[2] where noises and ground tremors were very small. It was also necessary to avoid various acoustic noises such as those due to running equipment or to high winds. This resulted in a considerable improvement over previously observed fluctuations.[1,2]

The beams of two independent and free-running He-Ne masers were mixed in a photocell as indicated in Fig. 1 so that their relative frequency variations could be detected. These variations were produced by both long-term drifts and by shorter term fluctuations. Under favorably quiet conditions, both were sufficiently small so that clear audio signals could be heard and recorded over periods of the order of a minute. Fig. 2 shows the trace of an oscilliscope on which the beat frequency between the two masers shows up at about 1700 cps. Fluctuations in the beat had an rms value of about 30 cps over a few tens of milliseconds, indicating a short-term frequency fluctuation of about 20 cps for an individual maser, since the two are presumably independent in this respect. This represents an improvement of about a factor of 10^4 over what was previously obtained under ordinary laboratory conditions.[1]

A fluctuation as small as 20 cps implies a constancy in relative mirror separation of about seven parts in 10^{14} or of 4×10^{-4} angstrom in 50 cm (the mirror separation), and hence the possi-

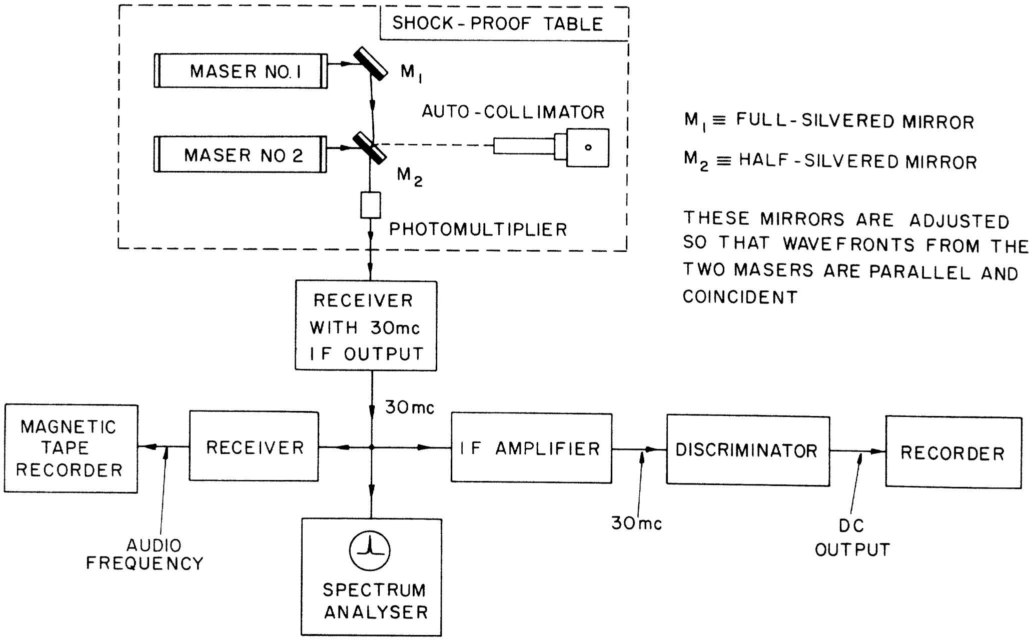

FIG. 1. Schematic diagram for recording the instability in the beat frequency of two optical masers. The apparatus on the shockproof table was isolated acoustically from the remaining electronic and recording equipment.

bility of measuring short-term variations in position which are correspondingly small. The mirror separation in question is, of course, some average over the surface which necessarily has irregularities at least as large as an atomic diameter. This monochromaticity also implies that interference could be obtained for path-length differences as large as about 10 000 miles, and hence changes in such a length determined to a precision somewhat less than one light wavelength. The maser beam can, furthermore, be made directional enough to give sufficient intensity for interferometry over this distance. The most difficult practical limitation in such performace is probably in obtaining a sufficiently perfect and constant light path over this large distance.

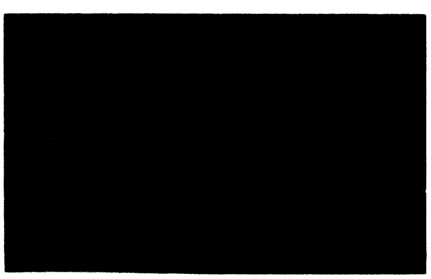

FIG. 2. Audio-frequency (1700 cps) waveform of the beat between two He-Ne masers.

The short-term fluctuations which were found may be due in part to residual 120-cycle ripple in the power supply which drives the He-Ne discharge, or to a residual acoustic background. Both of these can probably be further improved, but present performance is already within one order of magnitude of the thermal fluctuation limit given by (2).

There is no simple theoretical limit to the longer term frequency drifts which occur over many seconds. These were recorded as shown in Fig. 1 as well as observed through changes in pitch of the beat frequency recorded on magnetic tape. On favorable occasions, the drift was as small as a few tens of cycles per second per second for some minutes. A recording of the drift which is about 6 kc/sec in a period of two minutes is shown in Fig. 3. Since the spacers for the mirrors were rods of invar with a temperature coefficient near 10^{-6} per degree, a constancy of 100 cps in maser frequency or hence a constancy of length to four parts in 10^{13} implies no change in temperature between the two masers greater than 4×10^{-7} °C. It is hence not surprising that such precision is not maintained over times longer than about 10 seconds and that the total drift over larger times can be several orders of magnitude greater.

Another measure of the constancy of frequency or of length which can be maintained in an infrared

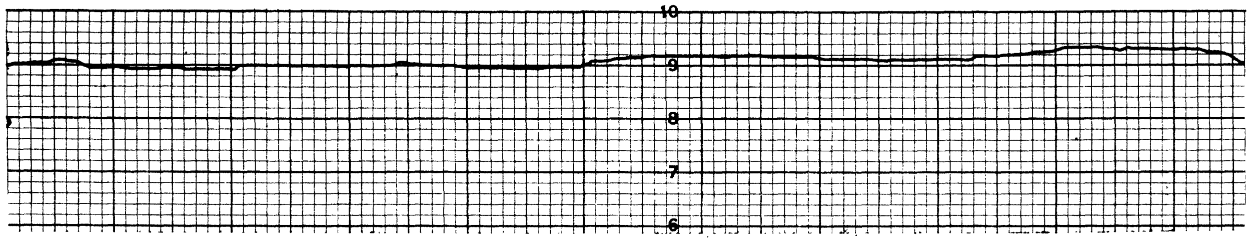

FIG. 3. Drift during two minutes of the beat frequency between two masers. One small division represents 4 kilocycles per second change.

or optical maser is the precision with which an individual maser can be reset to the same frequency after its frequency has been disturbed. In principle, there is no limit to the precision of resettability if sufficient time is taken for the purpose, and even for rather short times the limit to accuracy of resetting determined by fundamental noise is very high. However, many practical problems prevent any immediate approach to this limit. For the purpose of resettability measurements, two masers were kept at single mode operation and were adjusted very close to the threshold of oscillation. The frequency of each maser was then reset by varying the mirror separation until the oscillation disappeared and then setting the separation half-way between the two points of disappearance. On each trial, resetting the resulting beat frequency between the two was measured. Its variation among a number of trials was about 500 kc/sec. This shows that a single maser can be reset to a precision at least as good as one part in 10^9, and hence distances compared over a very long time to this accuracy. In this experiment the mirror separation was varied by magnetostrictive effects in the separators. It is believed that further work can much improve the long-term stability and resettability of optical masers, although they are already sufficiently good for many interesting measurements of length.

An experiment to detect "ether drift" or anisotropy in the velocity of light of the Michelson-Morley type previously outlined[4] is being carried out to capitalize on the precision in measurement of length indicated above. The first version of such an experiment can be considered to confirm the Lorentz-Fitzgerald contraction due to the earth's orbital velocity to about one part in one thousand. This work will be separately reported in more detail.

---

*Work supported by the National Aeronautics and Space Administration and by a Tri-Service Contract in the Research Laboratory of Electronics.

[1]A. Javan, E. A. Ballik, and W. L. Bond, J. Opt. Soc. Am. 52, 96 (1962).

[2]T. S. Jaseja, A. Javan, J. Murray, and C. H. Townes, Bull. Am. Phys. Soc. 7, 553 (1962).

[3]A. L. Schawlow and C. H. Townes, Phys. Rev. 112, 1940 (1958).

[4]C. H. Townes, Advances in Quantum Electronics, edited by J. R. Singer (Columbia University Press, New York, 1961), p. 3.

POSSIBILITY FOR COPIOUS PRODUCTION OF THE INTERMEDIATE VECTOR BOSONS*

Gyo Takeda†
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 10 January 1963)

We study the possibility that some of the intermediate vector bosons of the weak interaction might be produced by several orders of magnitude more than previously estimated in various literature.[1]

The intermediate vector bosons, W, if they exist at all, interact with the strangeness-nonchanging baryon current $J_\mu{}^B(\Delta S=0)$, the strangeness-changing baryon current $J_\mu{}^B(\Delta S=+1)$, and the lepton current $J_\mu(\text{lep})$.[2] Let us call the respective coupling constants g_0, g_1, and g_{lep}. If there exists more than one kind of intermediate boson besides its charge multiplets, the coupling constants may be different for the different kinds of bosons.

The circumstances which could give rise to

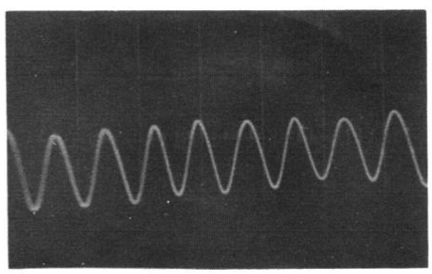

FIG. 2. Audio-frequency (1700 cps) waveform of the beat between two He-Ne masers.