determined. This effect was investigated by measuring slot efficiencies as the size of the ground plane was reduced. Surprisingly, the ground plane dimension had little effect on the efficiency. At least, this was the case at the two values of k_0b which were considered. The ground plane was reduced to a 10-inch diameter flange and no appreciable change in efficiency was noted. Consequently, the ground plane was removed so that the launching structure consisted of the dielectric rod mounted on the coaxial exciter. Efficiency was measured at k_0b equal to 3.4 and 3.8. The results are presented in Table III which includes, for comparison, the efficiency that was measured *with* the large ground plane. Note that these data have not been corrected to account for the system losses.

TABLE III

k_0b	k_0a	Efficiency With Ground Plane	Efficiency No Ground Plane
3.4	1.70	0.44	0.428
	2.12	0.65	0.647
	2.34	0.76	0.779
	2.55	0.835	0.847
	2.76	0.77	0.829
↓	2.98	0.65	0.696
3.8	1.90	0.48	0.545
	2.38	0.775	0.776
	2.61	0.85	0.835
	2.85	0.77	0.776
	3.08	0.63	0.63
↓	3.32	0.44	0.413

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Proposal for a Tunable Millimeter Wave Molecular Oscillator and Amplifier*

J. R. SINGER†

Summary—**An atomic beam apparatus suitable for a millimeter wave generator is theoretically discussed. The beam consists of atoms having a net magnetic moment. The upper and lower Zeeman levels of the atomic beam in a magnetic field are spatially separated by an inhomogeneous magnetic field. The upper state atoms enter a cavity where transitions occur at a frequency determined by a static magnetic field. The resonant frequency of the cavity is set at the transition frequency. The positive feedback of the cavity allows operation as an oscillator. Some of the more important parameters for oscillator operation are evaluated. The upper frequency limit is determined primarily by the resonant structure design.**

INTRODUCTION

THE ammonia gas maser invented by Gordon, Zeiger and Townes[1] shows considerable promise as a frequency standard and as a narrow band amplifier. One limitation is the fixed frequency operation which is determined by the natural transition frequencies of the NH_3 molecule. An extension of the molecular beam technique which permits operation of a molecular oscillator amplifier in the mm wave region with a power output of the order of the ammonia maser is suggested in this paper.

The present scheme uses a Stern-Gerlach[2] type of molecular beam arrangement for achieving a polarized beam of atoms. The atoms in the lower energy state may be readily removed from the beam since they are spatially separated. The upper state atoms then adiabatically enter a homogeneous magnetic field region where they are subjected to an RF field polarized in the appropriate direction to induce atomic transitions. Induced transitions are always coherent in phase and amplification of RF is achieved if the rate of transitions times the energy from each transition exceeds the RF power input and the system losses. The system may be used as an oscillator since spontaneous emission will induce further transitions by use of a high Q structure

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[1] J. P. Gordon, H. J. Zeiger and C. H. Townes, "The maser," *Phys. Rev.*, vol. 99, pp. 1264–1274; August 15, 1955.

[2] W. Gerlach and O. Stern, "Der Experimentelle Nachweiss des Magnetischen Moments des Silberatoms," *Zeit. Physik*, vol. 8, pp. 110–112; December, 1921.

giving positive feedback. The method of achieving a polarized atomic beam and the operation of the oscillator is discussed in the following sections. Some suggestions for use as an amplifier are given.

POLARIZED ATOMIC BEAMS

Atoms in a magnetic field take up only $2j+1$ orientations following the rules of space quantization. Here j is the vector sum of the orbital angular momentum (l) and the spin (s). If atoms in an S state (monatomic hydrogen, alkali metals, silver, etc., in their ground state) are utilized, l vanishes and s equals $\frac{1}{2}$. This provides only two orientations for the atoms: parallel and antiparallel to the field. The orientations may be described by an upper energy state (pointing up) and a lower energy state (pointing down). The difference in energy is the Zeeman splitting $2\mu H$ where μ is the magnetic moment of the atom (a Bohr magneton for most cases of interest) and H is the homogeneous portion of the magnetic field. The time t taken to achieve the quantized orientations is given by $t \sim h/2\mu H$ where h is the Planck constant—this time is determined by the uncertainty principle and is much too short to measure under the usual circumstances.

If the magnetic atoms are subjected to an inhomogeneous magnetic field in the x direction, a force F is exerted on the atoms which is given by

$$F = \mu \frac{\partial |H_x|}{\partial x} . \tag{1}$$

Where the force is such that oppositely oriented magnetic moments are pulled in opposite directions as indicated schematically in Fig. 1. The average deflection d of each orientation depends upon the average time that an atom spends in the inhomogeneous field which may be expressed as

$$d = FL^2/2v^2M \tag{2}$$

where L is the length of path in the field, v is the average velocity of the atoms and M is the atomic mass. The average velocity squared, from kinetic theory is

$$v^2 = 4kT/M \tag{3}$$

where k is Boltzmann's constant, and T is the Kelvin temperature. By combining (1), (2), and (3) an expression for the deflection is obtained; that is,

$$d = \mu \frac{\partial |H_x|}{\partial x} L^2/8kT. \tag{4}$$

The separation of the oppositely pointing spins is twice the value of (4). If the beam separation desired is one cm, this can be readily accomplished with an inhomogeneous field of 5000 oersteds/cm, an atomic flight length of 100 cm, and a gas oven temperature of 500°K.

The atoms in the upper energy state will now enter a homogeneous magnetic field (see Fig. 1). The requirement that no transitions be induced in the course of a change in field strength is such that the change in static field be at a rate that many precessions occur during the change; that is,

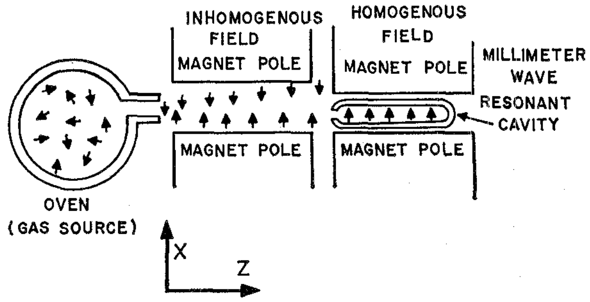

Fig. 1—A schematic of the Stern-Gerlach polarization scheme with oriented magnetic dipoles allowed access to the cavity for oscillation or amplification purposes.

$$\frac{dH}{dt} \ll \gamma H^2 \tag{5}$$

where t is the time and γ is the gyromagnetic ratio. It is easy to satisfy (5) which implies that changes in energy are adiabatic in the Ehrenfest sense.

OPERATIONAL CONSIDERATIONS

The portion of the beam entering the cavity is entirely in the upper energy state. The frequency ν for transition to the lower state is determined by the magnetic field H, where

$$\nu = 2\mu H/h \tag{6}$$

and h is the Planck constant.

There is considerable freedom in choosing the parameter H, but as shall be described later, the range of operation is held within the bounds of the resonant cavity chosen. Consequently, if a wide tuning range is desired, provision must be made for tuning the cavity. Oscillator parameters which need further discussion are power output, and conditions for oscillation must occur. The important feature of an oscillator is its positive feedback. This feedback, in the case of a maser device, occurs in the following way. A few spontaneous emissions occur. The radiated fields are reflected by a high Q cavity. The reflected fields act on the rest of the atoms in the cavity causing induced emissions; the radiated field is reflected again and more induced emissions occur, etc. If the oscillation builds up as described, it soon reaches a maximum amplitude determined by the total number of excited atoms in the cavity available for emission. The major limitations to very high-frequency atomic beam oscillators are 1) the available beam intensities, and 2) the size of the cavities which can be constructed with a reasonably large Q.

THE ATOMIC BEAM OSCILLATOR

The two possible states of an atom with spin $\frac{1}{2}$ in a magnetic field may be described by,

$$\psi = a\psi_1 + b\psi_2 \tag{7}$$

where ψ_1 is the lower state and ψ_2 the upper state. If all the atoms enter the cavity in the upper state, then initially b is unity and a vanishes. If an RF field is coupled into the cavity and the frequency of this field is equal to the transition frequency given by (6) then the atomic perturbation is

$$-\mu H_1 \cos 2\pi\nu t \tag{8}$$

where H_1 is the maximum RF magnetic field in the cavity depending upon the input RF power and the cavity Q and ν is the RF frequency.

The probability that an atom will have made a transition downward and be found in the lower energy state after a time t is given by[3]

$$|a|^2 = \frac{(\bar{\mu}H_1/h)^2}{(\bar{\mu}H_1/h)^2 + (\Delta\nu)^2} \sin^2\{\pi t[(\bar{\mu}H_1/h)^2 + (\Delta\nu)^2]^{1/2}\} \tag{9}$$

where $\Delta\nu$ is the frequency deviation from resonance and $\bar{\mu}$ is the matrix element of the dipole transition. In the case under consideration here, $\bar{\mu}^2 = \frac{1}{2}\mu^2$ where μ is a Bohr magnetron. H_1 is the RF field in the cavity, and t is the time spent in the perturbation field. The time t is the cavity length divided by the average velocity of the atoms.

In order that oscillation shall occur, losses in the resonant cavity must be equaled or exceeded by the power output of atomic transitions. The condition for equality is

$$\frac{1}{Q} = \frac{P}{2\pi\nu W} \tag{10}$$

where Q is 2π times the energy stored in the cavity divided by the energy loss per cycle, P is the power of atomic emission, and W is the energy stored in the cavity. The emitted power P of (10) may be put into the form

$$P = Nh\nu |a|^2 \tag{11}$$

where N is the number of atoms available in the upper energy state per second.

At resonance $\Delta\nu$ vanishes, and (9) becomes

$$|a|^2 = \sin^2(\pi\nu_1 t) \tag{12}$$

where $\nu_1 = \bar{\mu}H_1/h$. The value of $\sin^2 \pi\nu_1 t$ is approximately $(\pi\nu_1 t)^2$ for small values of $\nu_1 t$. This will be small as long as the stored energy in the cavity is small which is the physical situation of interest. Combining (8) and (10)–(12) and using our approximation, one obtains,

$$N = \frac{hV}{2(\pi t\mu)^2 Q} \tag{13}$$

where μ is the magnetic dipole moment of one Bohr magnetron, V is the volume of the cavity having the quality factor Q, and t is the time of flight of the atoms in the cavity as before.

Although the field in the cavity does not appear explicitly in (13) because of our approximation, the physical situation requires that the waveguide mode be such that the beam "sees" the RF magnetic field polarized in the proper direction for induced transitions. It is assumed that the beam is subjected to the average magnetic field in the cavity.

By using a cylindrical cavity of 12-cm length and 0.76-cm radius in the TE_{011} mode, one gets a theoretical Q of 17,800 according to Shimoda, Wang, and Townes.[4] This cavity was used by Townes and his group for the ammonia maser. The openings to admit passage of the beam were 0.4-inch diameter sections which were beyond cutoff for a 12.5-mm wavelength. Shimoda, *et al.*, have pointed out that this cavity is better suited for inducing magnetic transitions than the electric dipole transitions of the ammonia maser.

A beam input area of $\frac{3}{4}$ cm^2 is provided with this cavity at an operating frequency of 12.5 mm. In order to push towards higher frequencies with the scheme presented here, one would like to improve the Q. This may be accomplished by cooling the cavity with liquid helium to pick up a factor of two or three in Q.

Operation at 12.5 mm is relatively easy. Assuming an atom with a low boiling point, such as Rb^{87} and a Q of about 20,000 for the TE_{011} cavity described above, one requires an N of about 10^{17} atoms/second/cm^2 in order to satisfy (13) and get continual oscillation. This flux is larger than any commonly used in conventional atomic beam work. A method for obtaining this flux will be discussed in a following section.

The value for N calculated above may be compared with the value used in the ammonia beam maser oscillator—about 10^{13} molecules per second. The reason for the smaller value in ammonia masers is that the electric dipole moment is two orders of magnitude larger than the magnetic dipole used here. Beam intensities of 10^{15} to 10^{16} molecules/cm^2/second have been utilized by NH_3 masers.[5] However, in the case of ammonia masers, only a fraction (6 per cent) of the beam is available for transitions at the desired frequency.[5] In the present case the large magnetic fields cause a Paschen-Back decoupling of the nuclear and electron spins, and the hyperfine structure splits the transition frequencies into $2I+1$ levels. For isotopically pure Rb^{87}, $I=3/2$ and each electron transition is split into four levels. Consequently, about 25 per cent of the beam will have the desired transition frequency.[6]

The useful power output P_0 from the oscillator is given by

$$P_0 = \frac{2\pi\nu W}{Q_e} \tag{14}$$

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[3] L. I. Schiff, "Quantum Mechanics," McGraw-Hill Book Co., Inc., New York, N. Y., p. 191; 1949.

[4] K. Shimoda, T. C. Wang and C. H. Townes, "Further aspects of the theory of the maser," *Phys. Rev.*, vol. 192, pp. 1308–1321; June 1, 1956.

[5] J. C. Helmer, "Maser oscillations," *J. Appl. Phys.*, vol. 28, pp. 213–215; February, 1957.

[6] In second-order calculations, the electric quadrupole moment interaction will affect the frequency. However, this will only result in a broadening of the resonance line.

where Q_c is the coupling q to the output. Shimoda, *et al.*,[4] calculated that the optimum Q_c is twice the loaded Q of the cavity so that (14) becomes

$$P_0 = \frac{\pi \nu W}{Q} \tag{15}$$

which, for higher frequencies, should give higher output powers because of the linear dependence on frequency. It may be worth noting that the NH_3 maser used as an oscillator at K band provides about 10^{-10} watts.

OPERATION AS AN AMPLIFIER

The atomic beam amplifier has a low-noise figure just as in the case of the NH_3 maser. One advantage of the present system is the feature of tunability. It may be possible to provide a cavity which can be tuned at the same time that the homogeneous magnetic field is varied. Both should be simultaneously set to a variable frequency ν given by

$$\nu = 2\mu H/h. \tag{16}$$

This would permit sweeping a wide frequency range with a low-noise narrow-band amplifier. The power output must not be more than the order of millimicrowatts just as in the case of the NH_3 maser. This limitation is set by the power saturation of the atomic beam; when the input power is greater than saturation as determined by the number of atoms per second available for an induced transition, then further amplification is not possible.

BEAM INTENSITY

Practical beams of the order of 10^{15} atoms/second/cm^2 are easily obtained according to Silsbee.[7] However, to satisfy (13), the oscillation condition, another two orders of magnitude of flux are needed. To obtain such flux is an extremely difficult task, but is not impossible as the following discussion will show. Ramsey[8] discusses several methods of focusing which may be used to intensify the beam. One method which appears feasible is due to Rabi.[9] This scheme uses the analog of optical focusing and calculates the change of refractive index of a beam entering or leaving a magnetic field. One difficulty with this method is that many pole pieces of different shapes would be required to get a sufficiently dense beam since the bending is small at each change in refractive index.

A more convenient scheme of getting dense beams was invented by Stern[10] who called it the "multiplier." This consists of many converging beams each of which would be in an independent inhomogeneous field. Stern built such a device with 150 such converging beams.

The inhomogeneous fields consist of machined converging grooves in the pole pieces of the magnet used for separation of the upper and lower spin states. This provides an increase in flux density by a factor of 150 which is about the amount needed here. Further, this method may be extended to any number of channels. One ultimate limit is pressure broadening of the resonance line. The latter problem is not serious; even though atomic collisions may take place in the neighborhood of the cavity opening, the beam diverges once inside the cavity and the pressure is reduced. Consequently the collision probability is very small. Certainly operation at 12.5 mm will have no difficulties with pressure broadening. The major source of line broadening will be, as in the case of the ammonia maser, Doppler broadening.[4]

The beams which make a large angle with the central axis of the cavity could result in a somewhat reduced effect in starting oscillation. Thus a limitation to the number of useful beams appears. This may require careful design of the cavity so that the RF magnetic fields will act upon all of the diverging beam inside the cavity. By use of the symmetry of a rectangular cavity configuration somewhat more uniform transition fields may be possible. Further, the cavity may be designed with input and output slits so that the beams converge to a central region in the cavity and diverge towards an exit slit. Various cavity configurations have been thoroughly explored and calculated.[4] A cavity could be designed so as to contain the flux in about a 20° arc. This should permit the use of several hundred converging beams.

FURTHER CONSIDERATIONS

In order to get a long transit time in the cavity, it is desirable to use heavy atoms which are gaseous at low temperatures. However, this is not critical; any of the alkali metals would be satisfactory. As mentioned previously, the fields used here are large enough to observe the Paschen-Back effect between the nuclear and electron spins, consequently hyperfine-interaction will affect the frequency of electron transitions. It would be advantageous to use a low boiling point heavy metal such as Rb (696°C) in order to get low atomic velocities. Ag^{107} or Ag^{109} has the advantage of lower nuclear spin ($\frac{1}{2}$), but the disadvantage of a high boiling point (2200°C). Rb^{87} in isotopically pure form seems to be about the best choice. This is about 27 per cent of naturally occurring rubidium. With silver, the 107 and 109 isotopes are approximately 50 per cent each in nature. Use of silver may simplify the problem of securing the proper isotopes.

The discussion has generally slanted towards 12.5-mm operation. The reason for this is that the ammonia maser operates at that frequency. It is also advantageous to utilize a cavity design which has been well engineered.[4] Fundamentally, one has no limitation except the shrinking size of the cavity as one goes to shorter wavelengths.

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[7] H. B. Silsbee, private communication.

[8] N. F. Ramsey, "Molecular Beams," Oxford University Press, New York, N. Y., chap. 16; 1956.

[9] I. I. Rabi, "Refraction of beams of molecules," *Nature*, vol. 123, p. 163; February 2, 1929.

[10] O. Stern, "Zur Methode der Molekularstrahlen I," *Zeit. Physik*, vol. 39, pp. 751–763; September, 1926.

However, the upper frequency limitation is also set by the difficulties of getting magnetic fields greater than 25,000 oersteds. This sets the limit at wavelengths of about 3 mm. Because of the associated cavity size and beam requirements, it is unlikely that the proposed system will be extended below 5 mm. Certainly there would be much to be gained by working at 1.25 cm initially where the NH_3 maser can be used for a frequency reference.

For noise calculations, it would be difficult to improve upon the treatment given by Gordon and White[11] which applies to the NH_3 maser, and scarcely any modification is needed to extend the treatment to magnetic dipole transitions. There is good reason to believe that a noise temperature of a few degrees Kelvin is attainable.

It may be well to point out that a solid-state system presents certain advantages over the proposal outlined here.[12] The most important of these is a very much larger gain-bandwidth product. On the other hand, a continuously operating three-level solid-state maser requires a pump frequency higher than the operating frequency, and this is difficult to obtain at mm wavelengths. Also, a solid-state maser calls for very low temperatures in order to achieve long thermal relaxation times, while the gas beam maser has no such requirement.

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It is a pleasure to thank H. B. Silsbee for an interesting discussion on molecular beams and for suggesting improvements in this manuscript. In addition, comments from C. H. Townes and S. Silver have proved profitable.

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[11] J. P. Gordon and L. D. White, "Noise in maser amplifiers," PROC. IRE, vol. 46, pp. 1588–1594; September, 1958.

[12] Zacharias and A. Javan have been performing experiments related to the scheme proposed here. (Private communication from C. H. Townes.)

High-Speed Microwave Switching of Semiconductors—II*

ROBERT V. GARVER†

***Summary*—A relationship between low-power isolation and small-signal, low-frequency diode resistance is reported. A study of ambient heating indicates that with increasing temperature the diode characteristics tend to approach the line characteristic of the above relationship. Observed switching speeds of 1.5 to 3.0 mμs are reported. A theory is presented which agrees with the switching time data and predicts microwave switching times as low as 0.2 to 0.3 mμs. High speed switching is discussed with reference to significant parameters, *e.g.*, hole storage, internal heating, and pulse reverse diode characteristics.**

INTRODUCTION

It has been shown in previous publications[1–3] that an *n*-type point contact germanium diode can be used to switch *X*-band microwaves. Placing the diode across the center of the waveguide and impressing a reverse or forward voltage upon it will cause the diode to reflect or transmit the microwave power. The ratio of the microwave power past the diode in the reflecting state, to the incident microwave power, defines the isolation in db. The same ratio in the transmitting state, defines the insertion loss. Isolations of 25 to 35 db with constant insertion losses of 1 db were reported[1] over a 1000 mc band-width at 1 milliwatt incident microwave power. Using a 1N263, the only commercially available microwave germanium diode, rapid deterioration of isolation occurred for incident microwave peak powers greater than 5 milliwatts. Ambient heating showed constant insertion loss and only slight deterioration of isolation from 20°C to 150°C. It was shown[2] that decreasing the donor density of the germanium allowed the diode to switch up to 1 watt of incident microwave peak power. It was demonstrated by observing two pulses at succeedingly closer intervals that there was essentially no dead time between switching events. The pulse time constants of the diode switch were found to be a function of germanium donor density and to be of the order of 3×10^{-9} to 10×10^{-9} seconds (3–10 mμsec). Devices

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* Manuscript received by the PGMTT, October 31, 1958. Revised manuscript received, December 29, 1958.

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[1] M. A. Armistead, E. G. Spencer, and R. D. Hatcher, "Microwave semiconductor switch," PROC. IRE, vol. 44, p. 1875; December, 1956.

[2] R. V. Garver, E. G. Spencer, and R. C. LeCraw, "High speed microwave switching of semiconductors," *J. Appl. Phys.*, vol. 28, pp. 1336–1338; November, 1957.

[3] R. V. Garver, E. G. Spencer, and M. A. Harper, "Microwave semiconductor switching techniques," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-6, pp. 378–383; October, 1958.