

RECENT DEVELOPMENT OF QUARTZ OSCILLATORS

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ABSTRACT

Our company, NPC, has developed clock IC products for CPUs by applying the crystal oscillation circuit that began with the quartz watch. Now NPC is developing ICs for various types of oscillator module products. Nowadays, the demand for oscillators for IT and network-related devices is high, and high frequency and low jitter characteristics are desired.

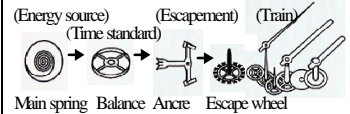
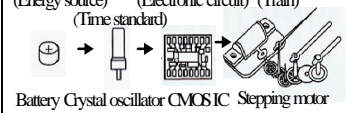
Conventionally, it has been difficult to use CMOS circuits in the manufacturing of the oscillator whose bandwidth is more than 100MHz. In order to meet the demand of high-frequency oscillators, NPC has adopted a BiCMOS process, which use bipolar transistors in the oscillation part. By using this technology, NPC has developed an ECL-output oscillator that oscillates up to 330MHz with much stability.

1. INTRODUCTION

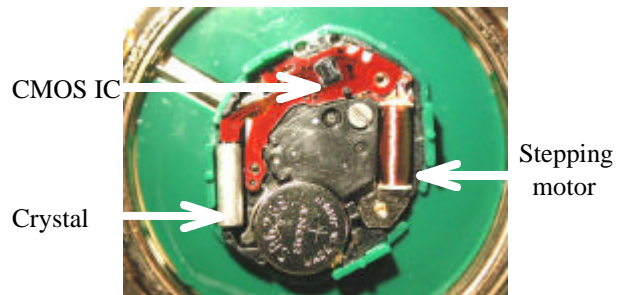
In 1968 SEIKO was the first company to commercialize home clocks, which use crystal oscillators. Since then, the quartz clock using CMOS ICs is the mainstream of clocks of nowadays. NPC was established in 1975 as one of SEIKO group's semiconductor manufacturers. The aim of the company was to mass-produce CMOS ICs for quartz clocks, which were rare those days. CMOS ICs have promoted smaller space, less power, and lower cost and in 1981 quartz clock exceed 80% to begin the quartz clock age.

The composition of a quartz clock is explained briefly according to Fig.1. The structure comparison between the mechanical clock and the quartz clock is shown in Fig.1 (a). While the mechanical clock generates time with aid of the main spring and the balance, the quartz clock generates time by using the electrical oscillation of the quartz crystal. The escapement of the mechanical clock corresponds to the electrical processing circuits and the motor drivers of the IC in a quartz clock. Fig.1 (b) is a photograph of a quartz watch and Fig.1 (c) shows the block diagram of the quartz watch. It consists

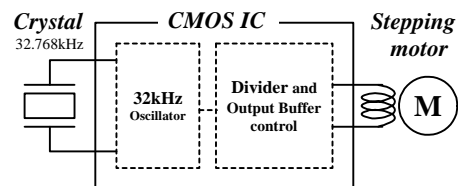
of a crystal oscillator, which generates accurate frequency, an IC, which oscillates the crystal and generates the output pulse every second by dividing the clock, and a step motor which moves hands. The crystal is the key element that clicks exact time.

Type	Accuracy After 24hrs	Principle of Operation
Mechanical Clock, Watch	$\pm 20\text{sec}$	 <p>(Energy source) (Time standard) (Escapement) (Train)</p> <p>Main spring Balance Anchor Escape wheel</p>
Quartz Clock, Watch	$\pm 0.2\text{sec}$	 <p>(Energy source) (Electronic circuit) (Train)</p> <p>Battery Crystal oscillator CMOSIC Stepping motor</p>

(a) Structure comparison between the mechanical clock and the quartz clock



(b) Internal photograph of a quartz watch



(c) Block diagram of a quartz watch
Fig.1 Composition of a quartz clock

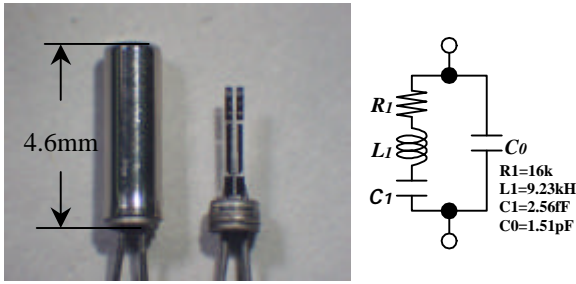


Fig.2 Crystal (32.768kHz)

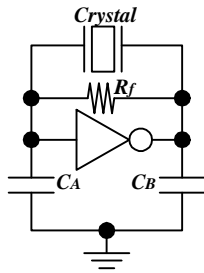


Fig.3 Colpitts oscillation circuit

Fig.2 shows a photograph of the quartz where the right part is the crystal quartz, the origin of exact time. The timing signal is taken out using the mechanical oscillation by the piezo-electric effect of the quartz. In order to lower the power consumption, the crystal is required to oscillate at a frequency, which is as low as possible. The quartz frequency of 32.768 kHz is now the most common for quartz clocks and it has succeeded in the miniaturization by having a crystal oscillator in the tuning fork form. The electric equivalent circuit of a crystal oscillator is represented by L, C, and R. The Colpitts oscillator, which is shown in Fig.3, is generally chosen because a capacitive load can be realized in an IC. The oscillation frequency of this circuit is given by the following equation.

$$f = \frac{1}{2\pi\sqrt{L_1 C_1}} \sqrt{1 + \frac{C_1}{C_0 + C_L}} \quad (1)$$

$$\text{where } C_L = \frac{C_A C_B}{C_A + C_B}$$

Because the value of C_1 is extremely small, the influence of the oscillator, external parasitic capacitance, etc. is negligible, as can be seen in equation 1. Besides using the crystal oscillator, it is very difficult to obtain very big values of L_1 and very small values of C_1 . Because the crystal oscillator can not be easily influenced by an external load, the quartz clock has very high stability.

The output signal of an oscillator is converted into a signal whose cycle is 1 second. The divider consists of flip flops in the IC. The signal is led to the stepping motor. Fig.4 is a conceptual figure of a step motor. The rotor is a magnet that is surrounded by an electromagnet with notches on the surface.

When there is no current flowing, the electromagnet does not exist and the rotor takes a position whereby the rotor (magnet) and the metal attracts each other. Due to the presence of the notches, the rotor takes a diagonal position.

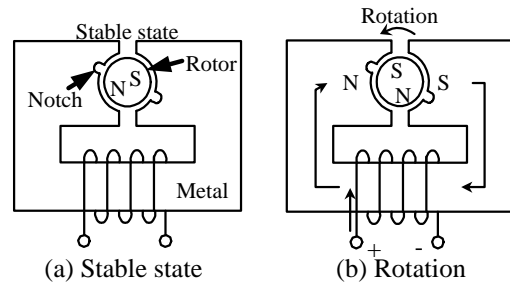


Fig.4 Stepping motor

When the voltage is applied to the electromagnet in the direction that the rotor and the electromagnet repulse each other, the rotor rotates 180 degrees. Such electric pulses are generated from the IC and applied to the electromagnet after every second in order to rotate the stepping motor. The motor power is then transmitted to the gears, which move the second hand and the hour hand.

The SEIKO quartz clock, which consists of three elements described above, a tuning fork type oscillator, a CMOS IC of low power consumption, and the stepping motor suitable for the miniaturization, is now a global standard.

Our company has been seriously involved in the CMOS IC crystal oscillator from its birth, and is producing various clock-signal-generation ICs for crystal oscillators, which evolved from the quartz clock. The composition of a crystal oscillator itself is simple, but a crystal oscillator design is unexpectedly difficult because of the frequent problems of unstable oscillation and non-oscillation.

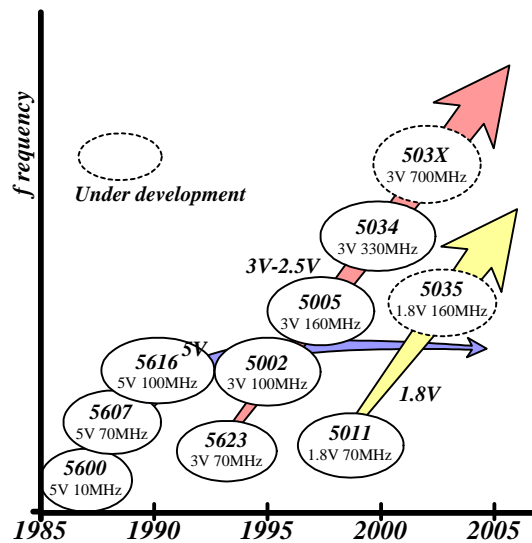


Fig.5 NPC Roadmap

In response to the high demand, our company has developed the CMOS ICs for the oscillator module with a quartz crystal and an oscillator unified in a package. This is one of the main products of our company. The developed and future oscillator products are shown as a roadmap in Fig.5. The example of high frequency oscillator related demand specifications are shown in Table 1.

Table 1. Example of high frequency oscillator related demand specifications^[1]

	1.25Gb/s	2.125Gb/s	2.5Gb/s	3.125Gb/s	Rambus
	1000Base-X	Fiber Channel	InfiniBand	10G Ethernet	1.0-3.4Gb/s
Transmit Jitter	0.28UI p-p (224ps p-p)	0.3UI p-p (141ps p-p)	0.35UI p-p (140ps p-p)	0.35UI p-p (112ps p-p)	0.3UI p-p (88ps p-p)
Receive Jitter	0.4UI p-p (320ps p-p)	0.39UI p-p (183ps p-p)	0.35UI p-p (140ps p-p)	0.35UI p-p (112ps p-p)	0.35UI p-p (103ps p-p)

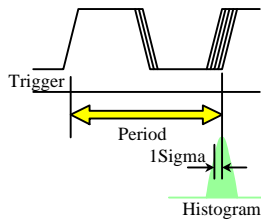
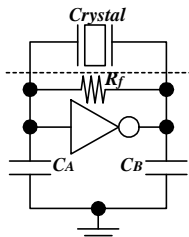


Fig. 6 Definition of jitter

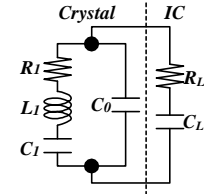
As a trend in recent years, the demand of oscillators for IT and network related market is increasing. The market needs higher frequency, higher precision, and lower jitter. The definition of jitter is shown in Fig. 6. Table 1 shows the example of the required jitter specifications of typical equipment that uses these high frequency oscillators. Normally a standard clock needs to have far lower jitter than this specification.

2. PRINCIPLE EXPLANATION OF CRYSTAL OSCILLATOR

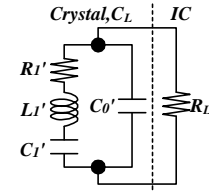
The basic principle of a crystal oscillator is explained in this section. Although there are various methods to realize an oscillation circuit, the Colpitts oscillator is generally selected because it is easy to integrate capacitors in ICs. The merits of the Colpitts oscillator exist in the higher Q-value and in the comparatively lower jitter because the Colpitts oscillator uses the resonance phenomenon at the series resonance point.



(a) CMOS oscillation circuit diagram



(b) Equivalent circuit



(c) C_L included in a vibrator side

Fig.7 CMOS oscillation circuit and equivalent circuit

Operation of CMOS oscillation circuit:

The circuit diagram of a CMOS oscillator is shown in Fig.7 (a). Its equivalent circuit is shown in Fig.7 (b). R_L and C_L are the model parameters of the equivalent circuit replacing the oscillation inverter and capacitors C_A and C_B . The value of R_L is called negative resistance because its value is negative. R_L and C_L are shown by the following equations.

$$R_L = -\frac{gm}{\omega^2 C_A C_B} \quad (2)$$

$$C_L = \frac{C_A C_B}{C_A + C_B} \quad (3)$$

When C_L in Fig.7 (b) is moved to the crystal side, the circuit in Fig.7(c) was obtained where R_1' , C_1' , and C_0' are shown in the following equations. The oscillation condition is that the sum of R_1' and R_L is negative.

$$R_1' = R_1 \left(1 + \frac{C_0}{C_L} \right)^2 \quad (4)$$

$$C_1' = \frac{C_1 + C_L^2}{(C_0 + C_1 + C_L)(C_0 + C_L)} \quad (5)$$

$$L_1' = L_1 \left(1 + \frac{C_0}{C_L} \right)^2 \quad (6)$$

$$C_0' = \frac{C_0 C_L}{C_0 + C_L} \quad (7)$$

The oscillation frequency is as shown in equation 8.

$$f = \frac{1}{2\pi \sqrt{L_1' C_1'}} \sqrt{1 + \frac{C_1}{C_0 + C_L}} \quad (8)$$

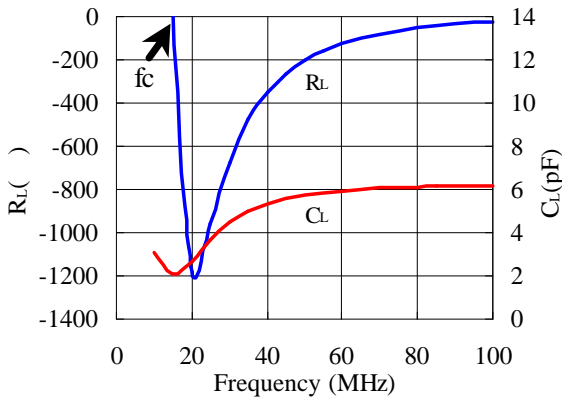


Fig. 8 R_L and C_L vs. Frequency

Fig.8 shows the graphs of R_L and C_L vs. frequency. The frequency that R_L becomes zero is called the cutoff frequency and is shown in the next equation

$$f_c = \frac{1}{2\omega C_L} \sqrt{\frac{gm}{R_f}} \quad (9)$$

Concerning high-order overtone oscillation circuit:

Generally an oscillator resonates at the odd-overtone frequency points such as $3f_0$, $5f_0$, $7f_0$, etc. The oscillation at the higher overtones (higher than the fundamental) is called the “overtone oscillation”. NPC has 3rd overtone oscillator ICs of which cutoff frequencies are set up at a higher frequency than the fundamental frequency in order to oscillate at 3 times the fundamental frequency. Equation 9 shows that the frequency is determined by R_f .

3. THE MOST RECENT CRYSTAL OSCILLATOR AS SHOWN BY 5034

In March 2002, NPC has announced the new crystal oscillator IC 5034 with a differential ECL (Emitter Coupled Logic) mode output. The BiCMOS process was used during the production of this IC. This product’s oscillation frequency ranges from 80MHz to 330 MHz, satisfying the demand of the stable clock signal for network related market. NPC is now developing products with frequency extending to 700 MHz.

The conventional way of manufacturing high frequency clocks is mainly done by multiplying the clock of low frequency by PLL system etc. Since the amount of data and the rate of transmission of data have increased in recent years, high stability of a clock signal is required. The demand to oscillate directly from 100MHz to around 1GHz with a crystal oscillator has become strong. Conventionally, the quartz manufacturers produce oscillator modules as separate

entities, but now the demand for miniaturization of packages, as shown in Fig. 9, has become strong. An outline of a high frequency oscillator is described.

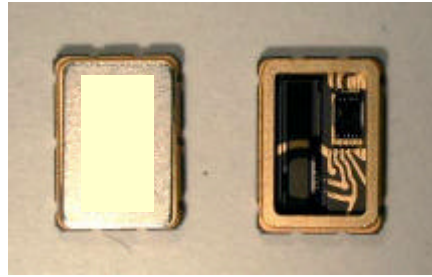


Fig. 9 7.5 x 5 mm SAW Oscillators

Oscillator beyond 100MHz:

The mass production of the crystal oscillators that covers 200MHz is attributed to the technical improvement of the crystal oscillator, and now it is also possible to use the SAW (Surface Acoustic Wave) resonators that can oscillate from 200MHz to about 1GHz. Though the resonance frequency of the equivalent circuit increase, the equivalent circuit of these oscillators can be expressed as the equivalent model of RCL introduced previously. Table 2 shows the equivalent parameters of a typical 3rd overtone 100MHz crystal oscillator [2] and a 300MHz SAW resonator [3].

Table 2 Equivalent Parameters of Oscillators

	$R1$	$L1$	$C1$	$C0$
100MHz 3O.T.	18.3	2.1mH	1.2fF	3.5pF
304MHz SAW	10.9	90.6uH	3.0fF	4.0pF

Adoption of Bipolar Oscillator:

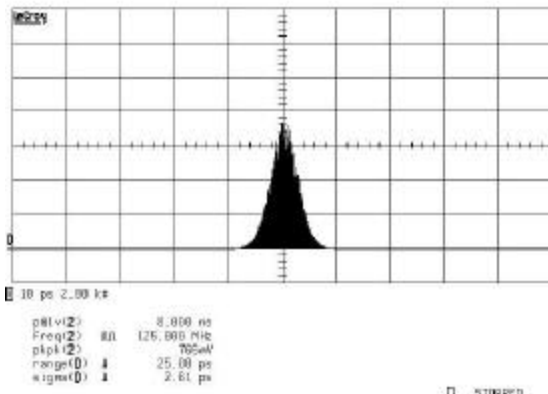
The high frequency does not greatly affect the parameters R_1 , C_0 , etc., of a crystal oscillator, but the following problem occur as frequency becomes high. As shown in equation 2, when the frequency increases, the negative resistance decreases sharply. The negative resistance R_L can be increased if either gm is increased or C_A and C_B decrease. However, reducing C_A and C_B results in decreasing C_L and increasing the effective crystal impedance R' . This does not contribute to the improvement of the oscillation margin, which implies that the only option is increasing gm .

However, it is not easy to increase gm of a CMOS inverter because it is proportional to the shrinking process. Although it is possible to earn the gm by connecting three or more stages of a CMOS inverter, a self-oscillation state that may cause a risk of abnormal oscillation is possible. This therefore implies that this problem can be solved by making bipolar oscillators using a BiCMOS process. Since the gm of bipolar

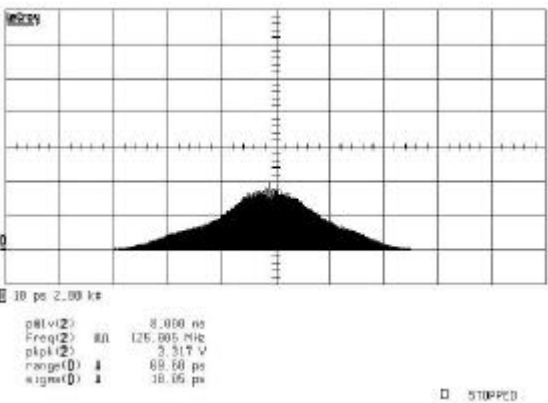
transistor is 10 times or more that of a MOS transistor in the same occupied area, using bipolar transistors is therefore advantageous.

Reduction of Jitter:

As described previously, one of the purposes of high frequency oscillators is that they reduce clock jitter. In the PLL synthesizer system, the frequency of VCO is controlled by the phase difference between the reference clock phase and the VCO clock phase. This results in the fluctuation of the frequency, which occurs theoretically when the jitter is in this system. On the contrary, direct oscillation with a crystal decreases jitter overwhelmingly. Fig.10 compares the results of the measured jitter characteristics of 5034 and a PLL system.



(a) Jitter of 5034 crystal oscillation (125MHz)



(b) Jitter of a PLL (125MHz by the multiplication of 20MHz)

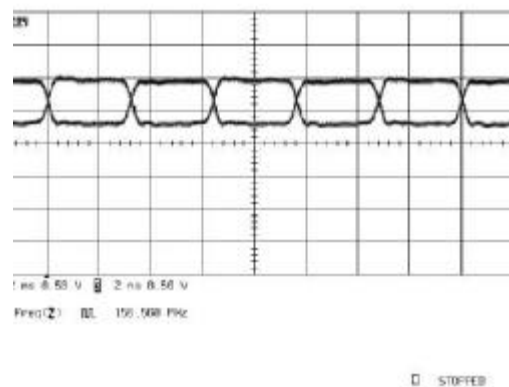
Fig. 10 Jitter comparison of 5034 (crystal oscillator) and a PLL

Adoption of the ECL differential output:

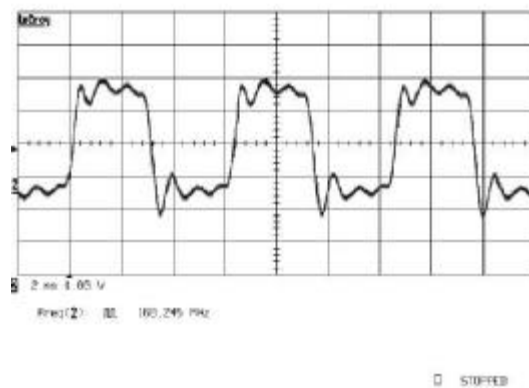
When the output frequency of an oscillator becomes high to the extent that the signal line length is about 1/100 of its wavelength, its standing wave or reflection wave begins to appear. In this case, the signal line becomes a transmitting antenna of unnecessary magneto-electronic noise. For example the print pattern wiring length that can ignore influence at 500MHz is

approx. 3mm or less.

That's the reason why the ECL differential output is adopted. Using ECL differential output prevents both the standing wave and the reflection wave by terminating with proper termination resistance. Theoretically, differential output eliminates unnecessary radiation noise. The value of the amplitude of the self-generated noise is small because of a small amplitude swing of approx. 0.75V. Fig.11 shows the comparison between the ECL 155MHz output of 5034 and the CMOS 155MHz output. In Fig.11 (b), one can see overshooting in the CMOS output, which is caused by the impedance mismatching. On the other hand, the waveform of ECL shown in Fig.11 (a), does not overshoot and it is expected to transmit the precision clock signal with little noise.



(a)ECL output (5034)



(b) CMOS output (5050)

Fig.11 155MHz waveform

4. CONCLUSIONS

As described above, our company, NPC, has been developing ICs for the crystal oscillator modules and this began with the manufacturing of quartz clocks. Because ICs for the crystal oscillator modules are the main products at NPC, the crystal oscillator module is the main pillar of NPC.

Development of a network brings about the always-connectable “ubiquitous” world.

We will enrich the products of the timing solution that generate these standard clocks necessary to the network from now on, and contribute to the “ubiquitous” world.

Our oscillator IC is a mixed-signal IC that consists of digital elements and analog elements. NPC is going to develop aggressively ASSPs (application specific standard products) under the concept of both “Mixed Signal” and “only at NPC and by NPC only”. Furthermore we intend to spread worldwide with this technical advantage.

5. REFERENCES

- [1] Rambus Inc. “Serial Communications Cells for High-Bandwidth Networking Applications” Gigabit Ethernet Conference 2001 Presentations Slide pp.4 , 2001
- [2] Nihon Dempa Kogyo co., Ltd. “Crystal Units” Catalogue 2002 pp.33-34, 2002.
- [3] Seiko Epson Corporation “The Crystal Master Product Catalog 2001” pp.88 ,2001.