ELIMINATION OF THE LIGHT SHIFT IN RUBIDIUM GAS CELL FREQUENCY STANDARDS USING PULSED OPTICAL PUMPING

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ABSTRACT

It is well known that changes in the intensity of the light source in an optically pumped, rubidium, gas cell frequency standard can produce corresponding frequency shifts, with possible adverse effects on the long-term frequency stability. Since this so-called "light-shift" effect is due to the simultaneous presence of pumping light and interrogating microwave radiation, it can be eliminated, in principle, by alternately pulsing the pumping light and the microwave radiation so that there is no temporal overlap.

We have constructed a pulsed optical pumping apparatus with the intent of investigating the frequency stability in the absence of light shifts. Contrary to our original expectations, a small residual frequency shift due to changes in light intensity has been experimentally observed. Evidence is given which indicates that this is not a true light-shift effect. Preliminary measurements of the frequency stability of this apparatus, with this small residual "pseudo" light shift present, are presented. It is shown that this pseudo light shift can be eliminated by using a more homogeneous C-field. This is consistent with the idea that the pseudo light shift is due to inhomogeneity in the physics package ("position-shift" effect).

INTRODUCTION

At the present time, there is a real need for compact, lightweight, low power, highly stable atomic frequency standards. This is exemplified by programs such as that for the NAVSTAR Global Positioning System, or GPS for short. This program calls for state-of-the-art size, weight and power reductions for atomic frequency standards, and a long-term stability requirement of one part in 10^{13} over periods of approximately 1 to 12 days for phases II and III of GPS {1}. Requirements such as these can be expected to be even more demanding in the future as the overall state-of-the-art of military technology moves forward.

Table 1 summarizes the state-of-the-art for small atomic frequency standards. The hydrogen and cesium devices have excellent stability over periods of weeks, months and even years. Rubidium is less satisfactory in this respect but has the advantage of much smaller size, weight and power consumption. The ideal frequency standard would combine the excellent long-term stability of hydrogen and cesium with the small size, weight and power consumption of rubidium. There are two possible methods of approach toward this goal. The first is to reduce even further the size, weight and power of hydrogen and cesium devices. While further small reductions might be possible, it is unlikely that these devices can be made to approach present day rubidiums in this respect. For example, even for cesium a factor of 9 in size and a factor of 7 in weight would be required. Moreover, relative to future rubidiums, factors of 18 and 12, respectively, would be required {2}. We are therefore led to the second method of approach, which is to improve the long-term stability of rubidium devices without significantly increasing size, weight, or power consumption. Table 2 shows that there is reason to believe that this can be done.

The best reported stability for rubidium is several parts in 10^{14} for an averaging time of about 7 hours. Two such measurements have been reported {3,4}, each on a different unit at different times and by different groups. In addition, a stability of parts in 10^{14} for τ = 6 hr to 12 days for one rubidium device has been reported at this conference (this device uses an Efratom physics package) {1}. This stability is on a par with cesium {5} and is only about a factor of 50 worse than the "best" reported stability for hydrogen {6}. For times longer than 7 hours, the stability of most rubidium devices worsens, most likely due to uncontrolled changes in device parameters. If the device parameters that are changing could be determined and controlled, better long-term stability would result.

FUNDAMENTAL PHYSICAL EFFECTS

Figure 1 lists those fundamental physical effects that can adversely affect the stability of rubidium devices. Let us consider these effects one at a time.

Light Shift

The insert at the lower left of Figure 1 shows the two hyperfine energy levels of rubidium which determine the rubidium resonant frequency. In general, when a rubidium atom is illuminated by the light used for optical pumping, these two energy levels are Stark shifted by the electric field of the light, thereby producing a change in the atom's resonant frequency {7}. This results in a frequency shift that is proportional to light intensity.

This effect can be eliminated by interrogating the atoms in the dark; that is, when the pumping light is absent.

Position-Shift Effect

The position-shift effect {8} is due to inhomogeneity in the physics package. The result of this inhomogeneity is to make the resonant frequencies of the rubidium atoms depend on their location within the cell, as indicated schematically at the lower right of Figure 1. This inhomogeneity is due mostly to C-field nonuniformity and also, to a lesser extent, to light shift nonuniformity. Since the optical pumping and the microwave interrogation are also nonuniform over the cell, the experimentally observed resonant frequency is a weighted average of the frequencies of the individual atoms in the cell. Now, if the intensity of pumping light were to change, then the weighted average would for example, shift so that those atoms in the center of the cell might be favored more than those at the ends. This would obviously result in an increase in the experimentally observed resonant frequency. We term this type of shift the "pseudo light shift" because it can mimic a true light shift.

Buffer Gas Shift

The buffer gas shift {9} occurs due to collisions between the rubidium atoms and the buffer gas atoms, and is dependent on buffer gas density and temperature, as well as on the buffer gas that is used.

Spectrum of Exciting Microwave Radiation

Frequency shifts due to the exciting microwave radiation are not usually a problem if care is taken to obtain a spectrally pure exciting frequency free of spurious and unwanted sidebands {10}.

Magnetic Field

Since the magnetic field sensitivity {10} for rubidium is only about 2 x larger than for cesium, magnetic field sensitivity for rubidium is not significantly more of a problem than it is for cesium.

It is very difficult to give estimates of the possible frequency changes due to these effects because they are a very strong function of the individual device configuration and parameters. In spite of this, we can still say that of the 5 effects listed here, the first 3 are the most important.

The objective of the experiments that we are carrying out is to improve the long-term stability of small rubidium devices. Today we will describe some preliminary results that lead toward this goal. These results deal with the reduction and elimination of the light-shift and the position-shift effects, and have been obtained with the expenditure of less than one man-year of scientific effort.

METHOD FOR ELIMINATION OF LIGHT SHIFT

Figure 2 shows the method that we have used to eliminate the light shift. This method was first suggested by Arditi {11}. First, the light is pulsed on and the atoms are optically pumped. Then the light is turned off and the interrogating microwave radiation is turned on. The microwave radiation is then turned off and the pumping light is turned on again. This basic cycle is subsequently repeated many times. Since the atoms are interrogated in the dark, the light shift should be eliminated. This, of course, assumes that the atomic coherence does not persist from one cycle to the next {12}.

Before passing to the next slide, we note that in our experiments, the atomic transition is detected by optically monitoring the absorption of the pumping light. This is essentially the same detection method as that used in all conventional rubdiums.

Figure 3 shows a block diagram of the apparatus. The pulser alternately pulses the light and the microwave radiation at a 280 Hz rate, as shown in the previous slide, so that the atoms are interrogated in the dark. The remainder of the apparatus is a conventional frequency locked loop. The modulation frequency of 10 Hz is chosen to be about an order of magnitude smaller than the pulsing frequency so that the two signals can be separated by filtering before synchronous detection of the 10 Hz.

Figure 4 is a photograph of the physics package, which is a modified version of the physics package used in the Efratom, Model FRK rubidium frequency standard. The base of the rubidium lamp is at the right, and the magnetic shield that encloses the resonance cell and microwave canity is at the left. The entire unit is less than 4 inches long.

The philosophy adopted in this work was that everything possible should be done to retain the small size.

RESULTS

Light shift measurements have been made on this apparatus and the results are shown in Table 3. Measurements were made of the fractional frequency shift resulting from a 30 % change in light intensity. Two sets of measurements were made - - one with the apparatus operated CW, and the other with it pulsed.

In the case of CW operation, we expect a large light shift. This was observed for each of two different rubidium lamps - - lamp A and lamp B. These two lamps differ in the ratios of their rubidium isotopes. Lamp A produces a positive light shift, and lamp B a negative light shift. This is in agreement with the theory of the light shift in rubidium 87 as worked out by Mathur, Tang and Happer {7}.

When the apparatus is operated in the pulsed mode we expect to see no light shift. Yet there is a change in frequency with light intensity. This change is about a factor of 10 smaller than the CW light shift, and we can tell that it is not a true light shift because it does not change sign in going from lamp A to lamp B. Other tests, which we will not describe here, also confirm this to be the case. For these reasons we dub this effect the "pseudo-light-shift effect." We will have more to say on this later.

Table 4 shows the results of some preliminary frequency stability measurements that have been made on our pulsed optical pumping apparatus. For pulsed pumping, the short-term stability is expected to be degraded somewhat by noise introduced in the pulsing process. The short-term stability for pulsed pumping has been measured for averaging times from 1 to 100 seconds and found to improve as $1/\sqrt{\tau}$ (footnote A in Table 4). This shows that we are dealing with white frequency modulation noise, as is usually the case for passive rubidium devices. The value of $\sigma_y(\tau)$ for 100 sec is given in column 2 and can be compared with that for our small commercial rubidiums. The result for pulsed pumping lies between the spec for our two commercial models and is better than that of an HP 5062C cesium. The short-term stability of the pulsed pumping apparatus is therefore quite good, even in this preliminary stage, and can almost certainly be improved further.

The long-term stability was also measured for a 24-hour averaging time and a preliminary value of approximately 5 parts in 10^{12} was obtained. This is not yet as good as our commercial units.

After these stability measurements were made it was discovered that there were several device parameters that were not under tight control. These included significant second-harmonic contamination of the 10 Hz modulation, and frequency changes due to changes in barometric pressure. All of these parameter changes can be expected to produce frequency changes of parts in 10^{12}, which is of the order of the observed instability over 24 hours. The pseudo-light-shift effect is not negligible at this level either, and it may be a contributor to the observed instability.

All of these parameters can be easily controlled except for the pseudo light shift. However, it was suspected that the pseudo-light-shift effect might actually be a manifestation of the position-shift effect, as mentioned earlier. To test this hypothesis, a new C-field was constructed for our physics package that greatly improved the homogeneity of the static magnetic field and which should therefore greatly diminish the position-shift effect.

Table 5 shows the result of using this new C-field. The first line of this table is a repeat of the data shown in Table 3 for the old C-field. The second line shows what happened when some small steel parts on the outside of the microwave cavity were removed. This improved the C-field homogeneity and also reduced the pseudo light shift by about 30 %. Finally, the last line of the table shows the results for the new C-field. The pseudo light shift is now undetectable, of the order of parts in 10^{12} or less for a 30 % change in light intensity.

To summarize, the residual light shift has now been reduced to an undetectable amount by using the method of pulsed optical pumping in conjunction with a homogeneous C-field. It is likely that the new homogeneous C-field will also have other beneficial effects, such as reduced sensitivity to changes in microwave power, but this has not yet been verified experimentally.

Our plans for the immediate future are to beat down the known sources of frequency instability to the level of parts in 10^{13} or below, and then to take additional long-term stability data. It is expected that this will lead to an improved long-term stability compared to the present value of about 5 parts in 10^{12} for τ = 24 hours which was taken before the pseudo light shift was eliminated. Stability data over longer periods of time will also be taken to see if there is an improvement there.

Table 6 compares our preliminary results with those obtained by other investigators, namely, Arditi and Carver, who were the first to use the method of pulsed optical pumping for elimination of the light shift, and a Russian group that has done several man-years of work in this area.

In their experiments, Arditi and Carver used a high sensitivity microwave receiver to detect the rubidium resonance. Because of the complexity of the electronics this method is not suitable for use in a practical device. The Russians used an optical detection method, that has the disadvantage of requiring 2 rubidium lamps. We also use an optical detection method but only one rubidium lamp is required. In addition, we have used a single rubidium cell that combines the filtering and resonance functions, thereby eliminating the need for a separate filter cell. For these reasons our physics package is extremely small, which is desirable in a practical device. In fact, this is the same physics package that is used in the Efratom small commercial rubidium frequency standards.

Arditi and Carver saw no light shift at the level of a part in 10^{10}. On the other hand, the Russians did observe true light shifts (due to persistence of the atomic coherence) but were able to minimize them by proper choice of operating conditions. In our experiments the light shift is undetectable so that if it exists at all, it is of order parts in 10^{12} or less for a 30 % change in light intensity.

As regards stability, Arditi and Carver made some short-term measurements at the level of about 1×10^{-10}. The Russians have not reported any stability measurements for reasons unknown to us. As already mentioned, we have measured the frequency stability for our apparatus and found it to be of the order of parts in 10^{12}. However, it should be emphasized that these measurements are preliminary and were made prior to elimination of the pseudo light shift.

NOTE ADDED IN PROOF

We have just learned that results similar to those reported here have also been obtained by J. Ernvein-Pecquenard and L. Malnar, "Horologe atomique à pompage optique séquentiel," C. R. Acad. Sc. Paris 268(B), 817 (1969). They reported no light shift (detection limit of $1 - 2 \times 10^{-11}$) for a 25 % change in light intensity using pulsed optical pumping with optical detection; no frequency stability results are given in their paper, however. Also, no pseudo light shift was observed in their experiments, presumably because they used a conventional, laboratory-type, optical pumping apparatus (very large physics package and very homogeneous C-field); for practical devices utilizing small physics packages, it is also necessary to consider the pseudo light shift effect (position-shift effect), as has been done in the present work. Thus, the results of the two investigations are in agreement, to the extent that the experimental setups were similiar. We would like to thank Prof. M. Têtu for bringing the paper of Ernvein-Pecquenard and Malnar to our attention.

PROGNOSIS

At the present time, the ultimate frequency stability attainable using the pulsed optical pumping method is not known. Possible limitations could be due to changes in buffer gas pressure, if they occur, and also to changes in the pulsing parameters, such as the durations of the light and microwave pulses. It is known that frequency shifts do occur due to changes in the pulsing parameters. We have investigated this phenomenon using the old C-field and have estimated that it certainly is important at the level of parts in 10^{13}.

Future efforts will concentrate on understanding and reducing frequency sensitivity to changes in pulsing parameters. Effort will also be devoted to devising a method for studying frequency shifts due to possible small changes in buffer gas pressure.

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REFERENCES

1. F. K. Koide, D. J. Dederich and L. H. Baker, "Rubidium Frequency Standard Test Program for NAVSTAR GPS," Paper 9 presented at Session III of this conference (10th PTTI, 1978).

2. T. C. English, presentation on rubidium frequency standards as part of the Discussion Form on Atomic Frequency Standards, Session II of this conference (10th PTTI, 1978).

3. H. Hellwig and A. E. Wainwright, "A Portable Rubidium Clock for Precision Time Transport," 7th PTTI, Dec 1975, p. 143.

4. Unpublished data, Rockwell International, Anaheim, California, 1977.

5. D. B. Percival, "Statistical Properties of High Performance Cesium Standards," 5th PTTI, Dec. 1973, p. 239.

6. M. W. Levine, R. F. Vessot and E. M. Mattison, "Performance Evaluation of the SAO VLG-11 Atomic Hydrogen Masers," Proc. 32nd Annual Symp. on Freq. Control, 31 May-2 June, 1978, p. 477.

7. B. S. Mathur, H. Tang and W. Happer, "Light Shifts in the Alkali Atoms," Phys. Rev. 171, 11 (1968).

8. A. Risley and G. Busca, "Effect of Line Inhomogeneity on the Frequency of Passive Rb^{87} Frequency Standards," Proc. 32nd Annual Symp. on Freq. Control, 31 May-2 June, 1978, p. 506.

9. W. Happer, "Optical Pumping," Rev. Mod. Phys. 44, 169 (1972), espec. pp. 221-24.

10. R. C. Mockler, "Atomic Beam Frequency Standards," Adv. Electronics and Electron Phys. 15, 1 (1961), espec. pp.51. Also, reprinted in NBS Special Publication, Volume 5, Precision Measurement and Calibration, Frequency and Time, 1972, p. 1.

11. It appears that the idea of pulsed optical pumping was originally conceived by Alley {C. O. Alley, "Coherent Pulse Techniques in the Optical Detection of the $0 \leftrightarrow 0$ Ground State Hyperfine Resonance in Rubidium 87," in Quantum Electronics (C. H. Townes, Editor, Columbia U. Press, N. Y., 1960), p. 146} . The application for the elimination of the light shift appears to have been due to Arditi {M. Arditi, "High Stability Gas Cell Frequency Standard," U. S. Patent 3, 234, 483, Feb. 8, 1966} .

12. E. I. Alexseyev, Y. N. Bazarov and G. I. Telegin, "Light Shifts in a Quantum Frequency Standard with Pulsed Optical Pumping and Optical Indication of the Ramsey Structure of the $0 \leftrightarrow 0$ Transition Line of Rb^{87} Atoms," Radio Eng. and Electronic Phys. 20, 73 (1975)

TABLE 1

SOME CHARACTERISTICS OF SMALL STATE-OF-THE-ART

ATOMIC FREQUENCY STANDARDS

DEVICE	LONG-TERM STABILITY	SIZE (LITERS)	WEIGHT (LBS)	POWER (W)	APPROX. COST (K$)
SPACECRAFT H-MASER	$< 1 \times 10^{-14}/10\ \mathrm{D}^{A}$	20-50[A]	50-90[A]	55[A]	- - -
SMALL COMMERCIAL CESIUM	PARTS IN $10^{12}/\mathrm{YR}^{B}$	9	22	24	18
SMALL COMMERCIAL RUBIDIUM	$< 1 \times 10^{-11}/\mathrm{MO}^{B}$	1	3	13	6

[A]PROJECTED

[B]TYPICAL MANUFACTURER's SPECIFICATION

TABLE 2

"BEST" REPORTED FREQUENCY STABILITIES FOR ATOMIC FREQUENCY STANDARDS

DEVICE	STABILITY, $\sigma_Y(\tau)$	AVERAGING TIME, τ	REF
SAO H-MASER	6×10^{-16}	11 HR	1
COMMERCIAL CESIUM (HIGH PERFORM)	2×10^{-14}	5 D	2
SMALL COMMERCIAL RUBIDIUM	$3\text{-}4 \times 10^{-14}$	7 HR	3,4
GPS SPACE CRAFT RUBIDIUM (S/N 2)	$\leq 8 \times 10^{-14}$	6 HR TO 12 D	5

REFERENCES:

1. LEVINE ET AL., 32 ND ANNUAL SYMPOS. ON FREQ. CONTROL, 1978, P. 477.
2. PERCIVAL, 5 TH PTTI, 1973, P. 239.
3. HELLWIG AND WAINWRIGHT, 7 TH PTTI, 1975, P. 143.
4. UNPUBLISHED DATA, ROCKWELL INTERNATIONAL, ANAHEIM, CALIFORNIA 1977.
5. KOIDE ET AL., PAPER 9, SESSION III, THIS CONFERENCE (10TH PTTI, 1978).

TABLE 3

PSEUDO LIGHT SHIFT EFFECT FOR PULSED OPTICAL PUMPING

RB LAMP	FRACTIONAL FREQUENCY SHIFT DUE TO LIGHT INTENSITY CHANGE $(Y)_{I_o} - (Y)_{0.7I_o}$	
	CW	PULSED
A	$+1.4 \times 10^{-9}$	$+1.5 \times 10^{-10}$
B	-1.6×10^{-9}	$+2.4 \times 10^{-10}$

TABLE 4

PULSED OPTICAL PUMPING

PRELIMINARY STABILITY RESULTS

DEVICE	σ_Y (100 SEC)	σ_Y (24 HR)
PULSED PUMPING (PRESENT WORK)[A]	2×10^{-12}	$\sim 5 \times 10^{-12}$
EFRATOM FRK-H RUBIDIUM[B]	1×10^{-12}	$(< 1 \times 10^{-12})$[C]
FRK-L RUBIDIUM[B]	3×10^{-12}	- - -
HEWLETT-PACKARD 5062C CESIUM[B]	7×10^{-12}	$(< 1 \times 10^{-12})$[C]

[A] $\sigma_Y = 2 \times 10^{-11} \tau^{-1/2}, \quad 1 \le \tau \le 100$ SEC

[B] MANUFACTURERS's SPECIFICATION

[C] UPPER LIMIT

TABLE 5

LIGHT-SHIFT MEASUREMENTS FOR DIFFERENT C-FIELD CONFIGURATIONS (LAMP A)

C-FIELD	FERROMAGNETICS ON CAVITY	FRACTIONAL FREQUENCY SHIFT DUE TO LIGHT INTENSITY CHANGE $(Y)_{I_o} - (Y)_{0.7I_o}$	
		CW	PULSED
OLD	YES	$+1.4 \times 10^{-9}$	$+1.5 \times 10^{-10}$
OLD	NO	$+1.3 \times 10^{-9}$	$+1.0 \times 10^{-10}$
NEW	NO	$+1.0 \times 10^{-9}$	$< 1 \times 10^{-11}$

TABLE 6

SUMMARY OF PULSED OPTICAL PUMPING RESULTS

STUDY	DETECTION SCHEME	LIGHT SHIFT	STABILITY DATA
ARDITI & CARVER[A] (1964)	MICROWAVE SUPERHET	NO ($< 1 \times 10^{-10}$)	YES $\sim 1 \times 10^{-10}$
ALEXSEYEV _ET AL_[B] (1974)	OPTICAL (TWO RB LAMPS)	YES	NO
PRESENT WORK	OPTICAL (SMALL PHYSICS PACKAGE)	NO ($< 1 \times 10^{-11}$)	YES (PRELIMINARY) TO PARTS IN 10^{12}

[A] IEEE TRANS. INSTR. MEAS., JUNE - SEPT., 1964, P. 146.

[B] RADIO ENG. ELEC. PHYS. 20, 73 (1975).

FIGURE 1

FUNDAMENTAL PHYSICAL EFFECTS THAT CAN ADVERSELY AFFECT THE LONG-TERM STABILITY OF PASSIVE RUBIDIUM DEVICES

- LIGHT SHIFT ($\sim 3 \times 10^{-11}$ FOR $\Delta I_{LIGHT}/I_{LIGHT} = 1\,\%$)
- POSITION-SHIFT EFFECT (UP TO PARTS IN 10^9)
- BUFFER GAS SHIFTS ($\sim 1 \times 10^{-10}$/MILLITORR)
- SPECTRUM OF EXCITING MICROWAVE RADIATION (UP TO PARTS IN 10^9)
- MAGNETIC FIELD (RB SENSITIVITY = 1.8 x CS SENSITIVITY)

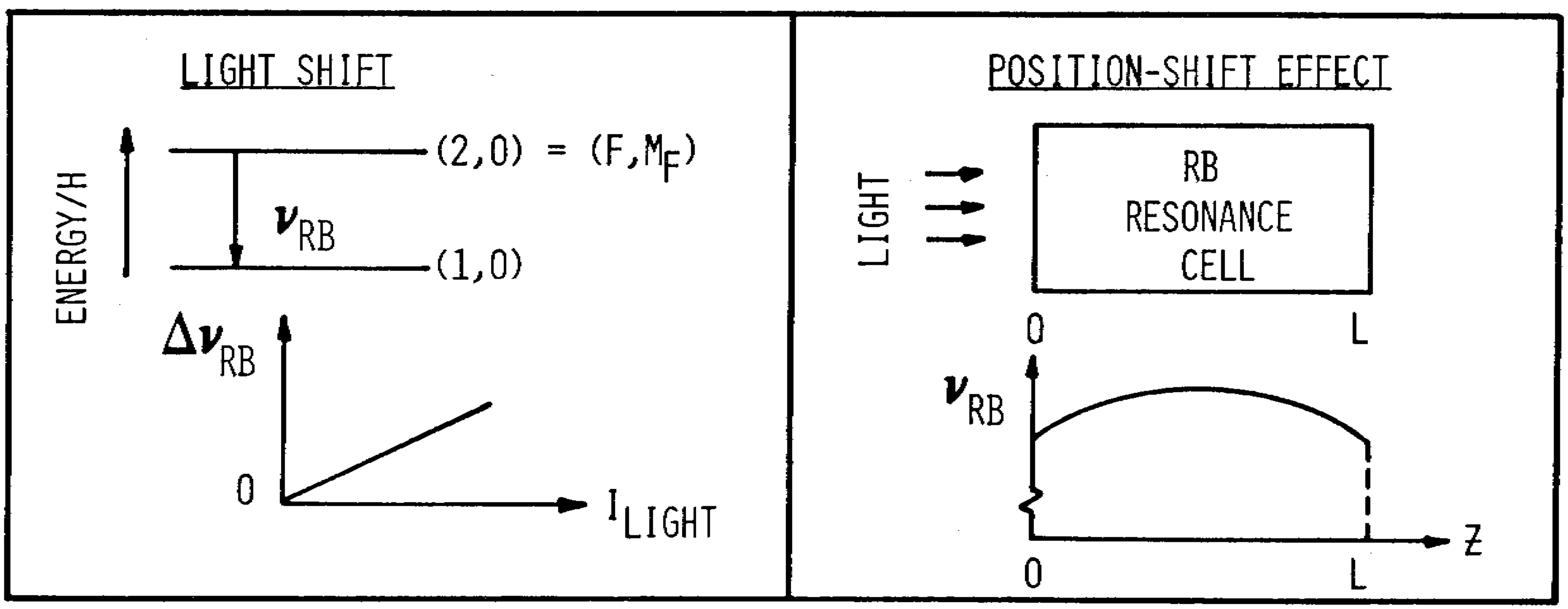
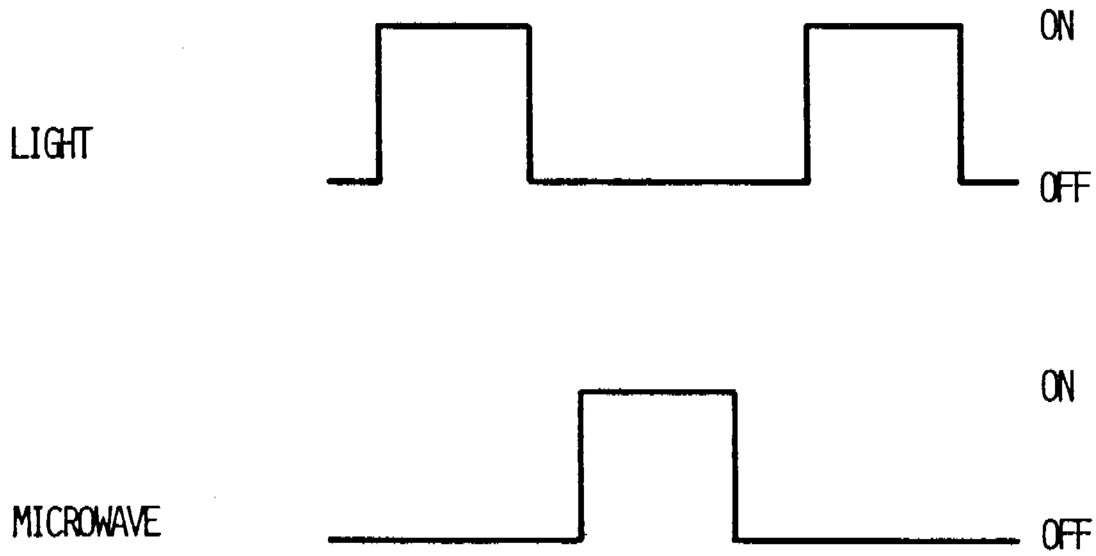


FIGURE 2

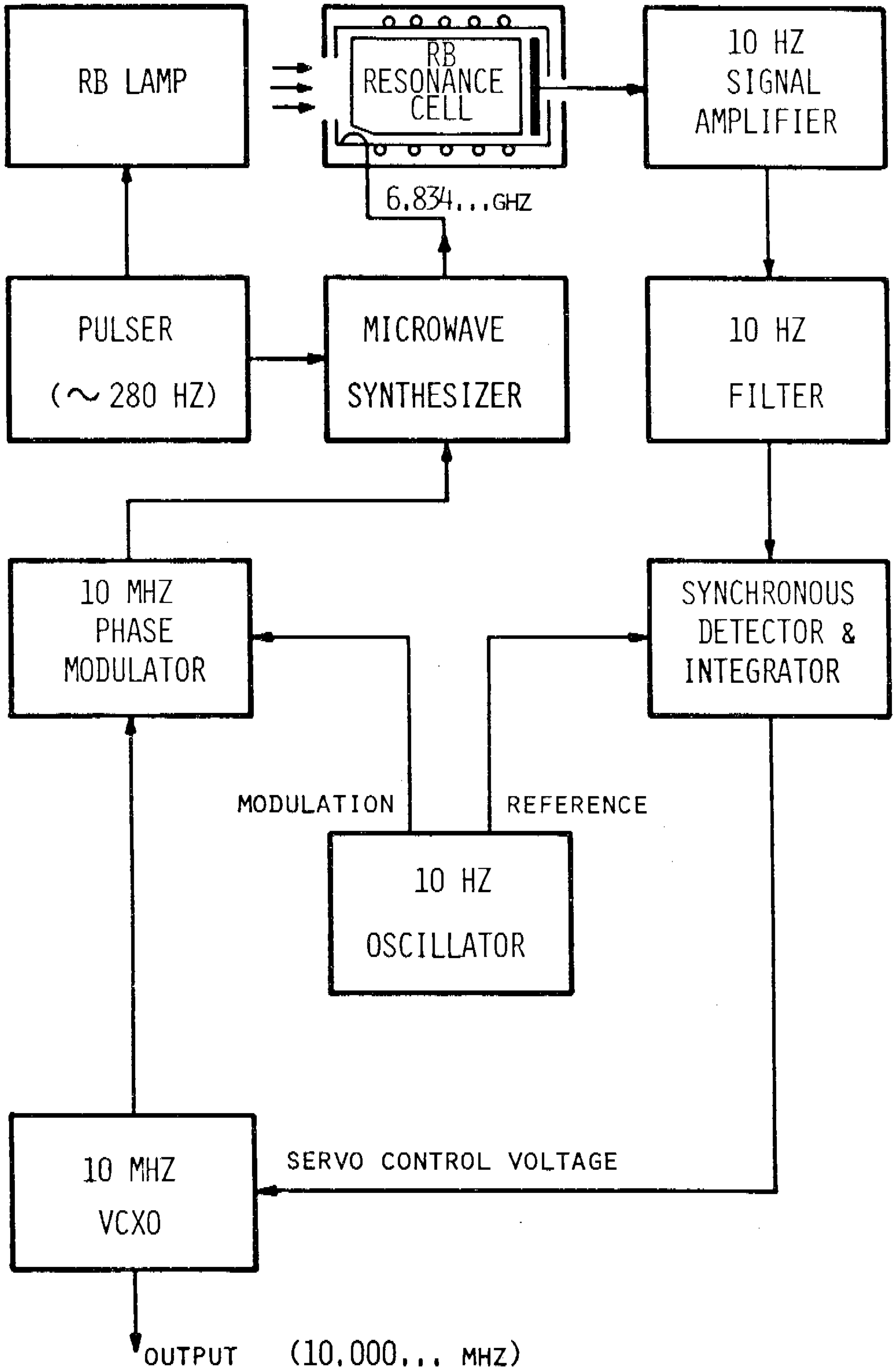
PULSING SCHEME



PULSE PARAMETER	TYPICAL VALUE (MSEC)
LIGHT DURATION	2.0
DARK TIME	1.6
MICROWAVE DURATION	1.2
REPETITION RATE	280 HZ

FIGURE 3

BLOCK DIAGRAM OF APPARATUS



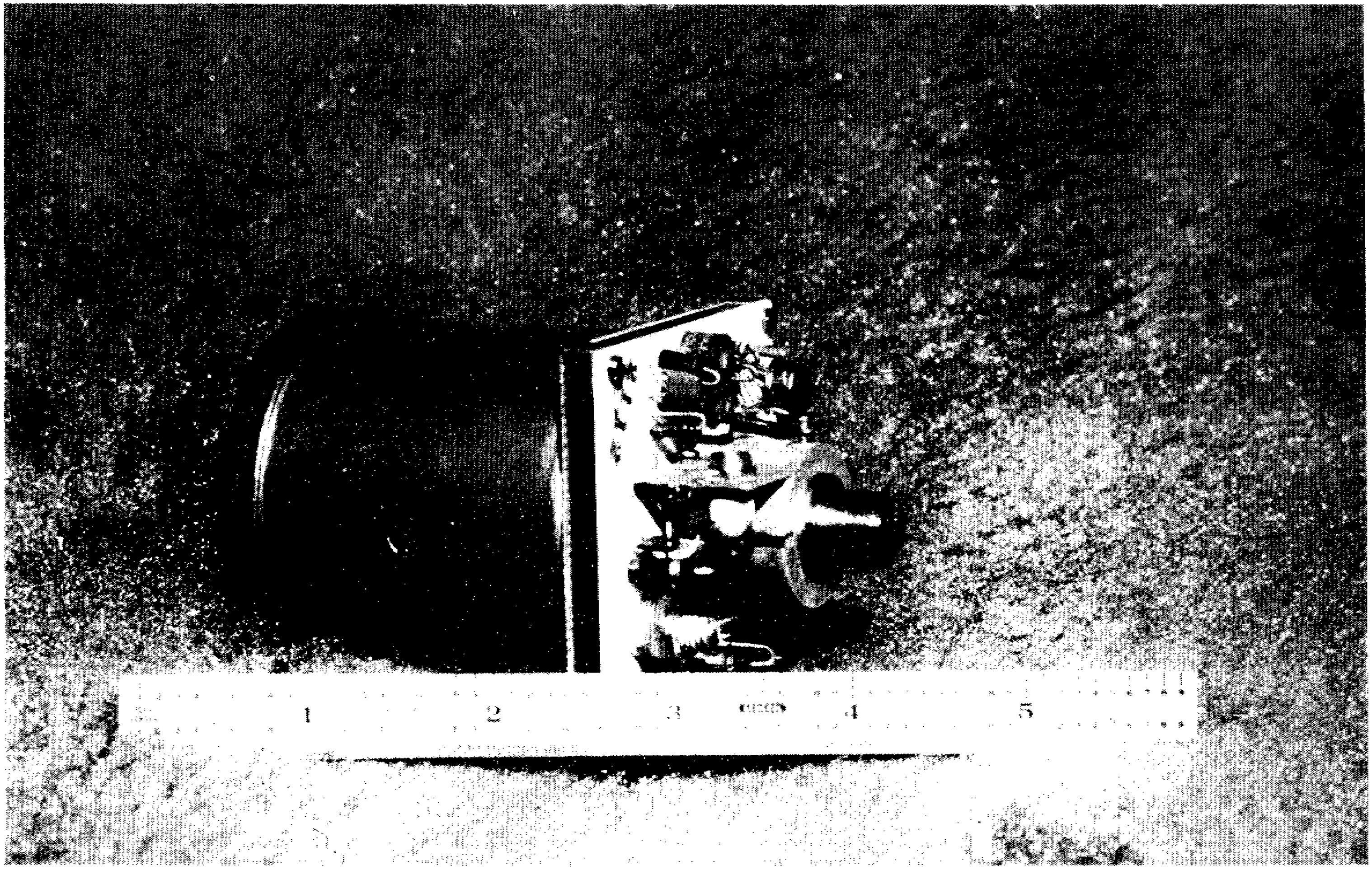


FIGURE 4. PHOTOGRAPH OF PHYSICS PACKAGE

QUESTIONS AND ANSWERS

DR. GIOVANI BUSCA, Ebauches, Switzerland:

I see you are using 10 hertz frequency for modulation. So you use phase sinusoidal modulation? What was the linewidth?

DR. ENGLISH:

Well, it is variable, and it depends upon how you choose the pulse parameters. Now if you run the units CW, it is on the order of a kilohertz. And if you really try to get the narrowest linewidth you can, where you are limited by the relaxation times for spin exchange, then you can actually get the linewidth down to a couple of hundred hertz. In these experiments, though, if you choose the narrowest linewidth, then your signal really goes to pot. So you work at some intermediate range. And we have been using roughly 700 hertz.

DR. BUSCA:

I see. I am asking myself if some of the results could be improved just by increasing the modulation frequency.

DR. ENGLISH:

It is possible. I wouldn't rule it out.

DR. BUSCA:

You are very far from the optimum value, which is. . . .

DR. ENGLISH:

Yes, you are absolutely right. It affects the signal-to-noise ratio, and it is possible if you went to a higher modulation frequency, you could increase your signal and therefore the short-term stability.

DR. BUSCA:

Okay. I have a second question. It seems that you use data on light shift when you use the Lamp in continuous CW and you extrapolate this data to a case in which you use the excitation pulse. We have done that before, and we see that the spectrum could change very much from pulsed to continuous excitation. So you must take a little bit of care in extrapolating from continuous data to pulsed data.

DR. ENGLISH: Yes.

DR. BUSCA:

The change in the sign, for example, from pulsed to continuous excitation would be just something like that. That means changing the spectrum of the light.

DR. ENGLISH:

Well, the Russian work seems to indicate--and they worked out a rather complicated theory for the whole thing--that you should have more or less a correspondence between the CW value and the pulsed value, not necessarily one to one, but at least a sign change is a strong indication that it is not a true light shift. In addition, there were the other factors which I don't have time to go into, which have to do with how the effect varies with the duration of the various pulse parameters.

I think the most convincing evidence that it is what I call a pseudo light shift is that it did disappear when all we did was improve the C-field homogeneity.

DR. BUSCA: Okay.

DR. GERNOT M. R. WINKLER, U.S. Naval Observatory:

I have a dim recollection that the scheme of using pulsed pumping originated in Princeton, 1958 or 1959, by Carroll Alley.

DR. ENGLISH:

It is quite possible. I know Arditti has a patent on this, and that is the basis for my saying that I believe he originated it. Now Arditti and Carver wrote a paper together on it. It is the first one I am aware of in regular journals. But you could be right. It could have been an idea that was sort of floating around Dicke's lab and they picked it up. I don't really know. I have never talked to him about it.

DR. HELMUT HELLWIG, National Bureau of Standards:

I only have one comment. Many things we are now working on are not really new ideas if you analyze them. What is a new idea, really, but the rather childish curiosity which makes us ask the same questions today that were asked five years, ten years, twenty years ago? And things have changed sufficiently that you might get answers you did not dream about.

DR. ENGLISH:

Could I make one comment? One of the reasons for doing this is that the light shift is a very messy effect. And so if you really want to study a device and vary the parameters in it to study the other effects, it is really desirable to get rid of the light shift. And that is one of the major motivations behind the experiment--to get rid of this really messy effect. And then you are free to vary the other parameters.

Now you can devise rubidium devices that run CW where they have very little light shift. But you have to restrict yourself to a very specific operating point. And as soon as you mess with the parameters of the device, then you start changing the light shift as well as everything else. And the problem is to try and isolate the variables in such a way that when you change parameters in the device, you are not changing all of these different effects at once in ways that you can't separate.