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Invention of a Temperature-Insensitive Quartz Oscillation Plate, 1933

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***Abstract*—In April 1933 Isaac Koga invented a temperature-insensitive quartz oscillation plate. This invention was used at first for radio transmitters and later for clocks, and has proven indispensable to all radio communication systems and much of information electronics. This achievement was approved as an IEEE Milestone, which was dedicated to Tokyo Institute of Technology in March 2017.**

Keywords*—*quartz oscillation; frequency stability; temperature coefficient; cutting angle

I. Introduction

Issac Koga (Fig.1) was born on 5 December 1899 in Saga Prefecture, Japan. He graduated from Department of Electrical Engineering, Tokyo Imperial University in 1923. He then worked for the new Tokyo City Electrical Institute as a radio engineer. Koga became associate professor of Tokyo Institute of Technology in 1929, and was making efforts to study quartz oscillation. In 1930 he received PhD degree from Tokyo Imperial University by his dissertation "Characteristics of the crystal oscillator". From theoretical and experimental research he invented a temperature-insensitive quartz oscillation plate in 1933. He also invented a frequency divider in 1927, and developed Koga-type quartz clock KQ1 in 1936, which was displayed at EXPO 1937 Paris. He became full professor of Tokyo Institute of Technology in 1939, and concurrent professor of Tokyo Imperial University in 1944. In 1960 he was awarded the status of Professor Emeritus from Tokyo Institute of Technology and from University of Tokyo (former Tokyo Imperial University). He then served as Advisor to KDD (presently KDDI) till 1982.

II. Issac Koga

Issac Koga started his study of quartz crystal oscillators following Cady's initial discovery (1922) of quartz plate oscillation. At that time, investigations of quartz oscillation were mostly undertaken experimentally by making actual oscillation plates without any back-up design principle. In order to overcome the inherent complexities, Koga strove successfully to establish a precise theory for the vibration analysis of quartz plates. In 1932, when Koga established his precise theoretical analysis of thickness vibration of anisotropic quartz crystal, no similar theory existed. Therefore, Koga's theory was readily adopted in the field together with the practice of rotating the cutting angle around the crystallographic axis. This contributed worldwide to the application of zero-temperature-coefficient quartz plates.

Fig. 1 Issac Koga

In late 1929 and early 1930, several proposals appeared for realization of zero-temperature-coefficient plates. Among them, a ring-type plate was considered promising, however it was unusable in actual transmitters owing to delicate design constraints. Koga concentrated on producing a zero-temperature-coefficient plate by rotating the cutting angle around the X-axis (see Fig.2) and realized an actual plate having a zero-coefficient in 1933. Koga's pioneering studies in the theory and technologies of quartz oscillation continued unabated, in collaboration with his group after World War II. These works have further contributed to the establishment of present-day quartz technologies.

III. History of Invention

In the early 20th century, a precise and stable source of radio frequencies was wanted and radio engineers sought about its realization. Walter Guyton Cady found that quartz resonates with small equipment and good temperature stability, and developed the first crystal oscillator in 1921.

Soon later Issac Koga started his study of quartz crystal oscillators. He happened to measure the temperature dependence of Y-cut crystal and found that the temperature coefficient was plus. On the other hand, that of X-cut was known being minus. He thought that zero-temperature coefficient cut should locate in some angle between X- and Y-cut. However, there did not exist.

In parallel, Koga investigated the characteristics of R cut plates cut out in parallel to the face r and R' cut plates in parallel to the r′ face (reverse side of r face). He noticed that R' cut plate exhibits a negative temperature coefficient while Y cut plate a positive one. From these experiments, he hypothesized the existence of a zero-temperature-coefficient plate in between those cutting angles.

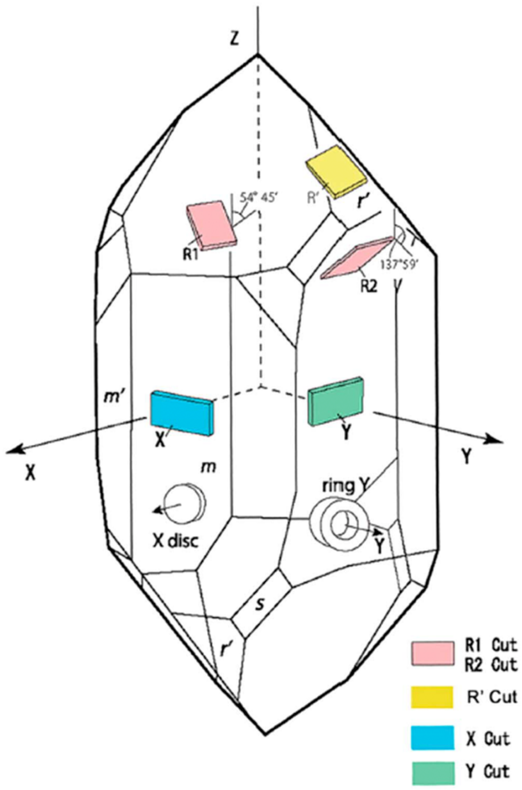

Fig. 2 Various Cuts in Quartz Crystal

At the same time, Koga felt a necessity of some guiding theory to find an adequate cutting angle. Then he tried to make a theory for the vibration of quartz plates.

It had been well known that for any isotropic plates the resonant frequency f of vibration is expressed as

$$f = \frac{q}{2a}\sqrt{\frac{c}{\rho}}, \tag{1}$$

where q is any integer, a is plate thickness, ρ is density, c is a certain adiabatic elastic constant of the medium.

At that time there was no vibration theory for anisotropic media. In 1932 Koga performed a theoretical analysis of thickness vibration of anisotropic quartz crystal. Actually, it turned out from the theory that X- and Y-cut plates belong to different modes of vibration and there should be some jumps of modes and no zero-temperature angle between two.

Finally in August 1932, Koga showed that there could be 3 normal modes of thickness vibration and obtained an equivalent elastic constant c^{eq} corresponding to the thickness vibration of quartz plates cut in parallel to X axis with the rotating angle θ from Z axis [1]. He expressed the equivalent elastic constant c^{eq} expressed as

$$c^{eq} = \frac{1}{2}(c_{11} - c_{12})\sin^2\theta + c_{44}\cos^2\theta - c_{14}\sin 2\theta, \tag{2}$$

where c_{ij} with i and j referring to $1, 2, 4$, are adiabatic constants. The resonant frequency f is simply obtained by using c^{eq} in place of c in (1).

The present authors have tried to obtain cutting angles having zero temperature coefficient of the resonant frequency, from Koga's theory. By differentiating (1) with respect to temperature T, we have

$$\frac{\partial f}{\partial T} = \frac{1}{2a\sqrt{\rho}}\frac{\partial\sqrt{c^{eq}}}{\partial T} = \frac{1}{2a\sqrt{\rho}}\frac{1}{2\sqrt{c^{eq}}}\frac{\partial c^{eq}}{\partial T}. \tag{3}$$

Using (2) and setting (3) equal to zero, we get

$$\frac{1}{2}(\dot{c}_{11} - \dot{c}_{12})\sin^2\theta + \dot{c}_{44}\cos^2\theta - \dot{c}_{14}\sin 2\theta = 0, \tag{4}$$

where the dot means $\partial/\partial T$. This is a transcendental equation and Koga and Takagi numerically solved it in late 1933[3,4].

In this paper, we attempt to solve and prove the existence of two cutting angles having a zero temperature coefficient based on the knowledge in the year of 1932.

Assuming $\theta \neq \frac{\pi}{2} + n\pi$, we divide (4) by $\cos^2\theta$ to get

$$\frac{1}{2}(\dot{c}_{11} - \dot{c}_{12})\tan^2\theta - 2\dot{c}_{14}\tan\theta + \dot{c}_{44} = 0. \tag{5}$$

This is a quadratic equation in terms of $\tan\theta$. Depending on its determinant, (5) may have 2 real roots, 1 real double root, or no

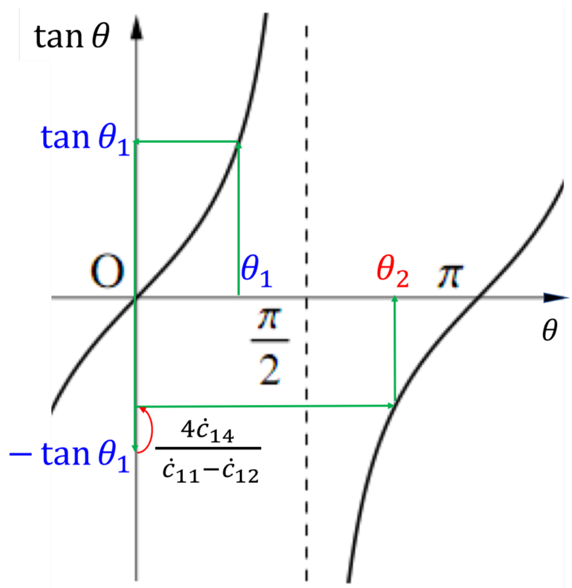

Fig. 3 Relationship of two solutions of (5)

real root. Note that $\tan\theta$ and θ have one-to-one correspondence in $0 \le \theta < \pi$. Vieta's formulas show that if one real solution θ_1 for (5) is found, another one θ_2 is obtained from

$$\tan\theta_2 = -\tan\theta_1 + \frac{4\dot{c}_{14}}{\dot{c}_{11}-\dot{c}_{12}} \quad (6)$$

as shown in Fig.3. The authors consider that two cutting angles could be easily hypothesized within 1932, if one carefully examined Koga's equation of resonant frequency as Bechmann did as introduced in the following section.

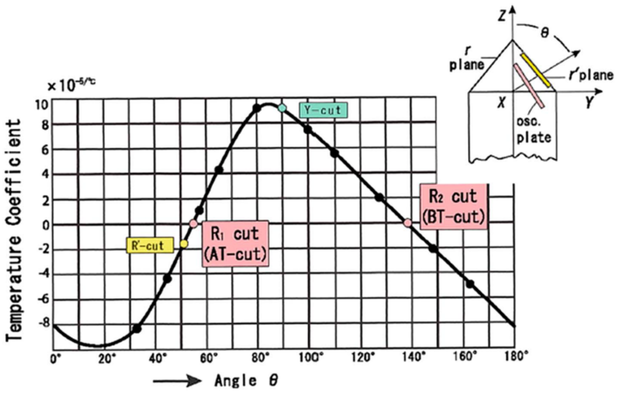

Fig. 4 Rotation Angle and Temperature Coefficient

Koga and his colleague Ichinose actually showed the existence of a zero-temperature-coefficient plate (at around $\theta = 55°$) in their report in April 1933 [2]. His continued in-depth research clarified a precise angle of $54°45'$ which was reported in October 1933 [3]. Koga experimentally confirmed the existence of another possible zero-temperature-coefficient angle $137°59'$ (Fig.4). That work was published in December 1933 [4]. These cuts were later called R_1 and R_2 cut, respectively.

Fig. 5 Transmitter Used in Experiment in Yosami

Koga's R_1-cut was experimentally used at Yosami Radio Transmitting Station (Figs.5, 6) in the summer of 1933. One hour after the transmission there came a response from a German receiving station about the frequency stability. They realized a sudden stabilization of the transmitting frequency and wondered what happened.

Yosami Radio Transmitting Station, established in 1929 for wireless communication between Japan and Europe using a long wave, was accredited another IEEE Milestone in 2009. From mid-1920s short wave communication emerged as an alternative of long wave, and Koga's temperature-insensitve quartz showed its importance in that transmission.

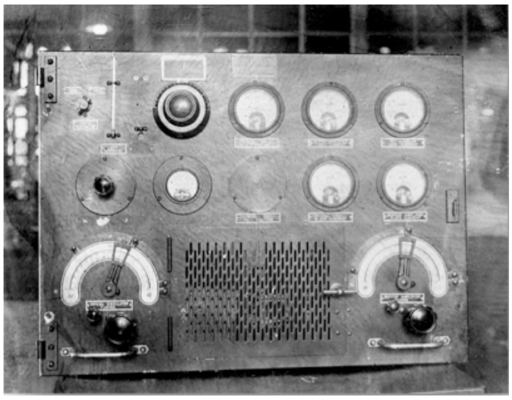

Fig. 6 Transmitter Used in Experiment in Yosami

IV. Related Work

Ten days after Koga's report [3] on 10 October 1933, Rudolf Bechmann of Telefunken Co., independently reported theoretical prediction of the existence of zero-temperature-coefficients, citing Koga's 1932 paper as a starting point.

In July 1934, F. R. Lack, G. W. Willard, and I. E. Fair of Bell Laboratories found zero temperature coefficient angles by rotating the cutting angle about X axis starting from Y cut. The two angles were named AT and BT cut. Those two are substantially the same as Koga's earlier R_1 and R_2 cuts, respectively.

Those related achievements were summarized in Table I in [5]. In the last column of Table I, Seiko's Quartz wristwatch is listed, which received yet another IEEE Milestone in 2004. Quartz oscillators in wristwatches use tuning forks, because the necessary frequency (32.768 kHz) is much lower than that used in wireless communication purposes. Koga proposed tuning fork vibration components in his earlier studies.

TABLE I. BENCHMARKS OF RELATED ACHIEVEMENTS

	Koga	**Telefunken**	**Bell Labs**	**Seiko**
Fundamental theory	1932	–	–	–
Temperature-Insensitive Plates	April 1933	October 1933	July 1934	NA
Cut name	R_1 and R_2	(Similar angles)	AT and BT	(Tuning Fork)
Experiments	1933	(Theoretical)	1934	1969
Application	Transmitters and Clocks	NA	Transmitters	Wristwatches

V. Precise Clocks

He also invented a frequency divider in 1927, and developed Koga-type quartz clock KQ1 (Fig.7) in 1936, which was displayed at the open campus of Tokyo Institute of Technology in that year and at EXPO 1937 Paris. It was also sent to National Astronomical Observatory of Japan for practical experiments. His KQ6 was installed at KDD for the frequency standard and standard clock in 1955, and used until 1968 for international telecommunications without any problems (Figs.8,9).

Fig. 7 KQ1 Displayed at EXPO Paris in 1937

Fig. 8 Frequency Standard at KDD Otemachi

VI. Summary

Koga's pioneering studies in the theory and practical design of stable frequency have been used in communications and clocks for time standard. Today, this type of temperature-insensitive quartz crystal plate has proven indispensable to most of radio communication systems and much of information electronics.

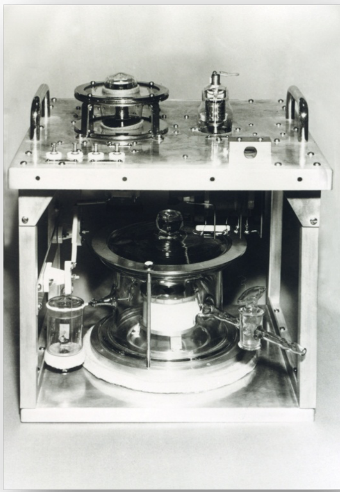

Fig. 9 Oscillator in KQ6

Koga was awarded the Japan Academy Prize in 1948 for "Theoretical and Experimental Investigation upon the Fundamental Characteristics of Piezoelectric Oscillating Crystal and Quartz Crystal Oscillator Circuit and Their Applications to Wireless Communication and Crystal Clock", the Order of Cultural Merit award in 1963 and became a member of the Japanese Academy in 1971. He served as the president of International Union of Radio Science (URSI) from 1963 to 1968.

Koga passed away on 2 September, 1982. For his memory, the International Union of Radio Science, URSI, founded the Issac Koga Gold Medal in 1984.

Acknowledgment

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References

[1] I. Koga, "Thickness Vibrations of Piezoelectric Oscillating Crystals," J. Appl. Phys., vol. 3, pp. 70-80, Aug. 1932.

[2] I. Koga and K. Ichinose, "Quartz Oscillating plates with small temperature coefficients for short-wave", Proc. 8th Joint Conf. Eng., Elect. Eng. Section, pp.205-206, Apr. 1933 (in Japanese).

[3] I. Koga and N. Takagi, "Piezoelectric oscillating quartz plates with temperature coefficients less than 10^{-7}/°C", J. Inst. Electr. Eng. Jpn, vo.53, 10, p.940, Oct. 1933 (in Japanese)

[4] I. Koga and N. Takagi, "Temperature coefficients of elastic constants of quartz", J. Inst. Electr. Eng. Jpn, vo.53, 12, p.1141, Dec. 1933 (in Japanese)

[5] K. Iga, "Invention of temperature-insensitive quartz oscillation plate enabling highly stable communications and clocks: Review of Issac Koga's works", Radio Science, Vol.51, 10, pp.1725-1730, Oct. 2016