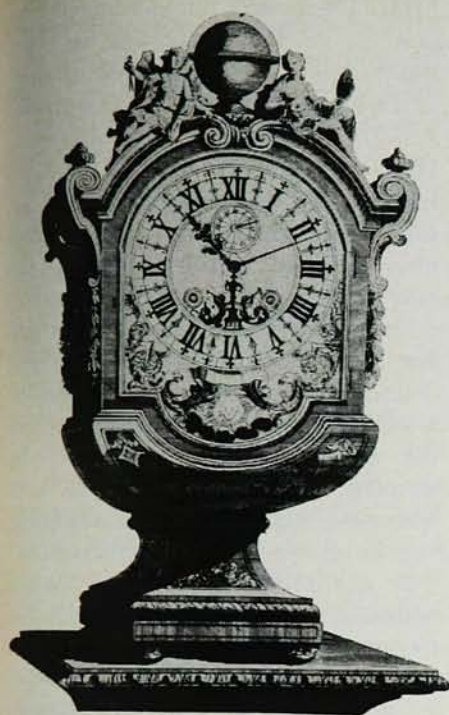




FREQUENCY CONTROL DEVELOPMENTS

With understanding of energy trapping, vibration theory is reducing crystal-filter design to handbook form. Masers and beam tubes too are enjoying developments giving frequency stabilities of one part in 10^{14} .

by Arthur D. Ballato and Robert V. McKnight

CRYSTAL VIBRATORS and atomic frequency standards are continuing to attract the interest of engineers and physicists. In particular, the energy-trapping concept has assisted in the application of theory to practical quartz resonators. Thus filter crystals have been extended to 125 MHz. Similarly, multiple-mode resonators of piezoelectric ceramic and quartz can now be made on a single crystal wafer, making possible a filter in a monolithic integrated form. Crystal oscillators, too, have been made, in which the crystal serves both as a control element and as an active device.

Meanwhile, improvements in frequency stability of atomic and molecular standards have been proceeding through greater maser output power and the elimination of cavity-pulling effects.

These and other developments in frequency generation and control, and aspects of time measurement, comparison and synchronization were the subject of the Twentieth Annual Frequency Control Symposium held in Atlantic City on 19-21 April 1966. The symposium was sponsored by the Electronics Components Laboratory, US

Army Electronics Command, Fort Monmouth, New Jersey.

CRYSTAL VIBRATORS

In the past year "energy-trapping" has led to the greatest progress in quartz-crystal frequency control. The concept itself is due to William Shockley who postulated a few years ago, while at Clevite Corp., that the experimentally observed suppression of undesired resonances in vibrating quartz plates by control of electrode geometry was due to a mass loading effect which lowered the eigenfrequencies of the plated portion below those of the unplated portion. This influence of electrode diameter and thickness has been observed experimentally.

When the frequency lowering is properly adjusted by the electrode width and thickness, the desired mode propagates in the region under the electrodes but cannot propagate elsewhere in the plate; it is cut off beyond the electroded portion. At the same time the unwanted modes of vibration are not cut off but are free to propagate beyond the electrodes; in other words, these modes are not confined and therefore do not contribute

appreciably to the piezoelectric current through the crystal element, as does the mode whose energy is "trapped" by the electrodes.

Shockley's explanation is based on a waveguide analogy. The acoustic case is, however, very much more complicated than the electromagnetic, because there are longitudinal as well as transverse motions and also because there is elastic coupling between



Arthur Ballato has been involved with quartz-crystal vibrations and the piezoelectric effect since 1958 when he joined Army Electronics Command at Fort Monmouth, New Jersey.



Robert McKnight has worked in far-infrared spectroscopy and frequency multiplication by nonlinear paramagnetic susceptibilities, also for the Army at Fort Monmouth, since 1960.

modes. Yet the analogy works, provided it is not pushed too far. But this isn't the whole story.

Vibration theory

Raymond D. Mindlin (Columbia) began the difficult task of exploring the complicated frequency behavior of bounded crystalline plates some fifteen years ago. As luck (or nature) would have it, the crystal plates of greatest interest for frequencies above about 1 MHz are cut at an angle with respect to a crystal axis to reduce the temperature coefficient. The rotation reduces the symmetry of the quartz plate from trigonal to monoclinic and compounds the difficulties involved in formulating and solving the elastic plate equations.

Yet Mindlin's systematic efforts have begun to produce a great deal of order and understanding out of the morass of equations. He has shown that the modes in general fall into ten families such as thickness- and face-shear, thickness-twist, extension and flexure travelling along different axes, and has investigated the couplings that exist between modes. In addition, he has computed the dispersion spectra for the various families of modes.

This systematic dissection of the problem of crystal vibrations had naturally proceeded on a rather abstract level so that to some it had seemed a rather academic exercise and little use had been made of the information obtained when it came to designing quartz resonators for practical devices. The waveguide analogy and energy-trapping concept proved to be the middle ground necessary for popularizing and reducing to practice the work of Mindlin. Had the analysis not been available to Shockley, energy trapping could not have been put on a firm quantitative basis and the directions made clear for future work.

The foregoing is a prelude to understanding what happened during the sessions devoted to classical frequency control at this year's symposium.

Resonance elimination

In the production of crystals for filters, the foremost requirement is elimi-

nation of all resonances near the main response because these seriously degrade the attenuation characteristic. D. J. Koneval, W. J. Gerber and D. R. Curran (Clevite Corp.) have improved VHF filter crystals using insulating-film techniques. Here the necessary attenuation of unwanted modes is accomplished by using energy-trapping theory. However, if a resonator is to be useful it must be precisely tuned to an exact frequency without degrading its electrical and mechanical properties. The theory demands a given electrode thickness for each particular electrode diameter, leaving little room for adjusting to frequency by varying the electrode plating, the standard method used before the discovery of trapping. Koneval and his colleagues approach the problem by vacuum depositing a dielectric layer of silicon monoxide over either the entire wafer or a portion of it, to lower the effective fundamental frequency. This layer can be used to increase, by as much as an order of magnitude, the range over which resonators can be tuned without introducing anharmonic overtones or otherwise affecting resonator characteristics. The rate at which the dielectric layer is deposited and the total amount deposited, that is, the amount of frequency lowering, and the area covered are the parameters over which control can be exercised.

Another useful application of this technique pertains to a problem unique to VHF resonators above 100 MHz: the energy trapping required for good resonator performance calls for a frequency lowering often too small to permit deposition of an electrode that is thick enough to form a good conductor. A solution discussed by Koneval and his co-workers is simply to deposit an electrode thick enough to satisfy conductivity requirements and coat the remainder of the wafer with the dielectric film so that the cutoff frequencies of waves propagating in each region obey the trapping laws.

Higher frequencies

When the trapping technique first became available it was used to establish preliminary designs for filter crystals up to frequencies of about 112

MHz. These were not considered optimal above 100 MHz but no basic limitations were known to preclude extension to still higher frequencies. A. D. Ballato, T. J. Lukaszek, H. Wasshausen and E. Chabak (Army Electronics Command), have been applying the theory to modern quartz filter crystals. Results reported this year included nearly optimal design extensions to above 125 MHz and permit the wide choice of electrode sizes necessary for greatest application by filter designers. This work obviates the old design bottleneck that demanded shrinking of electrodes with increasing frequencies and consequent degrading of crystal circuit parameters.

In addition to the electrode control necessary for proper application of trapping Ballato and his colleagues find that the degree of plate parallelism, but not necessarily flatness, also influences the mode spectrum. Optical interference patterns show a monotonic relation between fringe deviation over the plate face and unwanted mode strengths. Thus both electrode control and plate parallelism are necessary for suppressing undesired responses; neither is sufficient. As an added bonus plates parallel to within a tenth of the wavelength of visible light and better have 25% lower resistances than normal plates parallel only within half that wavelength. Fifth overtone units, resonant at 125 MHz and having nearly parallel faces, produce motional resistances and capacitances of 105 ohms and 140 aF (140×10^{-18} F) respectively, and Q values of 85 000. Unwanted resonances produce representative resistances greater than 20 000 ohms. With such units low-insertion-loss crystal filters are practical at these frequencies.

The next logical steps with the theory beyond the single-mode filter crystal have been taken by at least three teams of investigators who report similar results. Instead of building electric-wave filters incorporating filter crystals with other lumped circuit elements in the now standard method, one can fashion the entire filter from a single wafer of quartz that is suitably covered with a number of electrode spots. The entire arrangement is equivalent to a me-

chanical filter: the frequency of each resonant element is governed by the mass loading of the electroding and finite plate boundaries; adjacent elements are coupled by lateral electrode separation, and input and output electromechanical coupling take place through the piezoelectric effect.

Multimode resonators

M. Onoe, H. Jumonji and N. Kobori (University of Tokyo) are using high-frequency crystal filters with multiple-mode resonators vibrating in trapped-energy modes. In a conventional resonator that has but one electrode pair proper trapping normally leads to confinement of the main-mode vibrational energy near the electrode, with an exponential decay into the surrounding region. The one trapped mode produces a piezoelectrically induced charge on each electrode that is symmetric with respect to center lines along them.

When the mass loading is increased, however, another mode becomes trapped. This mode cannot be excited by the conventional electrode because the induced charge on the electrode is antisymmetric with respect to a certain center line and is cancelled out. To excite both symmetric and antisymmetric modes one divides the electrode in half along the center line, one half forming the input and the other the output. Because of the polarity reversal of induced charge, the output signal through the antisymmetric mode is out of phase with that through the symmetric mode. Hence, characteristics equivalent to a full-lattice filter with two different resonator pairs can be obtained by such a divided-electrode multiple-mode resonator. No external inductor, capacitor or hybrid transformer is required. A number of multiple-mode resonators can be fabricated on the same crystal wafer because the energies of individual resonators are trapped so that interresonator isolation can be regulated by design. Hence a complete filter is obtained in a truly monolithic integrated form making possible substantial reductions in size, weight and cost. These multiple-mode resonators have been made successfully of piezoelectric ceramic as well as of quartz.

With high-frequency monolithic crystal filters, R. A. Sykes and W. D. Beaver (Bell Labs) apply various crystal filter networks to single-frequency and voice-frequency channels. Particular emphasis is placed on the divided-electrode crystal unit and its lattice equivalent. Previous attempts to use multiresonant high-frequency crystal units with divided platings in conventional filter configurations have been limited by the range of resonance frequency placement and resultant image impedances of the filters. Proper choice of resonator-electrode disposition gives more latitude in placement of critical resonant frequencies. Unconventional lattice equivalents permit improved



characteristic resistance over the transmission band with no additional components.

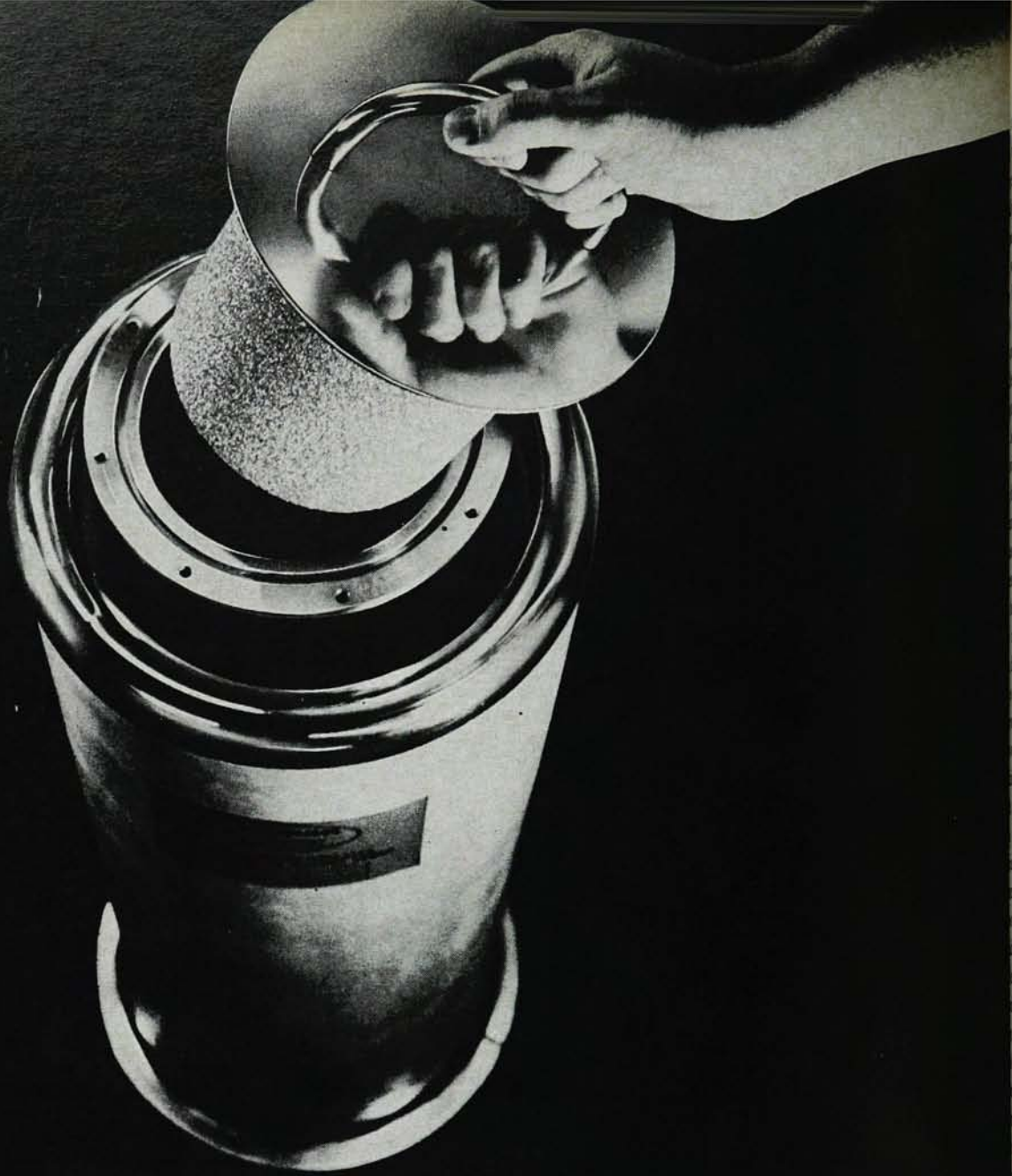
Performance characteristics of these monolithic crystal filters are simply stated: fractional bandwidth is a direct multiple of termination resistance, the proportionality constant varying from 0.7×10^{-6} to 8×10^{-6} . In a specific case a single crystal plate forms a monolithic filter with a bandwidth of 0.0055% of the mean frequency when terminated in 75-ohm circuits. This can be used for a single-frequency selector such as carrier and pilot filters in the range 6–25 MHz over normal temperatures. Other conventional crystal filters can be realized by addition of inductors and capacitors within the limits that the equivalent lattice of a crystal unit imposes.

The general case for monolithic filters of this type can be considered as a mechanical filter formed by elastically coupled resonators and therefore can be dealt with by conventional transmission methods without having to make theoretical calculations for each design.

H. Mailer and D. R. Beuerle (General Electric Co.) are incorporating multiresonant crystals into filters for quantity production. Design criteria arising from the trapping concept permit considerable reduction in size and cost as well as increased reliability. Particular attention is paid to optimizing filter design with regard to performance and package size. The effect of wafer contour on unwanted-mode responses of multiresonant crystals is important, especially when resonator dimensions and frequencies differ on the same wafer.

Mode coupling

Thus the trapped-energy concept as applied to vibrations of finite crystal plates has reduced singly- and multiresonant vibrator designs to handbook form, at least in the lower VHF range. Monolithic filters can be similarly designed. The connection between elastic and electric equivalent circuits has been elaborated and applied to mass production of these all-in-one filters. These developments, all reported this year, should enable the monolithic quartz-crystal filter to compete directly with active RC filters. In his studies of the mathematical theory of vibrations of crystal plates during the past year Mindlin has achieved results for fundamental thickness-shear and thickness-twist modes in partially electroded plates. The thickness-shear motion couples strongly to short-wavelength flexure, and regardless of excitation frequency energy is lost under the plated region in flexural waves because the dispersion curves for flexural waves yield only real wave numbers. Last year Mindlin showed that whenever the flexural wavelength is such that there is a node of flexure at the edge of the electrode, most of the energy is reflected back to the electrode, resulting in high Q . He has now treated coupling of face shear with thickness shear and found its influence to be so weak as to be



The first all-plastic dewar for super conductivity experiments. $\frac{1}{7}$ the liquid loss of stainless.

This is the first all plastic dewar ever made for liquid helium service. Developed by Hofman especially for super-conductivity experiments. It is the first time a plastic dewar has been able to retain vacuum under liquid helium temperatures. And the new plastic dewar has $\frac{1}{7}$ the liquid loss of stainless steel dewars. Yet, with all these advantages, the

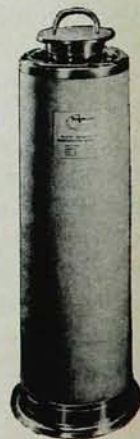
new plastic dewar weighs less and costs less than anything comparable in stainless steel. Hofman produces the dewars in a variety of diameters and depths.

For complete specifications and prices, write today. Hofman-Paul Cryogenic Div., 225 Parkhurst St., Newark, N.J.

West Coast facility: 6750 Caballero Blvd., Buena Park, Calif.



HOFMAN-PAUL CRYOGENIC DIVISION
Air Reduction



practically negligible. Thickness-twist waves were also considered. Basically thickness-shear waves, they propagate laterally and have lateral particle displacement reversals. These thickness-twist waves also couple to face-shear waves but much less than flexural waves couple to thickness-shear so that corresponding Q values are higher. The dispersion relations imply that the optimal electrode shape that will trap both thickness-shear and thickness-twist waves is an ellipse rather than the traditional circle.

Turning, then, from the fundamental modes and the approximate two-dimensional plate equations developed for their study, Mindlin disclosed a new method of approximate solution that aims at extending the analysis to harmonic (and anharmonic) overtones of thickness-shear and thickness-twist modes, opening a path to solutions for these modes in plates with all dimensions finite. Aspects of this method of attack were tested against an exact solution of the three-dimensional elastic equations for thickness-twist waves in an infinite plate, which Mindlin discovered last year. When used to compute Bechmann's number, the error in the approximation is about 1% for the fundamental and decreases with increasing harmonic order for normal values of electrode thickness. (Bechmann's number is the ratio of electrode size to plate thickness when the electrode size is equal to the wavelength of the disturbing wave of interest in the coated portion of the plate at the frequency corresponding to wave cut-off in the uncoated portion.)

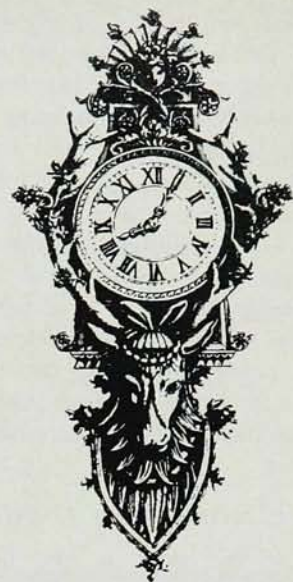
Several interesting features of energy trapping were brought up during the general discussion period at the Atlantic City symposium. E. A. Gerber (Army Electronics Command) introduced further evidence concerning the parallelism of VHF crystal blanks. He showed slides of optically polished crystals of varying degrees of parallelism made at Zeiss in 1943 and 1944. These were used in air-gap holders so that no electrode material touched the plate. The most nearly parallel of the plates had the cleanest mode spectrum. Energy trapping operates even in this case, he pointed out, because the piezoelectric effect

serves to lower the elastic stiffness of the quartz inside the electrode gap below that of the surrounding area producing different eigenfrequencies in each region, the necessary condition for trapping. Local thickness variations in the crystal plate measured by optical interference methods correlate with unwanted resonance frequencies too so that an additional trapping is associated with "lumps" on the plate surface. This fact indicates the necessity for surface inspection and control refinements because the problem increases with frequency.

Since the energy-trapping concept provides information concerning the distribution of active areas on the vibrating plate, the possibility of putting the circuit elements of an integrated oscillator on the nonvibrating portion of a quartz plate arises. This approach would lead to a monolithic oscillator, but because any crystal has to be enclosed in a sealed can, consideration was also given to placing the circuitry and quartz plate in the same enclosure.

An even more radical departure from these methods is the bulk-effect oscillator, where one piece of crystalline material is used both as a frequency-control element and as an active device. The active crystal resonator of D. L. White and W. C. Wang (Bell Labs), an ultrasonic distributed amplifier, oscillates in a pure, stable, high-frequency mode when it has net round-trip gain and is driven under dc conditions. This condition usually occurs when the electron drift velocity exceeds the sonic velocity of a given mode by more than 50%. The crystal oscillates on a high mechanical overtone of the mode at a frequency near that of maximal ultrasonic gain. Sometimes harmonics and subharmonics of this frequency are also prominent; other overtones are suppressed by 60 dB or more. Frequency of maximal gain is proportional to square root of bulk conductivity so that a light source can be used as an experimental convenience to vary the frequency in discrete steps from one harmonic to another.

Oscillations have been observed up to nearly 1 GHz with cadmium sulfide but several gigahertz is possible with zinc oxide; most detailed observations,



however, have been conducted in the 100-MHz region. These frequencies correspond to the 100th to 200th overtones of the thickness-shear mode of the crystal. Applied voltage, sample conductivity and temperature affect the frequency, but one-part-per-million stability appears possible with reasonable effort, thereby providing a stable source for the VHF and UHF ranges.

Electrostrictors

Describing a second type of bulk-effect device A. A. Gundjian (McGill) considered the characteristics of the electrostrictor as a lumped active resonator. When a mechanically unconstrained germanium slab is subjected locally to a strong electric field (5×10^6 V/m), it can break into electro-mechanical oscillations. The electro-mechanical coupling is through the electrostrictive property of germanium. Mechanical displacement is quadratic with field strength as with ordinary dielectric electrostriction, but the mechanism may be different. The oscillation frequency is the mechanical resonance frequency of the entire system: germanium slab, electrodes and mounting. The geometric excitation of the system, together with the bias field strength required to reach the threshold of oscillation, determines the mode of mechanical vibration.

The frequency stability of an oscillator using the electrostrictor principle was discussed. Samples covering the frequency range 10–100 kHz can

be tuned simply by changing the mass of the lumped vibrating system. The low Q values (~ 50) reported were probably due to mounting losses since the material has small internal loss and should have $Q \approx 10^4$ for large strains and greater than 10^6 for small strains. Since stability depends on Q , realization of at least part of the intrinsic value may lead to a new generation of frequency-control elements.

Will energy trapping be applied directly to active devices? One can only surmise what will be presented next year.

ATOMIC, MOLECULAR STANDARDS

Much of the work in the field of atomic and molecular frequency standards is directed toward improvement of frequency stability. Among the approaches are development of actively oscillating frequency standards with relatively high output powers for short-term frequency stability, and elimination of cavity-pulling effects in masers for long-term improvement.

Jacques Vanier (Varian) has analyzed factors limiting rubidium-maser output power and shown that maser operation can be characterized by a quality factor Γ_m that places an upper limit on its physical parameters. For a given combination of photon flux and ^{87}Rb density a maximal power can be predicted that is proportional to the ^{87}Rb density.

A high power, optically pumped, free-atom maser oscillator proposed by R. Novick, W. Happer and W. A. Stern (Columbia) is claimed to have unsurpassed short-term stability. In this maser hyperfine-structure (hfs) levels of free alkali or thallium atoms would be inverted by optical pumping in a large length of the free-atom beam that would then enter a cavity where coherent emission would take place. The output of such a maser would be about one microwatt. Its long-term stability would be severely limited by cavity pulling, but for periods of 1 sec stability would be one part in 10^{14} .

A Stark-effect hfs filter, described by Novick, Happer and Stern could be used for intensity pumping of new alkali- and possibly thallium-maser oscillators. Absorption lines of an atomic vapor normally coincide with the emission lines of its atomic-resonance lamp.

If in an absorption cell the lines are Stark shifted toward a lower frequency, the unwanted low-frequency hyperfine component of the resonance lamp will be absorbed. This allows the high-frequency hyperfine component of the lamp spectrum to be used for intensity pumping. This method, however, requires high electric fields for Stark shifts so that electric-breakdown problems might have to be solved.

J. J. Gallagher, R. E. Cupp and R. A. Kempf (Martin Co.) have developed a millimeter-wave molecular-beam tube using hydrogen sulfide with a line-width as narrow as 350 Hz at a resonance frequency of 168 GHz. Preparations are being made to lock an oscillator to the resonance frequency of this beam tube so that its performance can be compared with a cesium-beam tube or rubidium maser.

Hydrogen masers

In hydrogen masers Norman F. Ramsey (Harvard) has greatly reduced the cavity-pulling effect, which is the principal cause of frequency instability, by improving thermal stability of the maser cavity. He has measured frequency stabilities of 3×10^{-14} for a 24-hour period.

A high-magnetic-field hydrogen maser has been used to determine accurately the ratio of the electron magnetic moment to the proton magnetic moment by measuring magnetic-field resonance frequencies for the $F=1$, $m_F=0 \rightarrow m_F=+1$ and the $F=1$, $m_F=-1 \rightarrow m_F=0$ transitions, respectively.

A few developments currently in progress are improvement of cavity stability by electronically locking the cavity resonance frequency to the hydrogen hfs frequency, experiments with new wall coatings such as xenon and perfluoroethane (C_2F_6), determining the best operating temperature for the wall coating, and increase of bulb size to about 60 inches in diameter.

Two simultaneous relativity experiments are planned with a hydrogen maser orbiting the earth in a satellite: measurement of the gravitational red shift and measurement of possible dependence of the rate of a clock on its velocity relative to the fixed stars or, essentially, the center of mass of the observable universe.

H. G. Andresen and E. Pannaci (Army Electronics Command) are working on servo-controlled hydrogen-maser cavity tuning. The sensing method of cavity tuning is based on a periodic linewidth quenching of the hydrogen resonance that vanishes when the hydrogen and cavity resonances coincide.

Performance of a servo-controlled maser cavity tuning system has been compared for the pressure, magnetic-relaxation and Zeeman-transition-line-width-quenching methods. The result is that the pressure method gives the best servo-system performance because of the relatively large linewidth-quenching ratios that can be achieved with this method.

Reliability, always an important consideration of any frequency standard, is one of the advantages to be gained if one could replace the electron-multiplier cesium-beam-tube detector with a field-effect transistor. J. H. Holloway (Varian) and Paul Penfield (MIT) say that it may be possible to carry out this change without loss of signal-to-noise ratio and with the advantage of improved reliability and simplification of the beam-tube power supply.

A study with a high-flux test beam tube indicates that selected metal-oxide semiconductor field-effect transistors would perform with existing high-intensity cesium-beam tubes as well as electron multipliers. With present commercial beam tubes having low beam fluxes, the $1/f$ noise is still too large to allow their application, but it seems reasonable to expect transistor technology to improve and $1/f$ noise to be reduced sufficiently that field-effect transistors can be used in a broader range of beam tubes.

Richard F. Lacey (Varian) discussed the advantages of a practical thallium-beam tube over present cesium-beam tubes. These include the very low vapor pressure of thallium, which eliminates background increase with tube lifetime, and its smaller sensitivity to magnetic-field fluctuations. There remain some problems to be solved and these are the development of an efficient ionizer, reasonably sized state-selection magnets, a cavity suitable for large beam apertures and a thallium oven that consumes low power. $\square$