TST Quartz Crystal Resonator, Oscillator & MCF

I. Quartz Crystal Resonator

It's 89th year since Walter Guyton Cady built the first quartz crystal oscillator in 1921. Quartz crystal is a piezoelectric material with excellent temperature stability. Resonator made by this material is used in quartz crystal oscillation circuit.

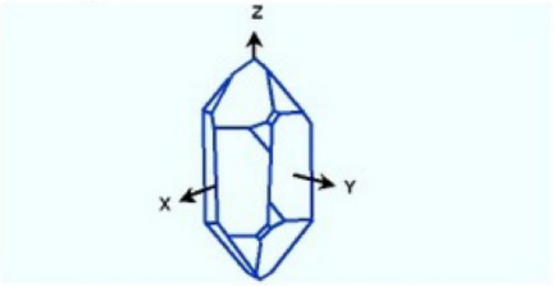


Fig. 1 Natural faces and crystallographic axes of quartz

The orientation of Quartz crystal bulk is defined in Fig. 1 by "Natural faces" of crystal. AT cut is popular as "Zero Temperature Coefficient Quartz Cuts" with almost perfect frequency-temperature characteristics are seen in Fig. 2.

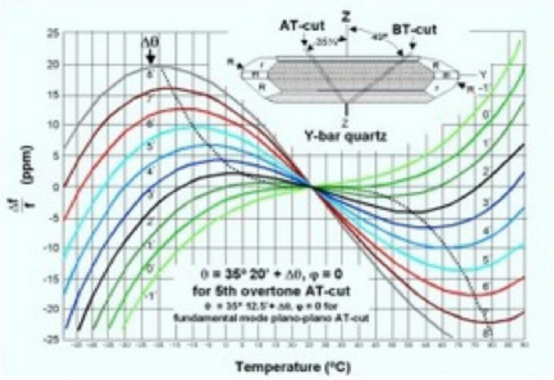


Fig. 2 Frequency-Temperature vs. Angle-of-Cut, AT-cut

In general, bulk acoustic wave (BAW) modes of motion exist in piezoelectric crystal materials like Quartz (SiO2), LiTaO3, LiNbO3, Langasite (La2Ga5SiO14)…. Fig. 3 describes the BAW modes of motion. AT-cut resonators vibrate in the thickness shear mode. Other modes are unwanted modes named **"Spurious modes"**.

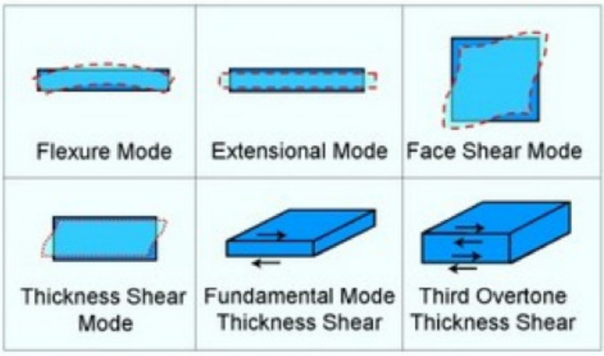


Fig. 3 BAW Modes of motion

The construction of a Quartz Crystal Resonator is seen in Fig. 4. Two metal electrodes plated on the Quartz blank to form a piezoelectric transducer. This transducer converts applied AC voltage on electrodes to mechanical vibration then converts back to AC voltage. At specific frequency near the natural frequency of this resonator, it gives very low loss of energy. Hermetic seal is needed to ensure the stability of transducer chemically.

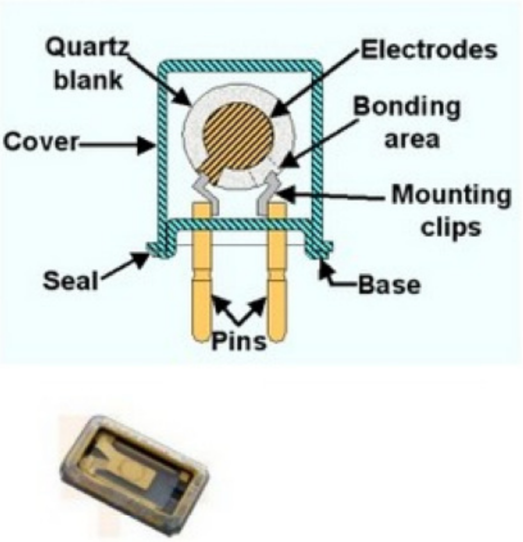
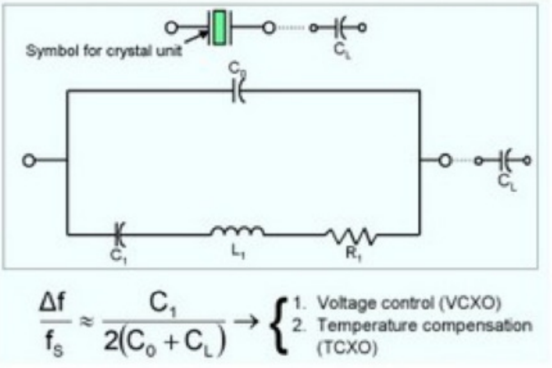


Fig. 4 Quartz Crystal Resonator structure

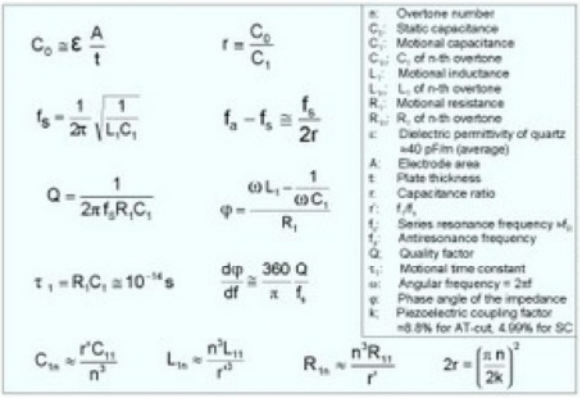
The equivalent circuit of Quartz Crystal Resonator is seen in Fig.5.



$$\frac{\Delta f}{f_S} \approx \frac{C_1}{2(C_0 + C_L)} \rightarrow$$

Fig. 5 Equivalent circuit of Quartz Crystal Resonator

In the oscillation circuit excluding resonator can be modeled as "Load Capacitance" CL simply. By adjusting CL values can make the oscillator as VCXO, TCXO… The equation describes the frequency increment by in series with CL. Derivative of this equation to CL gives $\frac{C_1}{2 \cdot (C_0 + CL)^2}$, which is the **"Tuning sensitivity"** by CL. **"C0"** is contributed by package parasitic and the static capacitance of electrodes-blank transducer. **"L1"**, **"C1"**, **"R1"** is the equivalent motional parameters. Well known equations can be found in Table 1. **"Q"** is an important factor to indicate quality of the resonator. The higher Q the less energy loss of resonator has.



$$C_0 \cong \varepsilon \frac{A}{t} \qquad r = \frac{C_0}{C_1}$$

$$f_S = \frac{1}{2\pi}\sqrt{\frac{1}{L_1 C_1}} \qquad f_a - f_s \cong \frac{f_s}{2r}$$

$$Q = \frac{1}{2\pi f_S R_1 C_1} \qquad \varphi = \frac{\omega L_1 - \frac{1}{\omega C_1}}{R_1}$$

$$\tau_1 = R_1 C_1 \cong 10^{-14}\,s \qquad \frac{d\varphi}{df} \cong \frac{360}{\pi}\frac{Q}{f_s}$$

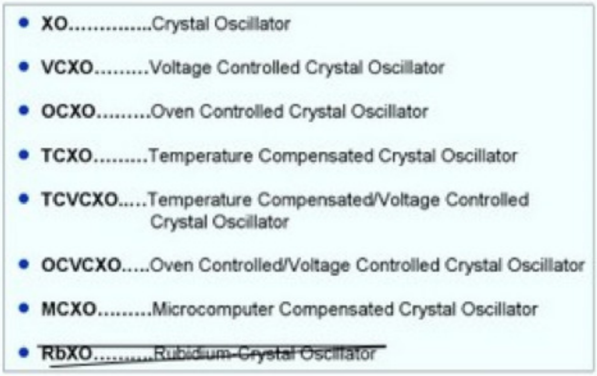
$$C_{1n} \approx \frac{r' C_{11}}{n^3} \qquad L_{1n} \approx \frac{n^3 L_{11}}{r'^3} \qquad R_{1n} \approx \frac{n^3 R_{11}}{r'} \qquad 2r = \left(\frac{\pi n}{2k}\right)^2$$

n: Overtone number
C_0: Static capacitance
C_1: Motional capacitance
C_{1n}: C_1 of n-th overtone
L_1: Motional inductance
L_{1n}: L_1 of n-th overtone
R_1: Motional resistance
R_{1n}: R_1 of n-th overtone
ε: Dielectric permittivity of quartz ≈40 pF/m (average)
A: Electrode area
t: Plate thickness
r: Capacitance ratio
r': f_1/f_n
f_s: Series resonance frequency ≈f_R
f_a: Antiresonance frequency
Q: Quality factor
τ_1: Motional time constant
ω: Angular frequency = 2πf
φ: Phase angle of the impedance
k: Piezoelectric coupling factor =8.8% for AT-cut, 4.99% for SC

Table 1 Equivalent circuit of Quartz Crystal Resonator

Thickness shear mode standing wave exists while resonating of a Quartz crystal resonator. 2 electrodes are the wave reflection boundary of standing wave or "Node" of standing wave. 1/2 wavelength is equal to the thickness of Quartz blank of **"Fundamental mode xtal"**. N is an integer number. An odd N multiple of 1/2 wavelength is the thickness of Quartz blank in **"N-th overtone xtal"**. There is no even N-th overtone because even N gives no electric field on the transducer to generate piezoelectric phenomenon.

II. Quartz Crystal Oscillator



- **XO**..............Crystal Oscillator
- **VCXO**.........Voltage Controlled Crystal Oscillator
- **OCXO**.........Oven Controlled Crystal Oscillator
- **TCXO**.........Temperature Compensated Crystal Oscillator
- **TCVCXO**.....Temperature Compensated/Voltage Controlled Crystal Oscillator
- **OCVCXO**.....Oven Controlled/Voltage Controlled Crystal Oscillator
- **MCXO**.........Microcomputer Compensated Crystal Oscillator
- ~~**RbXO**..........Rubidium Crystal Oscillator~~

Table 2 Oscillator Acronyms

1. General oscillation circuit

A simplified circuit diagram is shown in Fig. 6. The amplifier consists of at least one active device; the necessary biasing networks, and may include other elements for band limiting, impedance matching, and gain control. The feedback network consists of the crystal resonator, and may contain other elements, such as a variable capacitor (varactor diode) for tuning.

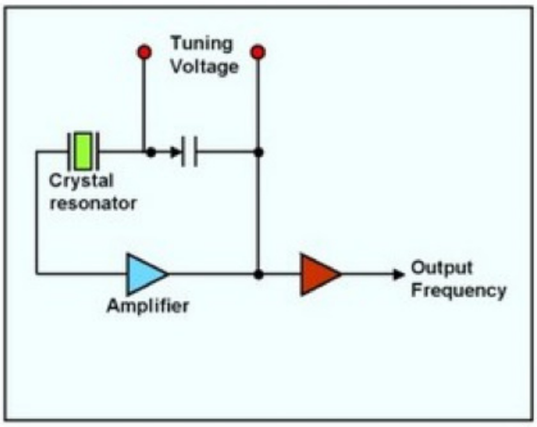


Fig. 6 Simplified Crystal oscillation circuit diagram

"Reactance of Xtal" is shown in Fig. 7. Most of the xtal oscillators operate at FL that is the resonance frequency of in series CL. At FL>Fs (or Fr) the reactance is positive that is conjugate to reactance of CL that is negative. Reactance of Xtal and CL cancel each other and give minimum impedance thus resonating.

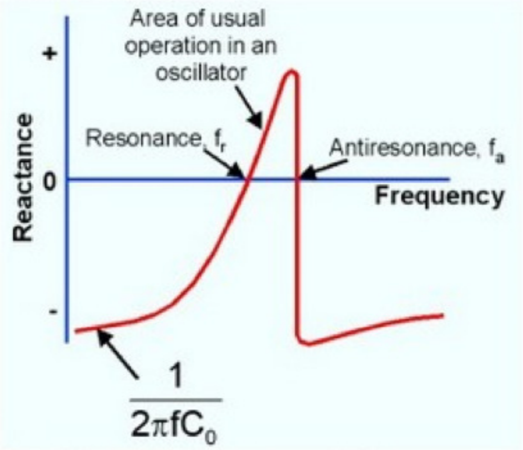


Fig. 7 Resonator Reactance vs. Frequency

"Negative Resistance" is a popular concept to analyze the general oscillation circuit.

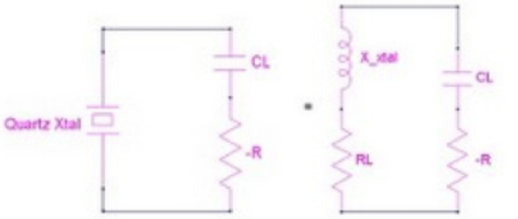


Fig. 8 "Negative resistance" circuit model

It needs to provide energy to compensate energy loss in the Quartz crystal resonator to make the oscillation circuit oscillating. "Positive resistance" is a general term to describe "Energy loss" in Physics. "Negative resistance" means "Energy supply". Active devices like Vacuum tubes, Transistors or Logic gates can be the "Energy supply" in the oscillation circuit. In the beginning of oscillation, "Negative resistance" |–R|>>RL where $RL = R_1 \cdot (1 + C_0/CL)^2$ thus ensure the starting of oscillation. The above condition means energy supplied is far larger than energy loosed in the beginning of oscillation. Generally, |-R|~=(3~10)*RL is good condition to start oscillation. After a finite **"Start up time"**, in steady state the |-R| will be exactly equal to RL. Quartz crystal resonator eats out the energy supplied exactly and the oscillation power is stable finally.

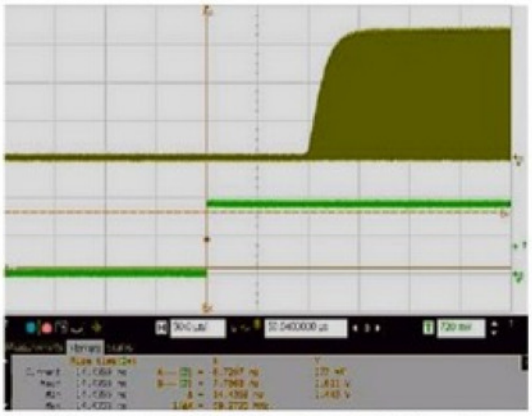


Fig. 9 Example of "Start up time"~=150 us. Green trace is power supply voltage off then on.

"Drive level" given by active device is the power dissipation of Xtal. $\vec{I}$ is the AC current phasor flow into Xtal and $\vec{V}$ is AC voltage phasor applied on both terminals of Xtal. "Drive level"= $\vec{I} \bullet \vec{V}$ by definition of power dissipation. Adequate "Drive level" for xtal is needed to provide stable performance of the oscillator. Typical "Drive level" is 0.1uW~100uW. The smaller size of transducer the smaller "Drive level" it endures. Too high "Drive level" make xtal working at nonlinear range. Significant frequency shift and unwanted modes stimulated by high drive level.

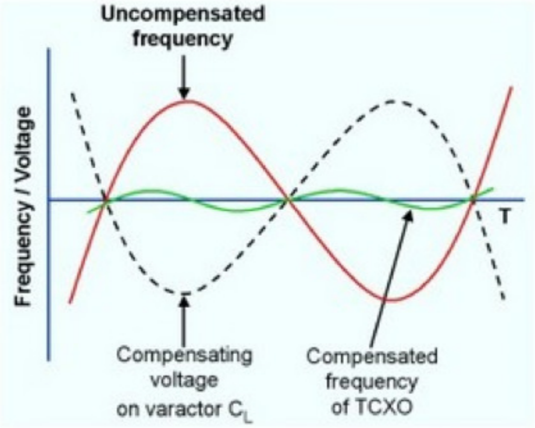


Fig. 10 Xtal oscillator FL vs. T compensation

"Frequency temperature stability" describes how stable a XO operated at specific temperature range. Fs-temperature curve is almost the same as Quartz crystal natural frequency-temperature curve in Fig. 2. The slightly difference is due to electrodes plating, mounting/packaging stress, Drive level… The FL-T curve is come from Fs-T curve pulled by the oscillation circuit, which is temperature dependent also. The shape of FL-T curve is similar to Fs-T that is cubic function of temperature. Fig. 10 illustrates the F-T curves of XO, TCXO and V-T curve of compensation voltage on varactor.

"Phase noise L(f)" is a measurement of the uncertainty in the phase of the signal. It is a common index of the oscillator signal purity on frequency domain. Ideal sinusoidal signal contain only one frequency mathematically. Real oscillator contain wide band phase noise result from Thermal noise, Flicker noise of active device… Basically, Xtal is a high Q narrow band filter to filter out those White thermal noise by sharp frequency transmission response.

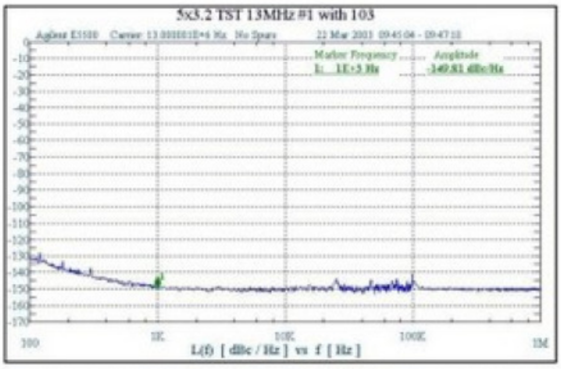


Fig. 11 Example of TST 13 MHz XO Phase noise

"Jitter" is a measurement of the uncertainty in the period of the signal. It is a common index of the oscillator signal purity on time domain. Ideal sinusoidal signal contain only one period mathematically. Jitter is also the integral of the phase noise L(f),offset frequency range is assigned by different application for studying the interference from oscillator. Typical periods of real oscillator distribute in normal distribution statistically. The smaller jitter is the better oscillator is.

Fig. 12 Example of TST 26MHz XO Jitter

"Waveform" is voltage-time curve of the oscillator. **"Vpp"** is peak-to-peak voltage amplitude. **"Tr (Rise time)"** is the time for low voltage rising to high voltage level. **"Tf (Fall time)"** is the time for high voltage falling to low voltage level. **"Duty cycle"** is the percentage of the high voltage level duration in a period.

Fig. 13 Example of TST 26MHz XO Waveform

"Pushing" is the frequency change caused by power supply voltage change. **"Load Pulling"** is the frequency change caused by output load change of oscillator. These 2 indexes are expected as small as possible in a stable oscillator.

2. Popular oscillation circuits

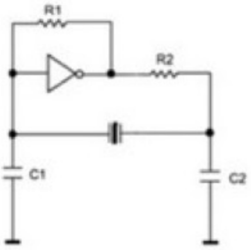


Fig. 14 Logic gate inverter oscillator

"Logic gate inverter oscillator" is seen in Fig. 14. This circuit is most popular in IC or discrete circuit. R1 is the feedback resistor to establish DC bias and make inverter as an amplifier with gain. Typical R1=1 M ohm. R2 reduce the "Drive level" of Xtal. Adequate C1=C2 and inductive Xtal form a pi circuit to provide another 180 deg. phase shift thus Open loop gain>1.0 and open loop zero phase delay. Oscillation start if fit above condition at specific frequency. Designer often forget to add R2 thus xtal suffer large Drive level. C1=C2 are too large or too small may stop oscillation at extreme temperature. Inverter gate, R1, R2 are always embedded in the IC. The cost of this circuit is low but the phase noise is high.

"Colpitts oscillator" is seen in Fig. 15. This circuit is popular in IC or discrete circuit. The transistor could be CMOS in modern IC. All components excluding Xtal can be embedded in the IC. Sometimes C1, C2 are put outside the IC. R1, R2 establish adequate DC bias. C4 is the decoupling capacitor. C1, C2 is the feedback capacitors to give "Negative resistance". They cannot be too large or too small else oscillation may stop.

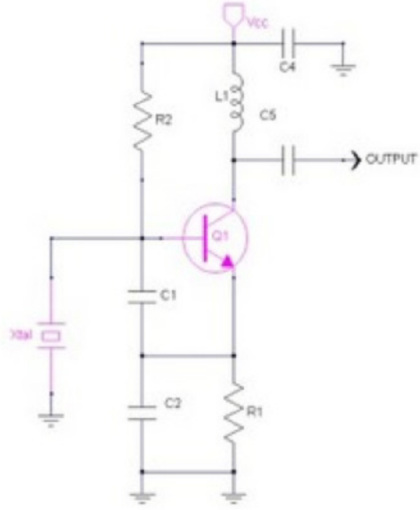


Fig. 15 Colpitts oscillator

3. Some notes for Xtal applications

[1] Xtal should be far away from vibration, shock, and heat source in the customer end product assembly if possible.

[2] The metal trace connecting Xtal to oscillation circuit should be as short as possible. Or shielded by ground plane if need to extend the length.

[3] Xtal should be placed at the location without too much deformation/bending of the circuit board.

[4] The CL, "Negative resistance" and "Drive level" need to be checked to give stable oscillation and correct frequency.

[5] Power supply of oscillation circuit should be decoupled by adequate capacitors to prevent interference.

III. MCF (Monolithic Crystal Filter)

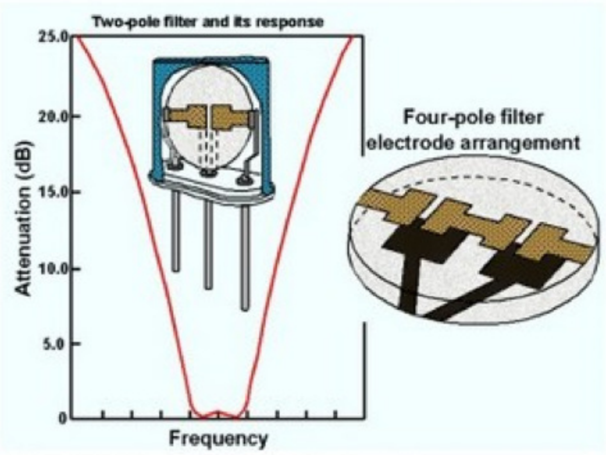


Fig. 16 MCF (Monolithic Crystal Filter)

"MCF (Monolithic Crystal Filter)" is a band pass filter made by Quartz crystal resonators on a single Quartz blank. Nakazawa described 1st coupled-resonator AT-cut MCF in 1962. "Coupling" is key factor to form a filter by multiple resonators. MCF utilizes "Thickness shear mode" mechanical energy coupling on the same substrate that is Quartz blank. Multiple piezoelectric transducers convert AC voltage to vibration coupling each other then covert back to AC voltage. MCF is a 2-port device. N-pole MCF contains N resonators on the blank. The equivalent circuit of 3-pole MCF is seen in Fig. 17.

Fig. 17 Equivalent circuit of 3-pole MCF

X1, X2 and X3 are Rm, Lm, Cm series resonate circuit without C0. Cg is the stray capacitance between input and output electrodes. C01 and C02 is static capacitance see into input and output terminals. Input and output impedance of MCF is high because the Cm is so small in several fF. order.

1. Design consideration of MCF on customer circuit

"Impedance Matching" is key job to do when putting MCF into customer's circuit. The input/output matching circuit transforms high impedance of MCF to "Conjugate impedance" of application circuit. MCF Input matches to mixer output and MCF output matches to mixer or amplifier input are popular examples in "Superheterodyne receiver". The purpose of "Impedance matching" is to make "Maximum power transfer" toward output load.

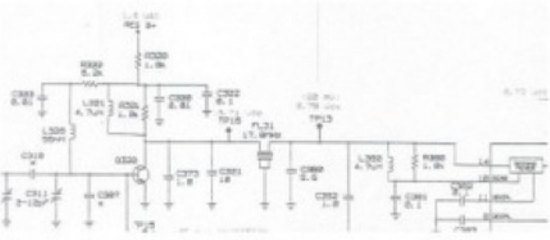


Fig. 18 Example of VHF Pager receiver IF 2-pole 17.9 MHz MCF

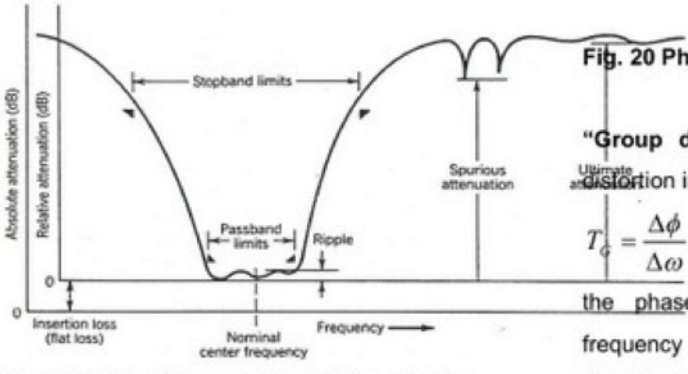


Fig. 19 Typical filter amplitude transmission response

Once "impedance matching" is well done, the correct frequency response looks like Fig. 19. Specified **"Passband"** is the frequency range of wanted signal. Specified **"Stopband"** is the frequency range of unwanted signal. **"ULT (Ultimate attenuation)"** is the attenuation of signal at very far end of "Passband" and "Stopband". **"Insertion loss (IL)"** is the loss of the top flat of the response. The smaller IL is wanted. **"Spurious attenuation"** is special for piezoelectric filter. Piezoelectric resonator always exists unwanted **"Spurious"** modes of motion, no matter BAW or SAW (Surface acoustic wave) device. Larger "Spurious attenuation" is better. **"Nominal center frequency"** is the center frequency wanted.

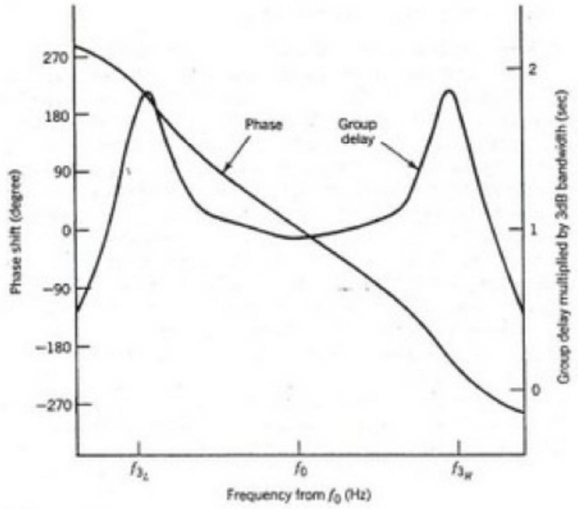


Fig. 20 Phase & Group delay of a 4-pole MCF

"Group delay distortion" describes the phase distortion in "Passband". "Group delay" is defined as $T_g = \dfrac{\Delta\phi}{\Delta\omega}$ (sec.) as $\Delta\omega \rightarrow 0$ where ϕ (rad.) is the phase and ω (rad./sec.) is the angular frequency of the phasor. The variation in "Group delay" across specified "Passband" is "Group delay distortion" or **"Differential delay"**. Smaller "Group delay distortion" is preferred in digital communication system.

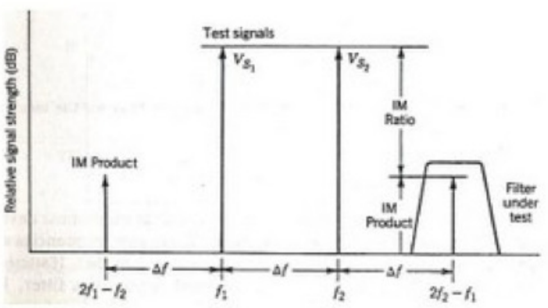


Fig. 21 IM distortion of MCF

"IM (Intermodulation) distortion" is caused by 3rd order nonlinearity of MCF. In the mobile radio environment it is common to find situation where strong interfering signals from base stations and other mobile radios exist. Large "IM distortion" degrades the sensitivity of receiver.

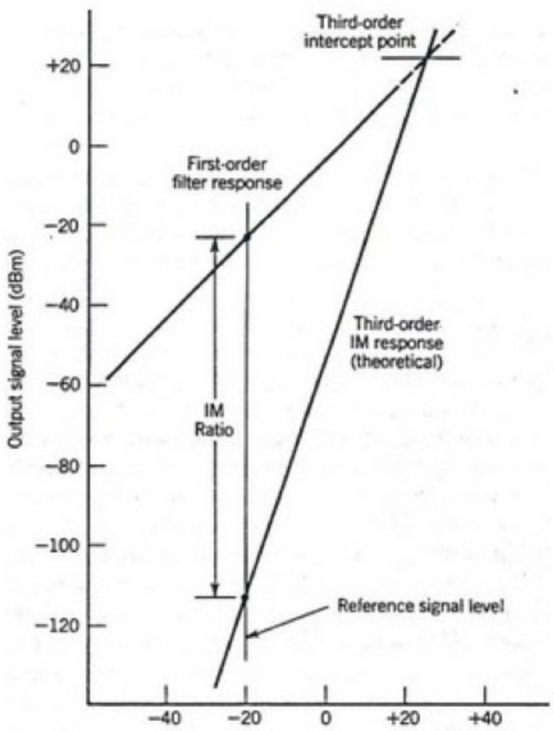


Fig. 22 Theoretical 3rd order IM distortion and TOI

"TOI (Third-order intercept point)" is a general term to describe the linearity of the devices including MCF. Theoretical relation between "IM distortion" and "TOI" is illustrated in Fig. 22.

"Drive level" means power fed into input port of MCF. MCF is usually matched to 50 ohm source and fed −20 dBm "Drive level" while testing typically. High "Drive level" makes MCF working at nonlinear range. Nonlinear MCF give frequency shift and passband response change.

2. Some notes for MCF applications

[1] MCF should be far away from vibration, shock, and heat source in the customer end product assembly if possible.

[2] The metal traces connecting MCF should be considered as part of matching circuit. Traces shielded by ground plane if needed to avoid interference from other circuits.

[3] MCF should be placed at the location without too much deformation/bending of the circuit board.

[4] Layout of the components of impedance matching circuit should be considered to avoid EM interference between input and output. Reduce the mutual inductance between input matching inductors and output matching inductors is effective to give better "Stopband" and "ULT".