

## Frequency Stability of Methane-Stabilized He-Ne Lasers

Helmut Hellwig, Howard E. Bell, Peter Kartaschoff,\* and James C. Bergquist†  
*Atomic Frequency and Time Standards Section, National Bureau of Standards, Boulder, Colorado 80302*  
(Received 20 August 1971)

Free-running laser stabilities of  $1.5 \times 10^{-11}$  for the millisecond region and methane-locked stabilities of  $10^{-13}$  for 10-s averaging time are achieved with a minimum of shock and vibration isolation in an ordinary laboratory environment. Superior stability performance is obtained with dc excitation as compared to rf excitation. The experimental setup is described in some detail.

The P(7) line of the  $\nu_3$  band of  $\text{CH}_4$  at  $3.39 \mu\text{m}$  (88 THz) is regarded as one of the most promising candidates for an accurate frequency and length reference for measurements in the infrared and visible radiation region. This line has been proposed as a successor for the present standard of length (krypton).<sup>1</sup> It is also proposed as a possible future unified standard for both length and time interval,<sup>1-3</sup> provided its accuracy is competitive and provided that the already spectacular results in frequency synthesis in the infrared region lead to an accurate frequency comparison between the standards of time interval and length. In view of these important possibilities, we investigated the performance of  $\text{CH}_4$ -stabilized He-Ne lasers.

The design closely resembles the one described by Barger and Hall.<sup>4</sup> The gas cell containing  $\text{CH}_4$  is located inside of the 60-cm optical cavity. Saturation of the absorption line results in a sharp increase in the laser output power at the center of the methane resonance. In our experiments this emission feature was typically

a few percent of the total laser power, with a linewidth of about 100 kHz (line  $Q \approx 10^9$ ). The methane pressure was about 10 mTorr ( $1.33 \text{ N/m}^2$ ). Coincidence of the center of the single-mode laser emission profile with the methane absorption was achieved by pressure shifting with 4.8 Torr ( $640 \text{ N/m}^2$ ) of  $^3\text{He}$ . We used typically 0.2 Torr ( $27 \text{ N/m}^2$ ) of  $^{20}\text{Ne}$ . The capillary of the laser gain cell was 18 cm long with a 3-mm i.d. No particular effort was made to reduce environmental disturbances. The experiments were performed in an ordinary laboratory without acoustical isolation. The apparatus was mounted on a  $\frac{1}{2}$ -in. steel plate which was buffered against shock and vibration from the support structure by a 1-in. foam-rubber pad.

In Fig. 1 we depict the measurement system. The outputs of both devices were combined with a mirror M and a beam splitter S and focused on a diode D (Philco-Ford L4530).<sup>5</sup> The resultant beat was amplified in  $A_3$ , a dc amplifier with a bandwidth of 1 MHz, and counted. For on-line evaluation of the frequency stability, we

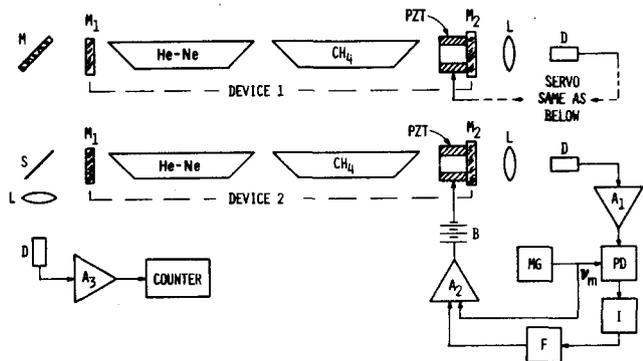


FIG. 1. Measurement system and frequency-lock servo.

used a computing counter (HP5360A) which was programmed to display directly the two-sample Allan variance.<sup>6,7</sup>

The servo system is shown on the right-hand side of Fig. 1. The infrared frequency was modulated by means of a piezoelectric transducer (PZT) driven at the rate  $\nu_m$  from the modulation generator MG. The tuning sensitivity (fractional frequency) with our PZT was  $5 \times 10^{-9} \text{ V}^{-1}$ ; a swing of 60 V in our PZT driver amplifier  $A_2$  was sufficient for maintaining lock over many hours. Each laser was pretuned by adjustment (75-V steps) of its battery B. The frequency lock to the methane-saturated absorption was accomplished in the usual way with the phase detector PD, the integrator I, and the amplifier-filter combination F. For unambiguous measurement of the Allan variance (Figs. 2 and 3), the frequency difference between the two lasers was typically 50 kHz (locked) and 500 kHz to 16 MHz (unlocked). In the locked case, the offset was introduced by placing a small dc bias at the input of the integrator I.

In our first series of experiments, both lasers were

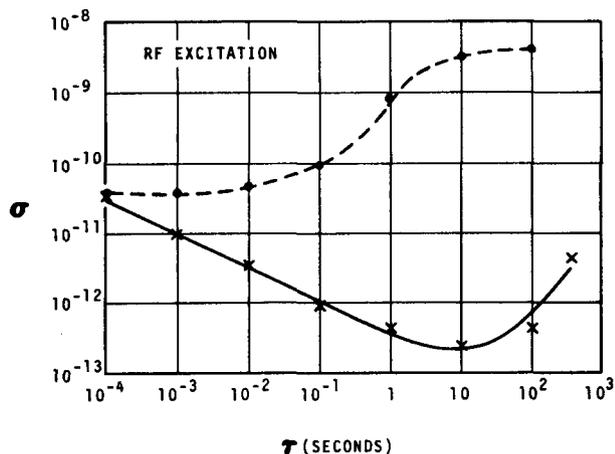


FIG. 2. Frequency stability of a free-running He-Ne laser (dashed) and a CH<sub>4</sub>-stabilized He-Ne laser (solid) using 40-MHz rf excitation. In Figs. 2 and 3 the square root of the Allan variance (Refs. 6 and 7)  $\sigma^2$ , ( $N$ ,  $T$ ,  $\tau$ ,  $B$ ) is plotted, where  $N=2$ ,  $T=\tau/3$  msec,  $B \approx 1$  MHz, and  $y$  = fractional frequency fluctuations. The gating of the counter was nonsynchronous with the modulation frequency  $\nu_m$ .

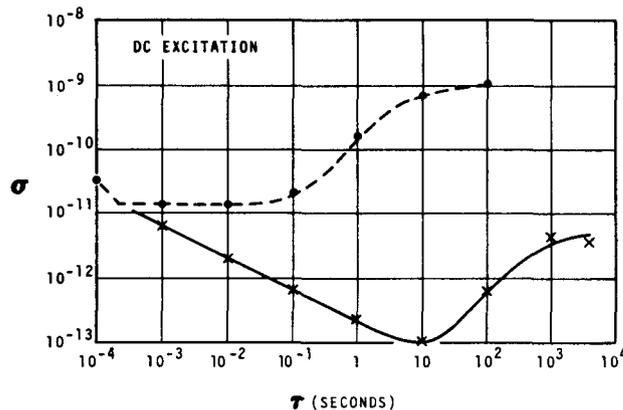


FIG. 3. Frequency stability of a free-running He-Ne laser (dashed) and a CH<sub>4</sub>-stabilized He-Ne laser (solid) using dc excitation. [M = mirror, PD = phase detector, S = beam splitter, I = integrator, D = diode, F = filter amplifier, L = lens, MG = modulation generator, A = amplifier, B = battery.]

excited with a 40-MHz radio-frequency discharge. The modulation frequency was  $\nu_m = 5$  kHz. The results, normalized to one device, are depicted in Fig. 2. The upper (dashed) curve gives the free-running laser stability, the lower (solid) curve gives the locked performance.

We used dc excitation of the laser discharges in the second series of experiments and obtained improved stability performance (see Fig. 3). The modulation frequency was set at  $\nu_m = 3$  kHz. We used a cylindrical cathode of about 2 cm in diameter and 5 cm long in a concentric position at the end of the discharge capillary. The electrode was made from pure aluminum. Typical discharge currents were in the range 1.5–2.0 mA. Exceeding 2.0 mA caused discharge conditions which resulted in excessive amplitude noise but which did not significantly affect the frequency stability performance.

The precision confidence limit of each data point in Figs. 2 and 3 is within the precision of the drawing, except for data points at  $\tau \geq 1000$  s, where the confidence is only about 50% of the value. We were able to record stabilities as shown in Figs. 2 and 3 repeatedly and reliably. From Figs. 2 and 3 we see that the servo responds in a few tenths of a millisecond. Out to  $\tau = 1$  s the locked stability improves as  $\tau^{-1/2}$ , i.e., as white frequency noise, and reaches  $1.1 \times 10^{-13}$  for  $\tau = 10$  s. This stability performance corresponds to a power-spectrum linewidth of  $W \approx 2$  kHz as can easily be calculated from (valid for white frequency noise)  $W = 2\pi\tau\nu^2\sigma^2$ , where  $\nu$  is the laser frequency. For time intervals greater than several seconds, the locked stability deteriorates from the  $\tau^{-1/2}$  dependency. There is evidence that this degradation is not inherent in the methane cell itself but rather involves the servo electronics. In particular, the RC product of the integrator was only 0.5 s. This leads to a dc servo gain of the order of  $10^3$  for  $\tau > 0.5$  s which is insufficient to provide for a better long-term stability. We expect that a redesigned electronics with a greater integrator RC time constant will enable us to significantly extend the  $\tau^{-1/2}$  stability performance.

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In agreement with previous measurements,<sup>4</sup> we also find that the frequency difference between two independent devices, i. e., the reproducibility, is better than a few parts in  $10^{11}$ . Our stability data (for  $\tau \leq 10$  s) are better than previously reported ones.<sup>1,8,9</sup> We believe that this is largely due to the better free-running stability of our lasers.

In comparing the results of Figs. 2 and 3 we note that the marked frequency stability improvement in the free-running laser and the resulting improvement of the methane-stabilized laser due to switching from rf to dc excitation may be the result of a quieter discharge in the case of dc excitation. We have no other explanation because the experimental setup was the same in both experiments; even the optical cavities remained unchanged.

We note that the performance of our methane-stabilized lasers, as compared to other oscillators, is already quite spectacular: The frequency stability from less than 1 ms out to 10 s matches or exceeds the stability of other oscillators which have been used as standard frequency sources, i. e., of hydrogen masers, cesium beam devices, crystal oscillators, etc.

We gratefully acknowledge the generous supply of information and advice from J. L. Hall and J. Levine, and the assistance in the construction of the lasers and the electronics by Miss R. Gillis.

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\* National Bureau of Standards Visiting Scientist on leave from

the Laboratoire Suisse de Recherches Horlogeres, Neuchâtel, Switzerland.

† Student at the University of Colorado.

<sup>1</sup>H. S. Boyne, IEEE Trans. Instr. Meas. IM-20, 19 (1971).

<sup>2</sup>This would be equivalent to a definition of the speed of light.

<sup>3</sup>H. Hellwig and D. Halford, Proceedings of the International Conference on Precision Measurements and Fundamental Constants, 1970 (unpublished), also available as Natl. Bur. Std. (U.S.) Report No. 9766 (U. S. GPO, Washington, D. C., 1970).

<sup>4</sup>R. L. Barger and J. L. Hall, Phys. Rev. Letters 22, 4 (1969).

<sup>5</sup>Names of manufacturers are used for the sole purpose of conveying scientific and technical information, and their citation is not to be construed as an endorsement or approval of commercial products or services by the authors or by the authors' organizations.

<sup>6</sup>D. W. Allan, Proc. IEEE 54, 221 (1966).

<sup>7</sup>Detailed information about the use of the Allan variance  $\sigma^2(N, T, \tau, B)$ —with  $N$  = number of samples,  $T - \tau$  = dead time,  $\tau$  = averaging (sample) time, and  $B$  = bandwidth—can be found in J. A. Barnes, A. R. Chi, L. S. Cutler, D. J. Healey, D. B. Leeson, T. E. McGunigal, J. A. Mullen, Jr., W. L. Smith, R. L. Sydnor, R. F. C. Vessot, and G. M. R. Winkler, IEEE Trans. Instr. Meas. IM-20, 105 (1971); also, Natl. Bur. Std. (U. S.) Technical Note No. 394 (U. S. GPO, Washington, D. C., 1970).

<sup>8</sup>R. L. Barger and J. L. Hall, *Proceedings of the Twenty-third Annual Symposium on Frequency Control, Fort Monmouth, N. J.* 1969 (Electronic Industries Association, Washington, D. C., 1971), p. 306.

<sup>9</sup>Recently, J. L. Hall, R. L. Barger, and G. Kramer obtained results which are comparable with ours using different techniques and a well-controlled environment (private communication); R. L. Barger, Bull. Am. Phys. Soc., 16, 347 (1971); also J. L. Hall, Isfahan Symposium on Fundamental and Applied Laser Physics, 1971 (unpublished).