A New Microwave Frequency Standard by Quenching Oscillator Control

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Summary—**This paper shows that in this new frequency standard system the multiplication is made by synchronizing oscillation, which is achieved by quenching a microwave oscillator with a standard quartz-crystal oscillator. The output frequency spectrum of this synchronizing oscillator includes only integral multiple frequencies of a quartz-crystal oscillator. Each spectrum can be utilized as standard frequencies. Theoretical calculations and experimental results are also described here. And to avoid the influence of noise voltage on the build-up of the quenching control microwave oscillator, the double modulation system is used, which is controlled and intermitted simultaneously by both f_1 voltage (output of the low frequency standard) and $n_1 f_1$ voltage (n_1 is an integer).**

By this double modulation method we can understand that the build-up and the stop of the microwave oscillation are exactly controlled by the constant phase of the waves from the standard generator, and also the experimental results of this are described. As an application of this new system, a method of precise frequency measurement is also described.

INTRODUCTION

FOR THE microwave communication industry, the technique of frequency measurement with high accuracy has become very important. As microwave frequency meters, cavity-type wavemeters are mostly used by reason of their simplicity, but their accuracy is not high. The fine measurement of the microwave frequency requires a frequency standard, and results of research on the subject have already been published, but the methods described are based on the principle of using vacuum-tube frequency multipliers of crystal oscillators to the vhf region, and using silicon crystal diodes as harmonic generators in the microwave region. In these systems the arrangements are considerably complicated and the microwave output power from the equipment is too small to calibrate the cavity wavemeters directly.

The authors have devised a new system for obtaining the standard frequencies by quenching the microwave oscillator at the low standard frequency.[1,2] This system can increase the member of the multiplication factor.

This paper describes the principle of the new system and the method for a fine measurement of microwave frequency as a new frequency standard, and also presents actual results of the tests obtained by an experimental device based on the system mentioned above.

BASIC PRINCIPLES

This method is a microwave application of R. Golicke's method which was applied to a frequency multiplier in low-frequency range.[3] To understand the operation of such a device, consider first the simple system shown in Fig. 1. The oscillation of the Klystron microwave oscillator is controlled and intermitted by the output of the standard crystal controlled oscillator, where the frequency of the crystal oscillator $\div f_1$, the frequency of the microwave oscillator $\div f_2$, and the microwave oscillator output is applied to the high-Q cavity resonator which acts as a band pass filter. If it is possible to control the build-up time and stop time of the microwave oscillator by a constant phase of the control voltage from the standard frequency oscillator, then the microwave output of the standard frequency wave could be driven through the cavity resonator.

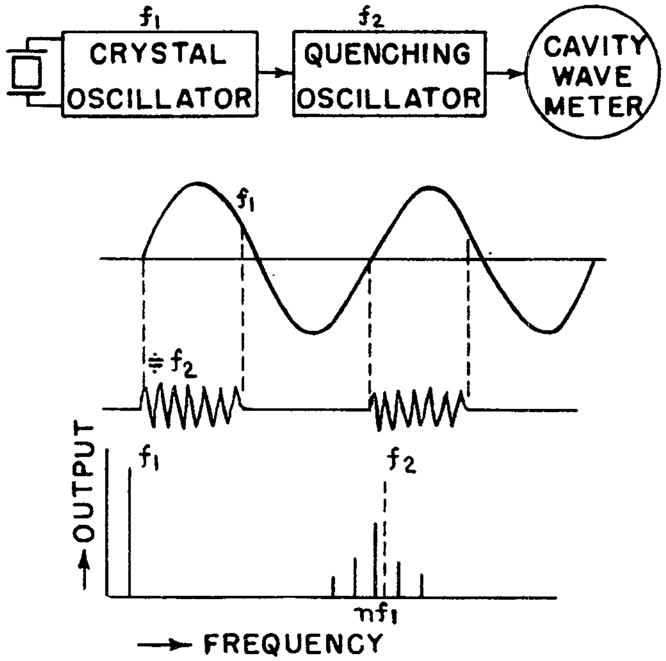

Fig. 1—Basic scheme of the system.

As far as the oscillation of f_2 repeats the same waveform in the period of $1/f_1$, the frequency spectrum of this microwave oscillator is expressed as shown in Fig. 1. We can see that the frequency spectrums of this oscillator are expressed only by the integer multiples

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[1] N. Sawazuki and T. Honma, "On a new frequency standard system at microwaves," *J. I. E. C.* (Japan), vol. 33, pp. 62–68; February, 1952.

[2] N. Sawazuki and T. Honma, "On a precise frequency measurement at microwaves," *J. I. E. C.* (Japan), vol. 35, pp. 69–73; February, 1952.

[3] R. Golicke, "Teilung und Vervielfachung von Frequenzen," *Elec. Nachr.-Tech.*, vol. 15, p. 134; March, 1938.

of f_1 and are independent of f_2. So we shall be able to pick up each spectrum one by one through a narrow bandpass filter, such as the Ho_{11}-type high-Q cavity resonator, which is coupled to the microwave quenching oscillator. For example, let us consider the case shown in Fig. 2, where

$$n_0 \cdots f_2/f_1 \qquad t, \cdots \text{time} \qquad \theta = 2\pi f_1 t$$

$$e \cdots \text{voltage},$$

then the wave shapes are given by,

$$e = \epsilon \sin n_0\theta \qquad 0 \leqq \theta \leqq 2\pi\alpha$$

$$e = 0 \qquad 2\pi\alpha \leqq \theta \leqq 2\pi(\alpha - 1).$$

By Fourier's series, the following equations are obtained

$$e(\theta) = \frac{1}{2}\alpha_0 + \sum_{n=1}^{\infty}(a_n \cos n\theta + b_n \sin n\theta)$$

$$a_n = \frac{1}{\pi}\int_0^{2\pi} e \cos n\theta d\theta$$

$$= \frac{E}{2\pi}\left[\frac{1}{n+n_0}\{1 - \cos 2\pi\alpha(n_0+n)\} + \frac{1}{n-n_0}\{1 - \cos 2\pi\alpha(n_0 - n)\}\right]$$

$$b_n = \frac{E}{2\pi}\left\{\frac{1}{n_0 - n}\sin 2\pi\alpha(n - n_0) - \frac{1}{n_0+n}\sin 2\pi\alpha(n_0+n)\right\}.$$

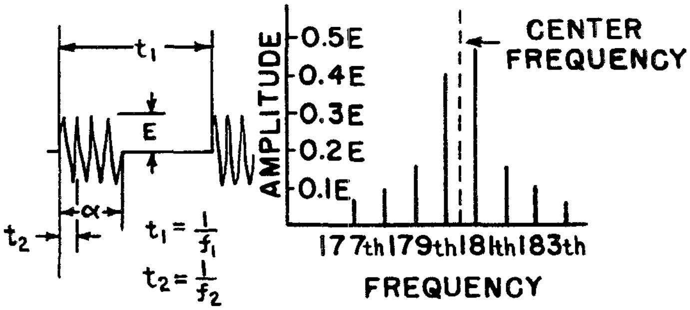
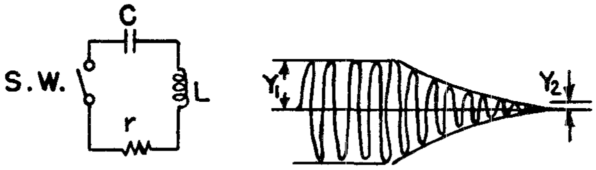


Fig. 2—Example of the calculation.

For example, putting $\alpha=1/2$, $f_1=23$ mc, $f_2=4,150$ mc and, if the oscillator is controlled as shown in Fig. 2, and computing by the equation above, the frequency spectrums of the microwave output are obtained as shown in Fig. 2. In this figure, the maximum amplitude of the output spectrums is about one-half of the original amplitude of the oscillation voltage. Therefore, if we use a Klystron tube as an oscillator whose output power is about several tens of milliwatts, the output power of this equipment will be far greater than that of the crystal frequency multiplier.

TECHNICAL PROBLEMS IN FREQUENCY MULTIPLICATION BY QUENCHING OSCILLATOR AT MICROWAVE RANGE

If we are able to control the microwave oscillator by means mentioned above, it is theoretically possible to generate a standard frequency. Practically reflex Klystrons are used as microwave oscillators for measuring equipments. The high-frequency circuit of a Klystron is a cavity resonator, and the shunt impedance and also the loaded Q of the resonator are very high. We must consider the transient phenomena of the quenching oscillator. For a better understanding of the problems, let us consider the major assumptions by the simplest L, C, γ circuit, which is shown in Fig. 3.



Y_2/Y_1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
n_{12}	0.735Q	1.47Q	2.2Q	2.92Q	3.68Q	4.4Q

Fig. 3—Relations between Y_2 and n_2.

In the first place let us consider the decaying case of oscillation. If charge q_0 is applied initially to condenser C, the circuit equation when the switch is closed is written as

$$\frac{d^2q}{dt^2} + \frac{\gamma}{L}\frac{dq}{dt} + \frac{1}{LC}q = 0,$$

when the circuit loss is small; *i.e.*,

$$\gamma^2 < 4\frac{L}{C}$$

the solution is as follows,

$$q = \frac{2\sqrt{\frac{L}{C}}}{\sqrt{4\frac{L}{C} - \gamma^2}} q_0 e^{-\alpha t} \sin(\beta t + \phi);$$

where

$$\alpha = \frac{\gamma}{2L}, \qquad \beta = \frac{\sqrt{4\frac{L}{C} - \gamma^2}}{2L}, \qquad \phi = \cos^{-1}\frac{\alpha}{\beta}.$$

Describing q_0 in a voltage term, $q_0 = CE$, the circuit current equation will be derived as

$$i = -\frac{2E}{\sqrt{4\frac{L}{C} - \gamma^2}} e^{-\alpha t} \sin \beta t.$$

The amplitude variations of the current or voltage with the time are shown in the form of $e^{-\alpha t}$ or $e^{-(\gamma/2L)t}$.

The number of the cycle of the alternating current (n_{12}), when amplitude y varies from Y_1 to Y_2, is described as

$$n_{12} = \frac{\omega}{2\pi}\int dt \qquad y = e^{-(\gamma/2L)t}$$

$$n_{12} = \frac{\omega}{2\pi}\cdot\frac{2L}{\gamma}\int_{Y_2}^{Y_1} dy$$

$$n_{12} = Q\cdot\frac{1}{\pi}\,[\log y]_{Y_2}{}^{Y_1}.$$

From this equation, the relations between Y_2 and n_{12}, where $Y_1 = 1$, are calculated as shown in Fig. 3.

The exciting voltage of the oscillator by the quenching voltage must be larger than that of the noise voltage, otherwise the build-up phase of the oscillator will be affected by the noise voltage, on the other hand, Y_2 must be smaller than the exciting voltage (which is the component voltage of harmonics of f_1 near the frequency of f_2), to control the quenching oscillation. By rough estimation, the value of Y_2 will be in the range, 10^{-5}–10^{-3}. Then

$$\text{if} \quad Y_2 < 10^{-5} \qquad n_{12} \doteqdot 3.68Q$$

$$\text{and } Y_2 < 10^{-3} \qquad n_{12} \doteqdot 2.2Q.$$

The next problem is the build-up time of the oscillation. The voltage (transient waveform) at the start of oscillation is expressed as follows:

$E = E_0 e^{\alpha t} \sin \omega_0 t$, where E_0 is the exciting voltage.

The value of the α is expressed by the function of the circuit Q, the characteristics of the oscillator tube, and the oscillating amplitude. Studies have been done on the build up of the oscillation in the case of triodes by Dr. Usui,[4] and in the case of magnetrons by Mr. Lloyd P. Hunter.[5] We cannot apply these theories to the Klystron oscillators, but from these results we can see the same rule for a general case in the transient of the oscillation build up. Shown in Fig. 4 is the relation between the build-up time of the oscillator and the circuit Q.

In the case of high Q, the build-up time is large and it is proportionate to the value of Q, and in the case of small Q, the oscillation stops when $Q = Q_1$; in this condition the build-up time is infinite. We can see on the build-up time curve where there is a minimum point. The build-up time is shorted when $Q = Q_2$. And in this condition the build-up time of the oscillator having the circuit of Q_2 is, by the rough estimation, nearly equal to the decaying time of the circuit Q_2. Let us consider the building up of the oscillation on the case of the oscillator with the circuit of Q_2. The initial amplitude is $Y_1 = 10^{-3}$ when oscillation starts. We find also that for the time in building-up for the case of decaying, it is necessary to satisfy the following equation:

$$n_{12} \doteqdot 2.2Q_2 \text{ cycles.}$$

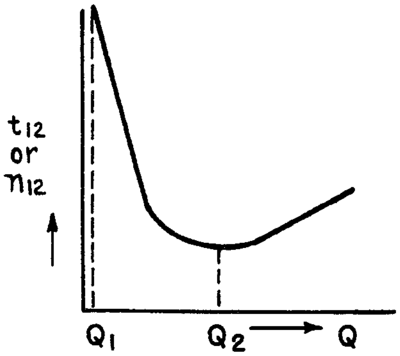


Fig. 4—Relations between Q and n_{12}.

It is also necessary at least nearly $4.4Q_2$ cycles to complete the start and the stop of the oscillation, and then frequency multiplication factor n_0 must be larger than $4.4Q_2$, or

$$f_2/f_1 = n_0 > 4.4Q_2.$$

For example,

$$f_2 = 4{,}000 \text{ mc} \qquad Q_2 = 100$$

then

$$n_0 > 440, \qquad f_1 < 9 \text{ mc}$$

So by the above reason, it is difficult to reduce the multiplication factor n_0 to a certain extent. But in the other point of view, if n_0 is too large, the f_2 component, by the quenching control voltage (f_1), in the beam current of the Klystron will be down lower than the noise level, then the build-up phase of the microwave oscillation (f_2) will be controlled by noise. It is very desirable to use a control voltage with large harmonic content and the square waveform for control voltage (f_1) is more desirable. But at the high radio frequencies, it is not so easy to generate a square waveform. To solve these difficulties, we applied the following methods. This is a double modulation method of which the schematic diagram and basic principle are shown in Fig. 5. In this system, two controlling voltages of f_1 and $n_1 f_1$ are applied simultaneously to the microwave oscillator. In this case, if n_1 is large number, or f_1 is of sufficiently low frequency, the system mentioned above would be used for a quenching control device with a standard oscillator, and the jittering of the build-up

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[4] R. Usui, "Transient phenomena and the building up of oscillation amplitudes in triode oscillators," *Rep. Rad. Res. in Japan*, vol. 7; 1937.

[5] L. P. Hunter, "Energy build-up in magnetrons," *J. Appl. Phys.*, vol. 17, p. 833; October, 1946.

point by the noise is suppressed by the harmonics of the applied n_1f_1 voltage. So by this system we can understand that the build-up and the stop of the microwave oscillator are exactly controlled by the constant phase from the standard generator.

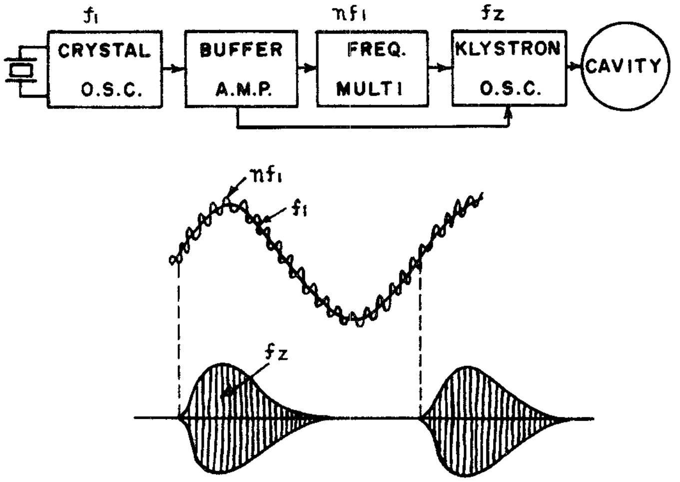

Fig. 5—The double modulation method.

For a example, if we put,

$$f_2 = 4{,}000\,\text{mc} \qquad f_1 = 2\,\text{mc},\ n_1 = 40, \quad n_0 = 2{,}000$$

$$n_1f_1 = 80\,\text{mc}, \qquad n_0/n_1 = 50, \quad Q = 100,$$

then

$$n_0 > 440.$$

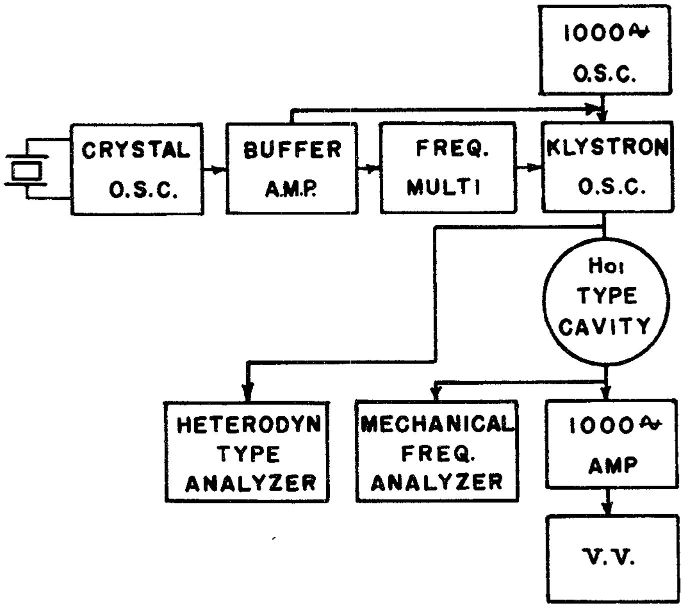

Fig. 6—Scheme of the double modulation method.

Experiments on the New System

The experiments are done using low power reflex Klystron oscillators in the frequency range of 3,500–4,500 mc and 9,000–10,000 mc. A block diagram is shown in Fig. 6. In the experiment, 2–6 mc standard quartz oscillator, and $n_1=4$–40 primary frequency multipliers were used, and the experiments were done both on the modulation method of single modulation and double modulation with the voltage of f_1 and n_1f_1 as mentioned above. This double modulation circuit is shown in Fig. 7. Standard frequency microwave output is measured with a cavity reasonator and analyzed with the spectrum analyzers. Experimenting by the single modulation method, the following results are obtained: where

$f_1=5-40$ mc,	$f_2 \doteqdot 4{,}000$ mc
$f_1 \doteqdot 40$ mc	microwave output $\doteqdot 0$
$f_1 \doteqdot 30$ mc	microwave output is very weak
$f_1 \doteqdot 25$–20 mc	microwave nf_1 output was measured but very weak
$f_1 \doteqdot 15$ mc	microwave nf_1 output is measured but very noisy
$f_1 \leqq 10$ mc	noise output only and microwave nf_1 output is not measured.

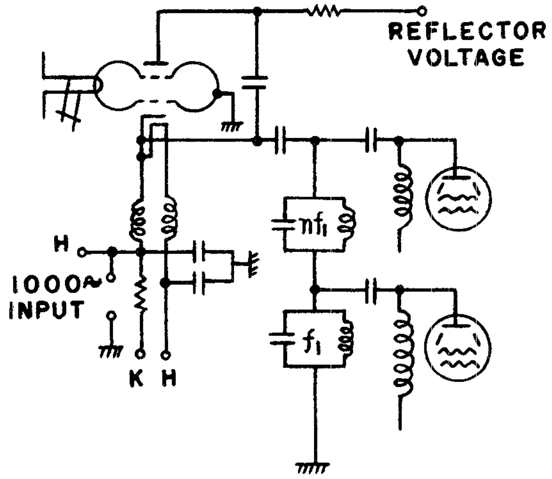

Fig. 7—Double modulation circuit.

As shown above, satisfactory operation was not obtained by this modulation method, and the signal was unstable and not free from noise.

But experiments by the double modulation method, satisfactory operation was obtained by frequency $f_1=5.7$ mc–2.8 mc, $n_1=16$–32. Under these conditions the microwave output which is frequency multiplied from a quartz crystal oscillator is very stable and relatively free from noise. Fig. 8 shows the experimental results of the double modulation, this figure obtained by a mechanical spectrum analyzer and Fig. 9 obtained by a heterodyne type spectrum analyzer. In this experiment when the modulation condition is changed by varying the control voltage (n_1f_1), the results are A, B, $\cdots$ E; in case A the modulation is complete single modulation, and in case B the modulation is complete double modulation. In case A the build-up of the microwave oscillator is controlled by noise only, and in case E, it is controlled by the n_1f_1 voltage only

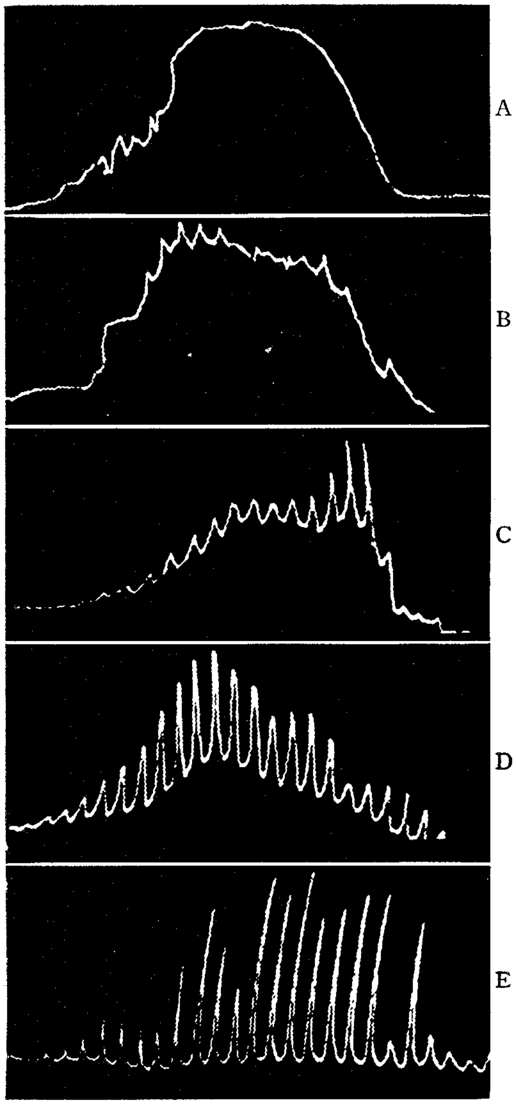

Fig. 8—Experimental results of the quenching control oscillator, obtained by the mechanical spectrum analyzer.

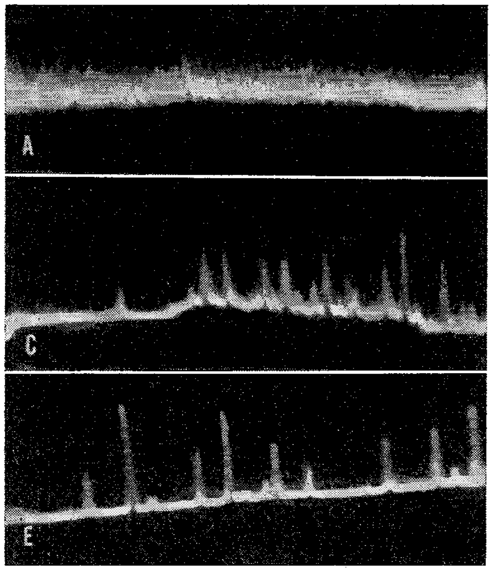

Fig. 9—Experimental results of the quenching control oscillator obtained by heterodyne type spectrum analyzer.

and is free from noise. Fig. 10 shows one of the examples measured at following conditions:

$f_1 = 5.1925$ mc $\quad n_1 f_1 \doteqdot 84$ mc $\quad n_1 = 16$

E_1 (control voltage of f_1) $\doteqdot 65$v $\quad E_1$ (control voltage of $n_1 f_1$) $\doteqdot 33$v.

The output power of nearly 1 mw at the standard frequencies are obtained by a 25 mw (cw power output) Klystron.

In these experiments, when the tuning of the Klystron cavity or the reflector voltage is varied slightly, position of the spectrums did not change and the amplitudes of them were only varied. Thus it is proved that the oscillation is perfectly synchronized by quenching control.

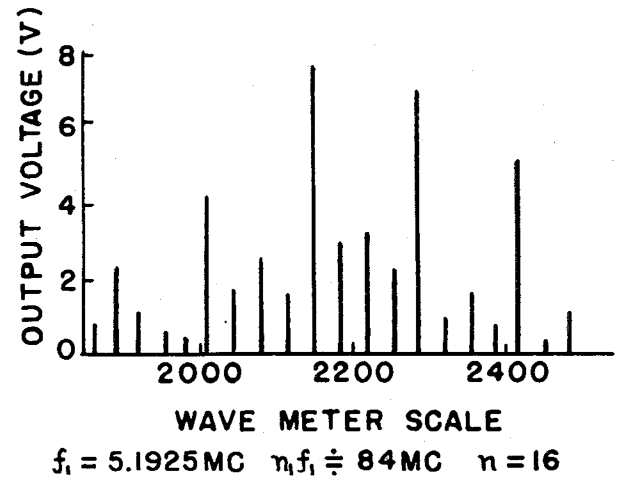

Fig. 10—Example of the measured spectrums.

Applications of the New Frequency Standard

When we compare the new system mentioned above with the previous one, the equipment of this new system is very simple, and its output power is considerably high. Fig. 11 shows the outside view of the microwave standard of this new system. Fig. 12 shows the comparison of output frequency spectrums of the new system with the previous crystal multiplier systems.

By applying the new system the authors have obtained a method of precise frequency measurement of microwaves. The basic principle is as shown in Fig. 13. The precise measurement is done by measuring the Δf (in Fig. 13) with the combination of the special cavity wavemeter as shown in Fig. 13, and the frequency standard by this principle.

Unknown frequency fx is measured in a form

$$fx = fs + \Delta f,$$

where fs is one of the spectrums of the standard frequency and Δf is measured with the cavity wavemeter by vernier rod B. Accuracy of this system is good, and

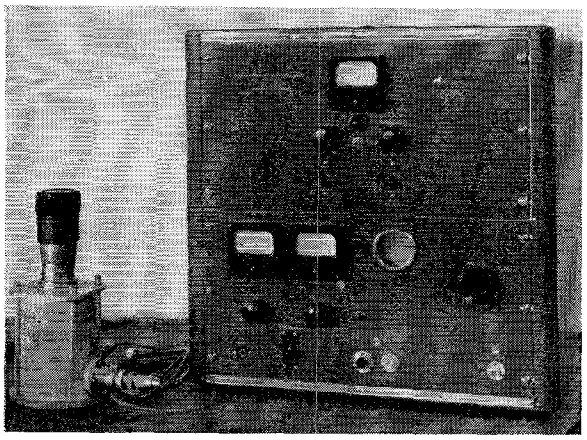

Fig. 11—Outside view of the new type microwave frequency standard.

over-all accuracy of 0.001 per cent or better is obtained. In the modified system of this principle, the measurement of Δf is done by the heterodyne principle. In this system, unknown frequency of fx is beaten down to Δf and then the frequency measurement of Δf is done with a heterodyne-type frequency meter of Δf range as customarily used, and the accuracy of 0.0001 per cent is obtained.

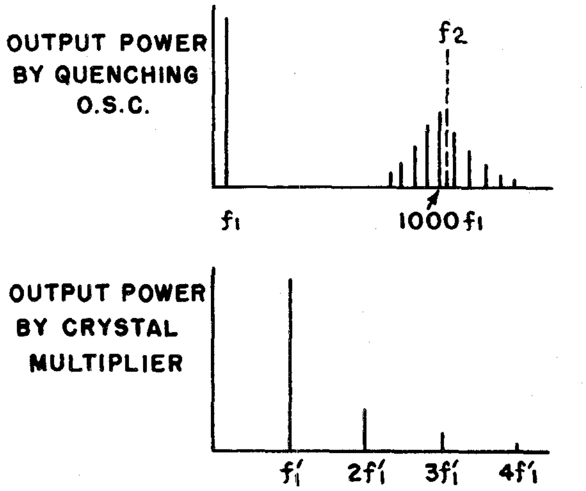

Fig. 12—Comparison of output frequency spectrums of the new system with the crystal multiplier system.

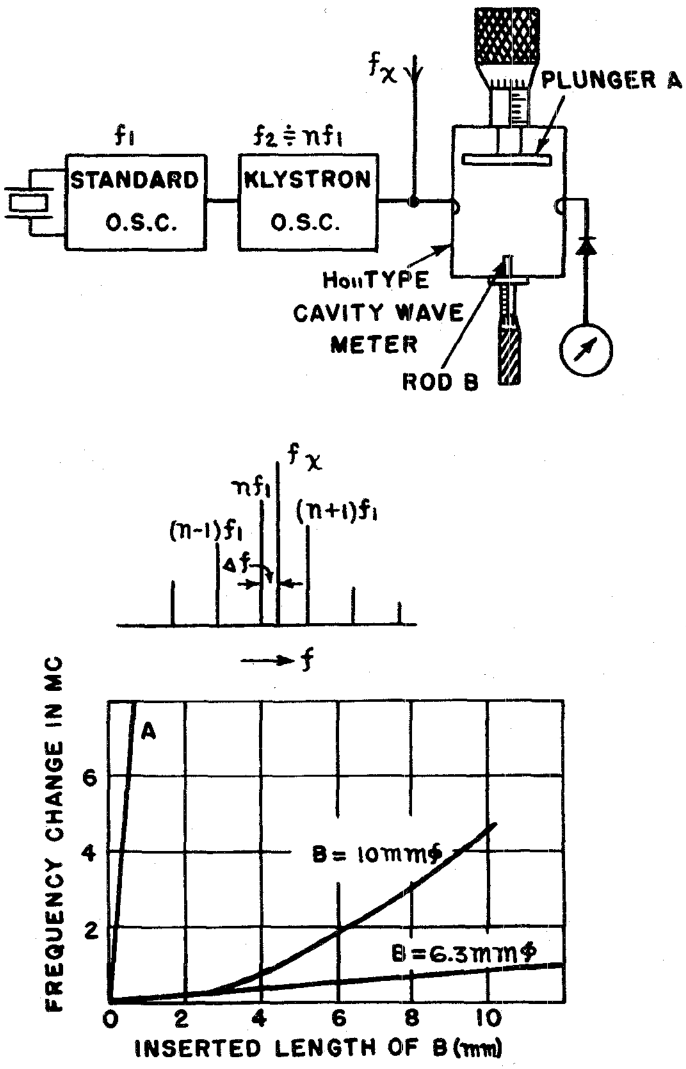

Fig. 13—The method of precise frequency measurement.

CONCLUSION

The equipment in this paper is one of the simplest and most economical for microwave frequency standards, and may possibly be the one for solving these problems by the precise measurements of the microwaves. They are now applied to commercial products. We consider that these methods will be applied to not only microwave region but also uhf or vhf regions.

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