COMPOSITE-TYPE ^{87}Rb OPTICAL-PUMPING LIGHT SOURCE FOR THE RUBIDIUM FREUQENCY STANDARD

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ABSTRACT

This paper describes the experimental results and theoretical analysis of a newly devised compact light source for the Rubidium Frequency Standard (RFS). The light source is composed of a cylindrical Rb-87 lamp 10 mm diameter and a Rb-85 filter cell 3-7 mm long attached to the front flat face of the lamp. This composite-type device is operated in an oven at about 100°C. Thus a light source for Rb-87 hyperfine optical pumping less than 4 cm long by 3 cm diameter has been constructed.

INTRODUCTION

Among the various types of atomic frequency standards, the passive rubidium-gas-cell type frequency standard (so called "Rb Frequency Standard (RFS)") is the smallest, simplest, and least expensive one(1). Improvement of this type of standards is now making progress for satisfying various requirements(2-4).

One of the requirements is the miniaturization of the standard. The use of the optical-microwave unit without a filter cell may be an approach to meet this requirement(5). A miniaturized RFS without a filter cell has been on the market for seven to eight years, but its operating mechanism is not clearly understood(6). In addition, the lamp installed in the filterless optical-microwave unit is applicable to the passive RFS only.

In a previous paper, we proposed a new composite-type Rb-87 optical-pumping light source incorporating the lamp with the Rb-85 filter cell(7). From this light source, light suitable for the Rb-87 hyperfine

optical pumping ($5S_{1/2}$, F=1 $\rightarrow$ $5P_{1/2}$ and $5P_{3/2}$) is directly obtained. This device can be used for the miniaturized RFS. The idea of this device can be also applied to the Rb maser (Rb-87 and Rb-85 maser) and other optical pumping experiments.

In this paper, we clarify the operating mechanism of the composite-type device from the viewpoint of the spectral profile of the pumping light. This light source was applied to the RFS, and the resonant signal of the Rb-87 hyperfine frequency (f=6834 MHz) was detected as a discriminator pattern. An attempt to make the composite-type device using natural Rb is also discussed.

SPECTRAL PROFILE OF THE PUMPING LIGHT

The composite-type Rb-87 pumping light source consists of the cylindrical Rb-87 lamp and the short-length Rb-85 filter cell as shown in Fig.1. The lamp is excited by an rf magnetic field of about 100 MHz in the coil. A simple self oscillator (transistor 2SC549) is used as the lamp exciter.

An elementary explanation of the Rb-85 filtering action is shown in Fig.2 in the case of the Rb D-1 line. If the spectral profiles of the Rb-87 and Rb-85 D-1 line are shifted and broadened by the foreign gas as shown in the figure, the combined cd component is greatly absorbed by the Rb-85 spectral profile. On the other hand, the combined ef component is less absorbed and almost unweakened. Efficient pumping light is thus obtained. The problems are in the designing of the filter-cell length ℓ, the foreign-gas pressure P, the operating temperature T, etc.

The composite-type device was first evaluated from the spectral profiles of the D-1 line by using a Fabry-Perot interferometer scanned piezo-electrically(8). The photodetector is an R374 photomultiplier tube.

Figure 3 shows the temperature dependence of the Rb-87 D-1 line spectral profiles emitted from the composite-type device having a filter cell of 3 mm long(A) and 7 mm long(B). As the temperature rises to 100 - 110 °C, the ef component which is necessary for pumping increases, while the cd component which is unnecessary is much absorbed by the filter cell.

To discuss the quality of the pumping light source, the evaluation values r and d which express the ratio of the intensity of cd' to ef' and the difference of the intensity, ef' minus cd', are introduced:

$$r = I_{cd'} / I_{ef'} = a' / b' \qquad (1)$$

$$d = I_{ef'} - I_{cd'} = b' - a' \qquad (2)$$

These values indicate the criteria for showing the filtering action of the Rb-85 cell. The smaller value of r and the greater value of d are desirable for pumping.

Figures 4 and 5 show the variations in the values of r and d against temperatures, which are calculated from the profile measurement of the composite-type light sources. The parameter is the length of the filter cell. A curve for $\ell = 0$ shows the value obtained by the Rb-87 lamp only (without a filter cell).

From Fig.4, we find that the device with the longer filter-cell (ℓ = 6 - 7 mm) emits excellent pumping light around 100°C. Figure 5 prepares a different evaluation. As is mentioned in the former paper (10), the value of d corresponds to the intensity of the microwave resonance signal. From such a stand point, the composite-type source having 3-mm-long filter cell has excellent pumping power at about 110°C, although the value of r is not small compared to others.

On the other hand, the value of d for the composite-type light source with 7-mm-long filter cell is almost constant in the temperature range of 95 - 110 °C. That is, the pumping light intensity of the present light source is stable against the environmental temperature variation. Because an increase of the light intensity of the lamp as a result of a temperature increase is killed by the increase of the absorption in the filter cell. Thus, we can get a light source with almost constant pumping power. This is a merit of the source using single oven.

The procedure for the analysis is shown in Fig.6. We applied the self-absorption model to the formulation of the temperature dependence of Rb-87 lamp profiles. It is assumed that the temperatures of the lamp and filter cell are equal and vary at the same time. In this calculation, values of the parameters such as the spectral line width of the component lines, pressure shift, and equivalent absorption-atom-layer thickness in the lamp, are assumed to be the same as in the references(10,11), which analyzed Rb-85 filtering action and Rb-87 lamp profiles.

Calculated results for the composite-type light source with the 7-mm-long filter cell are shown in Fig.7. These results agree well with the observed ones.(Fig.3(b)) From the calculated profiles, the temperature dependence of the values of r and d are obtained as shown in Figs.8 and 9.

THE DISCRIMINATOR PATTERN OF THE Rb-87 DOUBLE RESONANCE

Using the Rb-87 resonant cell containing 21 Torr of mixed gases (N_2 : Kr = 55 : 45), the discriminator patterns were observed. Measurement was performed with the experimental setup for the RFS(9). The resonant cell

temperature was kept at 50°C and the composite-type light source was operated at temperatures between 80 and 110°C.

The block diagram of the measurement is shown in Fig.10. When the frequency-modulated interrogating signal in the microwave cavity is swept around the Rb-87 resonant frequency (f=6834 MHz) through VCXO, the derivative of the resonance line, i.e. the discriminator pattern, is obtained on the phase sensitive detector output.

Figure 11(a) shows the discriminator patterns of the Rb-87 resonant cell pumped by the composite-type light source with 3-mm-long filter cell. At 80°C, the peak to peak value V_{pp} in the discriminator pattern is less than 0.1V. From 90 to 110°C, V_{pp} is increasing steadily. At 110°C, V_{pp} is greater than 8V. Figure 11(b) shows the discriminator patterns using the composite-type device with 7-mm filter. The temperature variation from 95 to 110°C did not remarkably change the discriminator patterns. These results agree well with the spectral profile characteristics.

COMPOSITE-TYPE DEVICE USING NATURAL Rb

The above discussion was concerned with the composite-type device using isotope Rb. Next, the same approach was taken into the device using natural Rb. Figure 12 explains schematically how the desirable Rb-87 pumping light is obtained by the combination of the natural Rb lamp and the natural Rb filter cell(12,13). Absorption profile of the filter cell is shifted to the longer wavelength side and broadened by the foreign gas such as nitrogen. If we choose the appropriate gas pressure, temperature, and length of the filter cell, unwanted components of the natural Rb line (EF, CD, cd components in the D-1 line) are much absorbed by this filter cell, and ef' component, which is necessary for pumping, remains as it is.

Through our experiments, the desired profile has been obtained under the following conditions: the natural Rb lamp had a pressure of 1.8-Torr krypton, the natural Rb filter cell was 5.5 mm long and had a pressure of 100-torr nitrogen. Spectral profiles of the D-1 line emitted from this device are shown in Fig.13. An optimum profile is obtained at about 110°C.

Although the output light intensity was reduced to one-third that of the device using isotope Rb, discriminator patterns of the Rb-87 hyperfine frequency were obtained with sufficient intensity for RFS operation.

DISCUSSION

To discuss the spectral profiles of the pumping light source, we introduced the evaluation values of r and d in Eqs.(1) and (2). If we compare these values with the experimental (Figs.4 and 5) and the calculated results (Figs.8 and 9), respectively, we find that there are some differences between them in the details. Especially, concerning the value of d, the discrepancy is distinguishable for the shorter length filter cell. The causes for this discrepancy are inferred as follows.

In the analysis of the profile as shown in Fig.7, we assume that the temperatures of the lamp and filter cell are equal and vary at the same time by the heater. In reality, the filter cell is positioned by the window glass of the oven, and the lamp radiate heat by itself due to excitation. Then the temperature of the filter cell tends to be lower than the lamp's. If the temperature of the filter cell is lower, the absorption by the filter cell is less, and higher output is obtained. This suggests that the temperature difference between the lamp and the filter cell must be taken into account in the analysis, especially, at higher temperature.

In the analysis we adopted the self-absorption model for the electrodeless spherical lamp(11). In this composite-type device, however, the shape of the lamp is cylindrical and the filter cell is attached to the front flat face of the lamp. Then the equivalent self-absorpiton atom layer in the model of Fig.6 is probably different from that of the spherical lamp. Some modification must be needed to clarify the characteristics completely.

Next we will discuss the profiles of the output light from the source with natural Rb only, not isotope Rb, both in the lamp and filter cell. The necessary component ef' at 80°C is low compared with the other unwanted components. However, the necessary component becomes higher as temperature increases, whereas the unwanted components hardly becomes higher. At 109°C, only the ef' component remains, while the unwanted components rather diminish. Although the output light intensity was reduced to one-third that of the device using isotope Rb, discriminator patterns of the Rb-87 hyperfine frequency were obtained with sufficient intensity for RFS operation.

These two kinds of the light source, made of isotope Rb or natural Rb, are available for not only RFS but also pumping light sources in other physical experiments and a maser. A parallel operation of the source is possible, if the output intensity of a single source is insufficient for maser oscillation. The size of the device is small as shown in Fig.1, and it is installed in a single oven, whereas the conventional source requires two ovens, one for the lamp and another for the filter cell with independent controls.

About the quality of the pumping light profile, it is necessary to discuss the symmetry of the spectral line. Some of the requisits to obtain the stable frequency from the RFS are that the spectral profile of the pumping light does not fluctuate in intensity and is symmetric. As is mentioned in Fig.3, the composite-type device having 3-mm-long filter cell has an excellent pumping power at about 110°C. However, if we look carefully at the pumping light profiles, we find the small dip near the peak of the ef' component line. This is so called self-reversal resulting from the self-absorption in the lamp. As a result, the line is asymmetric. This is a cause of the frequency shift in the RFS due to "light shift". On the contrary, the ef' component line's profiles from the device having 7-mm-long filter cell show symmetry. This source has two properties described above, that is, the symmetry in the profile and less variation in the intensity against the temperature.

When Rb-87 is enclosed in the lamp, and Rb-85 and 100-Torr nitrogen are in the filter cell, the length of the filter cell and the operating temperature of the composite-type device should be designed as follows according to the purposes. (1) To obtain the strong pumping power, ℓ should be about 3 mm and operated at about 110°C. The pumping profile is a little asymmetric. (2) To obtain the constant power against the environmental temperature variation of 95 to 110°C, ℓ should be about 7 mm. Though the pumping power is less than that of 3mm, the pumping profile is symmetric.

CONCLUSION

We have established designing methods for constructing a compact Rb-87 optical-pumping light source. By using isotope Rb, we can not only reliably miniaturize the size of RFS but also obtain a powerful pumping light source for use in applications such as a Rb maser. By using natural Rb, we can construct a compact RFS at low cost.

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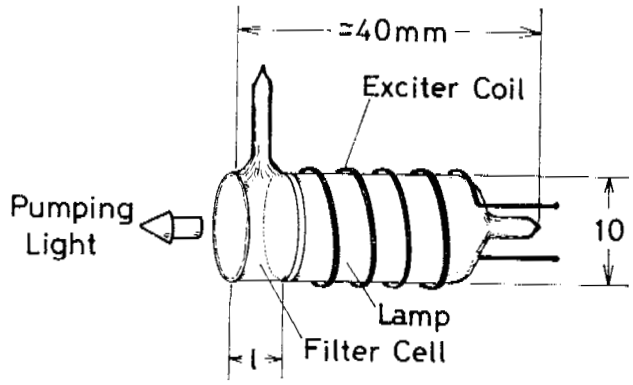


Fig.1
Composite-type Rb-87 optical pumping light source.

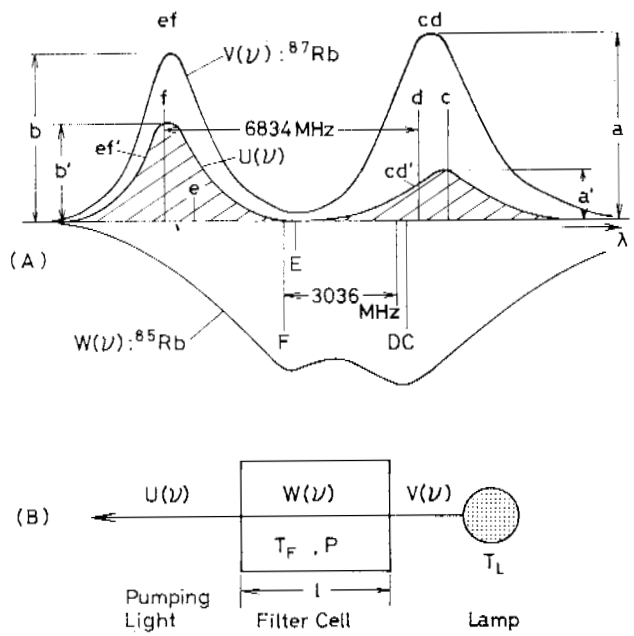


Fig.2
Schematic diagram of the Rb-85 filtering action for the Rb-87 lamp. (A) Spectral profiles of the Rb-87 D-1 line. Hatched areas are the pumping light profiles filtered by a Rb-85 filter cell. The Rb-85 spectral profile includes the shift and broadening due to foreign gas. (B) Arrangement of the usual Rb-87 pumping light source.

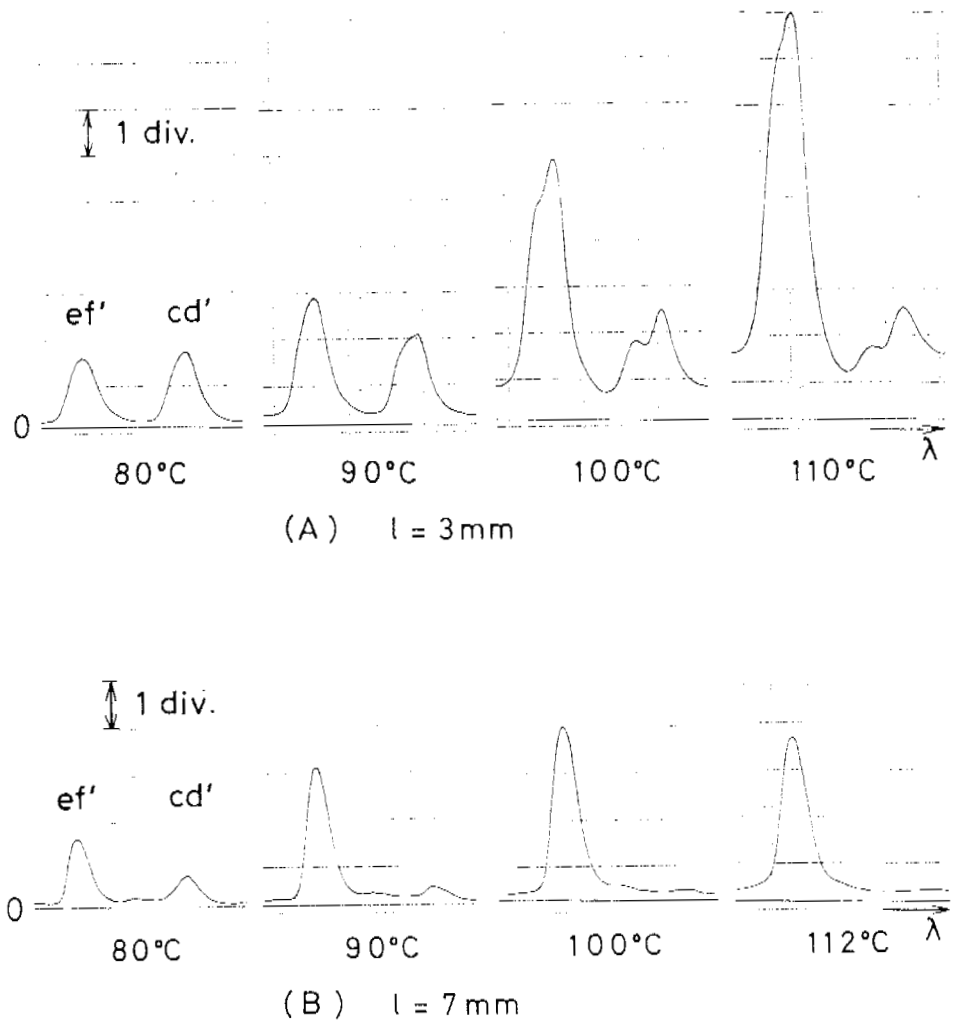


Fig 3.
Observed profiles of the Rb-87 D-1 line from the composite-type light source. 1.8-Torr krypton is in the Rb-87 lamp as a starting gas. Foreign gas in the filter cell is 100-Torr nitrogen. One division on the ordinate is 100 μV. (A) Filter-cell length is 3 mm. The lamp is excited by an rf magnetic field from an oscillator whose dc input is 1.1 W. (B) Filter-cell length is 7 mm. dc input to the exciter is 1.2 W.

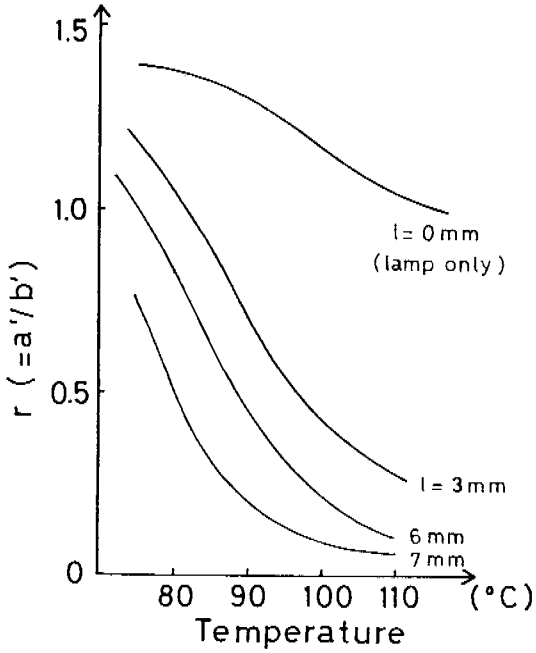


Fig.4
Values of r vs. temperature of the source, which are calculated from the experimental results.

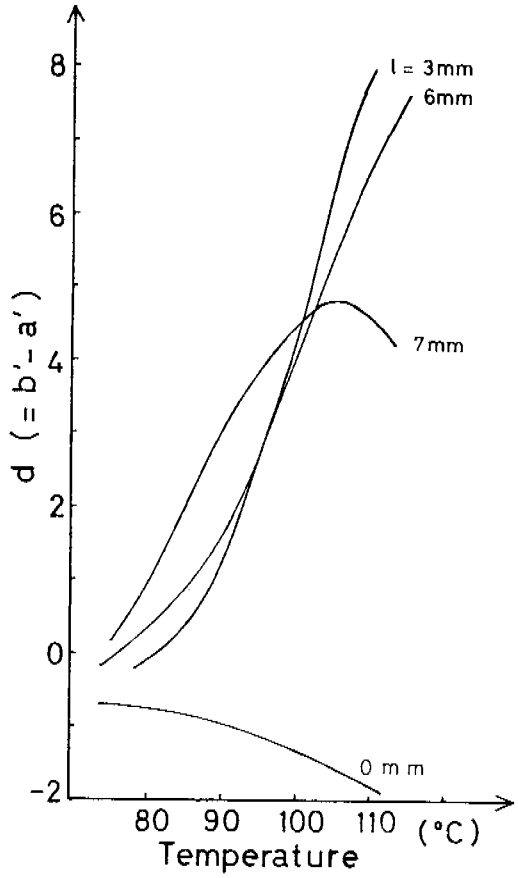
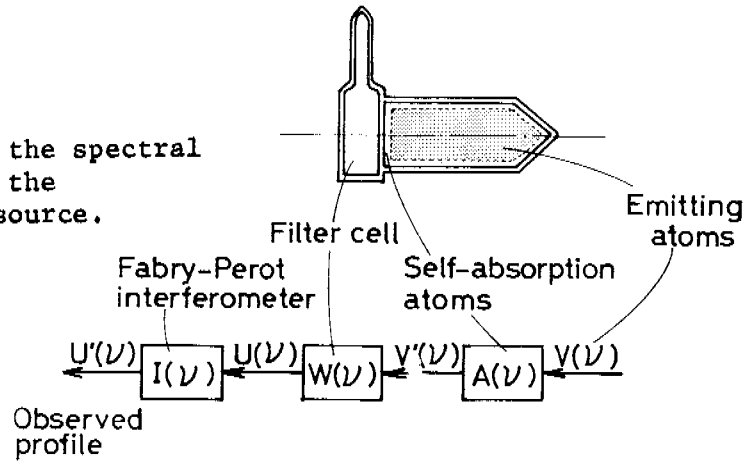


Fig.5
Values of d vs. temperature of the source, which are calculated from the experimental results.

Fig.6
A model for analyzing the spectral profiles emitted from the composite-type light source.



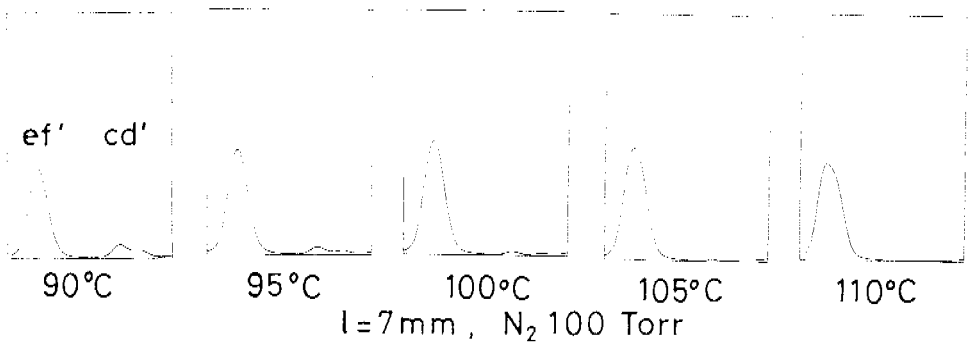


Fig.7
Calculated profile of the Rb-87 D-1 line from the composite-type pumping-light source.

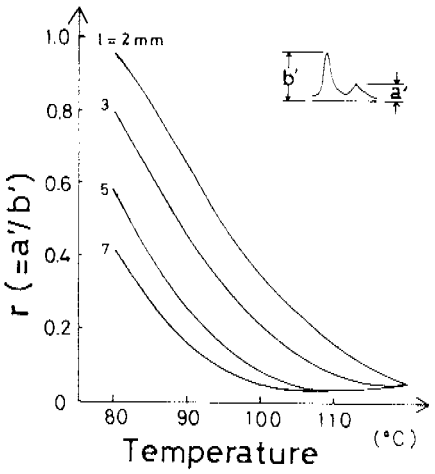


Fig.8
Values of r obtained from the calculated profiles.

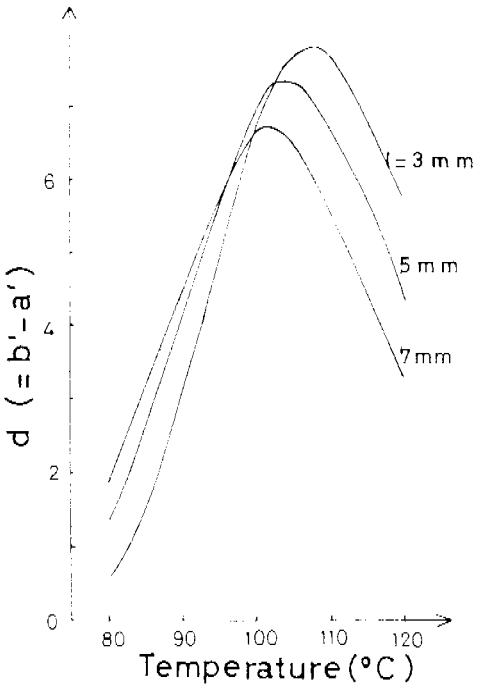


Fig.9
Values of d obtained from the calculated profiles.

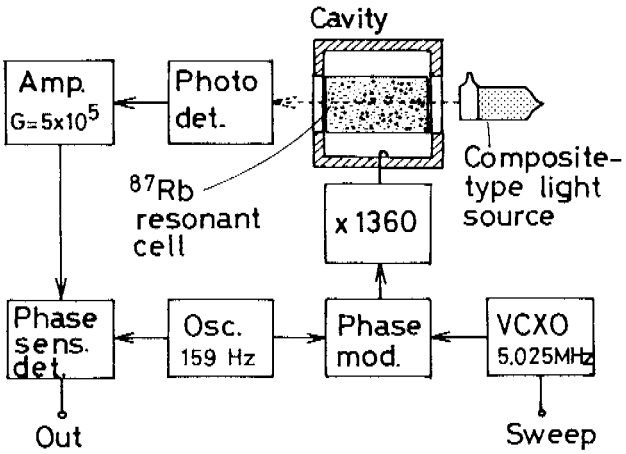


Fig.10
Block diagram for measuring the discriminator pattern.

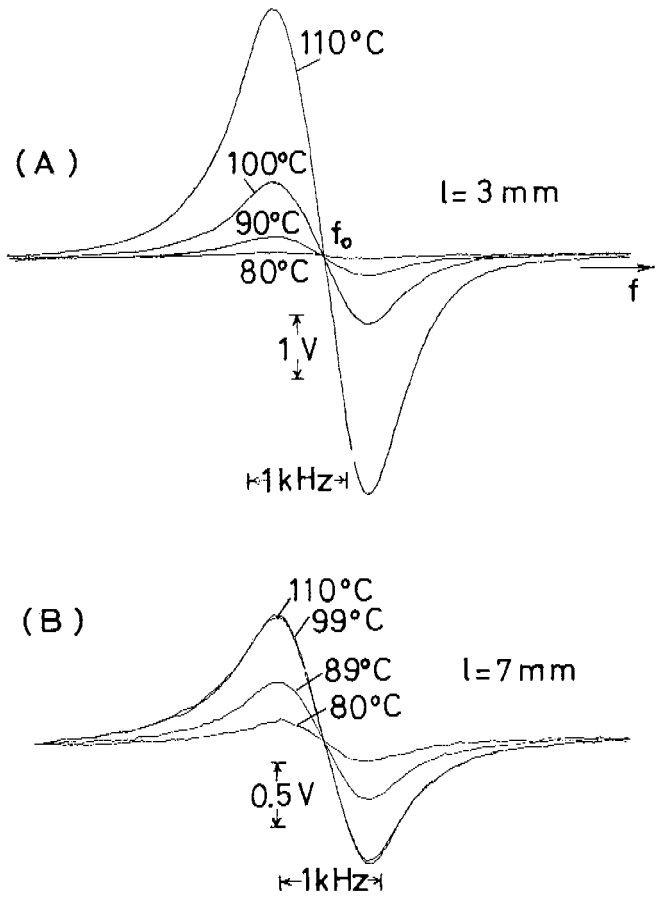


Fig.11
Discriminator patterns of the Rb-87 resonance line pumped by the composite-type light source. (A) Filter-cell length is 3 mm. (B) Filter-cell length is 7 mm.

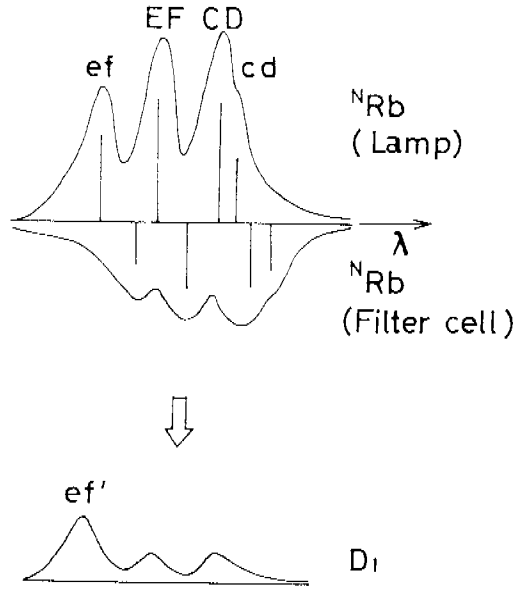


Fig.12
Schematic diagram of the filtering action of the natural Rb cell for the natural Rb lamp. Absorption profile of the filter cell includes the shift and broadening due to foreign gas.

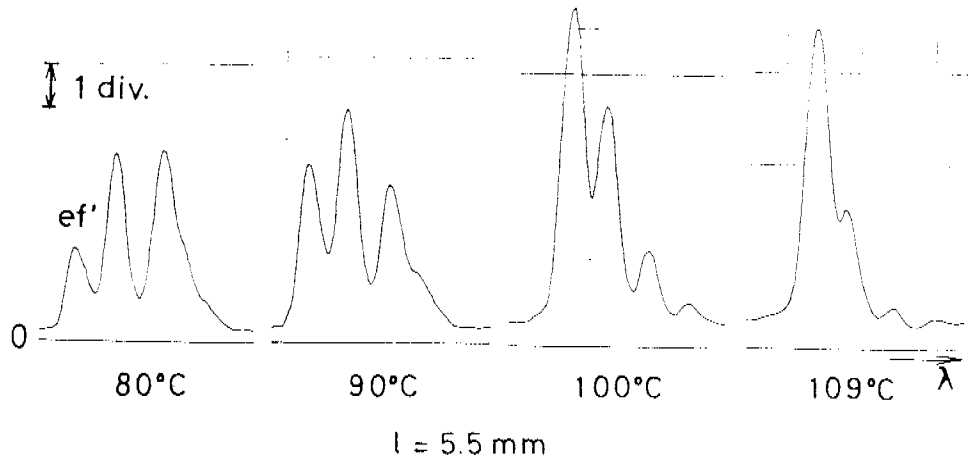


Fig.13
Observed profiles of the Rb-87 D-1 line from the composite-type device including natural Rb both in the lamp and filter cell. Foreign gas in the filter cell is 100-Torr nitrogen. One division on the ordinate is 30 μV. dc input to the exciter is 1.4 W.