# APPLICATION NOTE

# Oscillators on 8-bit microcontrollers (2)

## AN97090

Philips
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**Abstract**

*"Going digital" and "programmable architectures" are the product strategies of today. However no digital system will run without a clock oscillator circuit and "oscillation" is and old and very analogue phenomena that may still need additional clarification. Quite some theory and some practice on this subject based on microcontrollers is covered in this application note.*

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# Oscillators on 8-bit microcontrollers (2)

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**Summary**

Basically this application note is an addition to AN96103 “Xtal oscillators on 8-bit microcontrollers” It handles with harmonic Xtal resonation and ceramic resonators. Oscillator theory, component value calculations, parameter measurements is one part of this application note, application info with component type numbers is another part.

**(*) Honourable mention**

## *Wim Rosink*

Wim Rosink retired this year after contributing more than 39 years to the Systems Lab Eindhoven. Wim has a long experience with many analogue circuits, like: oscillators in many variations, phase locked loops, etc.. This, combined with his knowledge on CMOS-technology and CMOS-digital families, makes him the ideal resource for the subjects of this application note. Most of the research and documenting for this application note was done by Wim.

The microcontroller sales support group is grateful to Wim for his high level contribution on the oscillator subject and is convinced that it will be useful to those that want or need more background on the oscillation issue in relation to microcontrollers.

**Special thanks**

A special thanks is given to muRata* and their representives in Germany and the Netherlands for giving support by developing this application note.

(*TOYAMA MURATA MANUFACTURING CO., LTD)

## CONTENTS

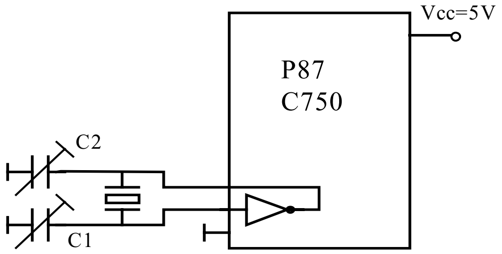
# 1. INTRODUCTION

Most microcontrollers include internal circuitry to generate the required clock pulses for the processor functions. The frequency rate of these clock pulses can be selected by some external components. For less demanding applications, simple LC circuitry or even an RC circuit can be used to fix the frequency. However, when a higher frequency stability is required, an oscillation circuit with a ceramic resonator or, for best stability, a circuit with external crystal should be used.

## 1.1 The case

Crystals are available for frequencies from 1MHz up to 100MHz and higher. For the higher clock frequencies, e.g. above 20 MHz, the resonators and crystals mostly will be used in a third or fifth overtone oscillation mode. This application note is basically build around one oscillator case with a microcontroller that runs on the higher frequencies also, so there is an opportunity to study behaviour of third overtone oscillation.

Fig.1 below shows this case, a typical circuit for a 39 MHz clock oscillator with a 39 MHz third overtone crystal and a P87C750 microcontroller.




Used Crystal: Third overtone,
Philips 39.130 MHz, nr. 02370991

Fig.1 Pierce oscillator circuit

The crystal is connected directly to input and output of the microcontroller inverting gate. Two capacitors $C_2$ and $C_1$ are connected from these points to ground to perform the required load capacitance of the crystal. For most applications, the values of these capacitors are between 10 and 30pF and both about equal or $C_1<C_2$. With $C_1>C_2$ , the feedback gain will be small, reducing the gate input voltage.

## 1.2 The subjects

The oscillation conditions are given by the crystal parameters, the external capacitors and the current gain or transconductance $g_m$ of the inverter. The next two sections will describe following subjects:

* how to calculate the oscillation condition ?
* how to measure the crystal parameters ?
* how to measure the oscillator gate circuit parameters ?

## 2. OSCILLATION CONDITION AND CIRCUIT PARAMETERS.

### 2.1 The crystal equivalent circuit

At the resonant point, the equivalent circuit of a crystal or resonator behaves like the circuit in Fig.2, hence a series connection of $R_s$, $L_1$ and $C_a$ in parallel with capacitance $C_b$. The example shows a third overtone crystal with two main modes of resonance, one at Fs= 13MHz, the fundamental mode, and one at the third overtone mode at 39 MHz. The circuit impedance is given by the equation below:

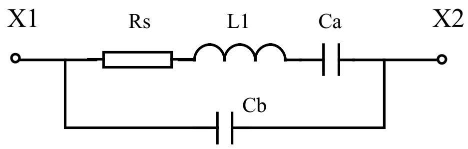



Fig.2 Equivalent crystal circuit.

$$Z_{XTAL} = \frac{\frac{1}{j\omega C_b}\left(R_s + j\omega L_1 + \frac{1}{j\omega C_a}\right)}{R_s + j\omega L_1 + \frac{1}{j\omega C_a} + \frac{1}{j\omega C_b}}$$

............................ Eq.1

The values of the equivalent circuit components were measured with a impedance/phase analyser HP4194 for both resonance modes, as explained in section 4. The results are given in section 4.2:

Crystal electrical data of crystal:

| | | |
|---|---|---|
| Fundamental mode: | Fs0=13.055MHz | Rs=57E, Ca=12fF, L1=11.9mH, Cb=2.8pF |
| Third overtone: | Fs3rd=39.13MHz | Rs=30E, Ca=1fF, L1=16.8mH, Cb=3.3pF |

In both modes, with the value of Cb>>Ca, the “series resonance” frequency with Fs given by L1 and Ca, will be very close to the value of the “parallel resonance” frequency, as given by L1 and Ca,Cb in series, because CaCb/(Ca+Cb) is close to Ca. Below it shows that a negative resistance has to be added to the circuit to compensate for the damping of Rs at oscillation by using the transconductance gain of the inverter for start up of the oscillator.

### 2.2 Equivalent circuit of the Pierce oscillator.

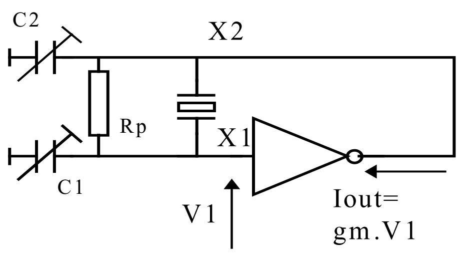



Fig.3a. Pierce oscillator circuit

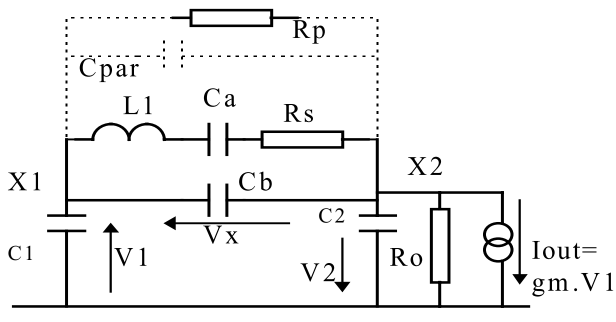



Fig.3b. Equivalent circuit

Fig. 3a+b shows the used Pierce oscillator circuit with its equivalent circuit diagram, in which the crystal is replaced by L1,Ca,Rs and Cb. The inverter is replaced by its output impedance Ro and the output current from the transconductance gain: Iout= gm.V1. Rp is a bias resistance to force the gate input to its threshold level to provide starting up. In most µcontroller-types the feedback transistor Rp is already integrated as a semiconductor resistor parallel to the inverting gate.

In such a Pierce oscillator, the crystal should be operated in a “parallel resonance” mode with the parallel components $C_b$ and C1/C2 in series. Therefore this circuit is also called the positive reactance oscillator, because the branch L1/Ca/Rs should be inductive. At resonance, the total impedance is high, with a 180 degree phase shift between gate input and output signal.

The circuit will oscillate, if the negative reactance of the transconductance current gain just compensates for the damping of the resistive elements Rs, Ro and Rp.

A very convenient way and also rather easy to prove the oscillation condition is to transfer all these elements in series with Rs by means of the power dissipation rule, saying that the elements Ro, Rp and gm.V1 are replaceable by a resistor in series with Rs, if this gives the same dissipation or damping to the circuit. Then the oscillation condition is true, if the total value of the resistive elements, including the own damping Rs of the crystal is less than zero.

After transferring all resistive elements into the series branch, the simplified resonance calculation model of fig. 4 can be used.

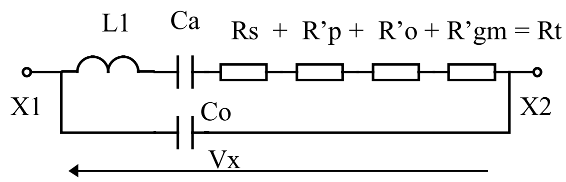



Fig.4 Resonance calculation model

Co= Cb + Cload + Cpar.
Cpar= parasitic capacitance across gate.
Cload = C1C2 / (C1 + C2)
C1,C2 include parasitics at input and output.
At resonance with Co>>Ca, $\omega_o$=1/v(L1.Ca)
Rt = $R_s$ +$R'_p$ +$R'_o$ +$R'_{gm}$.

In this figure, Co is the total parallel capacitance, including load capacitance Cload formed by the capacitance’s C1 and C2 in series and the parasitic capacitance's at input and output and in parallel with the gate. The value of Rt is given by Rt= Rs + $R'_p$ +$R'_o$ +$R'_{gm}$.

Assuming that in resonance, $I_{Rt} = I_{Co}$, then it follows for $R'_p$ :

$P_{Rp}= P'_{R'p}$ , or $(V_x)^2/R_p = I^2_{Rt} .R'_p$ or with $I_{Rt} = I_{Co} = (V_x).\ \omega_o.C_o$ it follows:

$(V_x)^2/R_p = V_x^{2.}.\omega_o^2.C_o^2\ .\ R'_p$ or...

$$R'_p = \frac{1}{\omega_o^2 \times C_0^2 \times R_p} \text{ ..........................................................................Eq.2}$$

For the output impedance Ro follows with $P_{Ro} = P_{R'o}$:

$V_2^2 / R_o = I^2_{Ro}.\ R'_o$, or with $V_2 = V_x.C_1/(C_1+C_2)$ and $I_{Ro}= I_{Co} = V_x.\omega_o.C_o$ it follows:

$V^2_x.C_1^2/(C_1+C_2)^2 / R_o = V_x^2\ .\omega_o^2\ C_o^2.\ R'_o$ or...

$$R'_0 = \frac{1}{\omega_o^2 \times C_o{}^2 \times R_o} \times \frac{C_1^2}{\left(C_1 + C_2\right)^2} \text{ ...................................................Eq.3}$$

Transferring Io= $g_m.V_1$ to $R'_{gm}$ means, with $P_{(gm.V1)} = P_{R'gm}$ :

$-g_m.V_1.V_2 = I^2_{Rt}.\ R'_{gm}$ , or with $V_1=V_x\ C_2/(C_1+C_2)$, $V_2 = V_x.C_1/(C_1+C_2)$ and $I_{Rt}= I_{Co}$ it follows:

$-g_m.V_x^2.C_1.C_2./\ (C_1+C_2)^2 = V_x^2\ .\omega_o^2\ C_o^2.\ R'_{gm}$. or...

$$R'_{gm} = \frac{-g_m}{\omega_o^2 \times C_o^2} \times \frac{C_1 \times C_2}{(C_1 + C_2)^2} \quad \text{..........Eq.4}$$

Combining these equations, we obtain for the total series resistance:

$$R_t = R_s + \frac{1}{\omega_o^2 C_o^2}\left(\frac{1}{R_p} + \frac{1}{R_o}\left(\frac{C_1}{C_1 + C_2}\right)^2 - g_m \frac{C_1 C_2}{(C_1 + C_2)^2}\right) \quad \text{..........Eq.5}$$

The circuit will oscillate, if the value of Rt is zero or negative. So the minimum value of $g_m$ should be:

$$g_m \geq R_s \times \frac{\omega_o^2 C_o^2 (C_1 + C_2)^2}{C_1 C_2} + \frac{1}{R_p}\frac{(C_1 + C_2)^2}{C_1 C_2} + \frac{1}{R_0}\frac{C_1}{C_2} \quad \text{..........Eq.6}$$

The first two products of this equation are reduced to a minimum value with C1 = C2. This means, that for easiest oscillation, both load capacitance's should be equal. In this case we find:

$$g_{m.\min} \geq R_s \times 4\omega_o^2 C_o^2 + \frac{4}{R_p} + \frac{1}{R_o} \quad \text{..........Eq.7}$$

The last equation for the minimum required value for $g_m$ confirms quite well with the values as derived in the publications as mentioned in references 3 and 4. To determine $g_{m\text{-}min}$ for worst case design, it should be noted, that the value of $R_s$ may vary with the drive level, and can be much higher than the specified value from device data at low drive level during start-up. See also section 2.6.

Ref.4. from Rusznyak also derives a maximum value for the transconductance , above which oscillation is not possible. In most cases this value is much higher than the minimum value and can be neglected. However for low frequency crystals, operating around 16 to 32 kHz, it might be of influence for the oscillation condition. The equation for this maximum allowable value for the transconductance is, with Cp= Cb + Cpar, see fig.(3+4) :

$$g_{m.\max} \leq \frac{1}{R_s} \times \frac{C_1 C_2}{C_p^2} \quad \text{.........(Rusznyak)..........Eq.7a}$$

## 2.3 Design considerations for a Pierce oscillator.

Based upon equation 7, a first estimation can be made about the oscillation condition for a certain combination of inverter gate and crystal. As an example we take the third overtone crystal as mentioned in the example above and the gate of a P87C750 microcontroller of which measured data are given in section 4.2, as crystal NR. 7.

The crystal electrical data:

| | | |
|---|---|---|
| Fundamental mode: | Fs0=13.055MHz | Rs=57E, Ca=12fF, L1=11.9mH, Cb=2.8pF |
| Third overtone: | Fs3rd=39.13MHz | Rs=30E, Ca=1fF, L1=16.8mH, Cb=3.3pF |

From the measurements in section 3 for the inverter gate it follows:

Transconductance $g_m$ = 2 to 5 mA/V (typical, not worst case!), output impedance $R_0$ = 3000 Ω
Bias resistance Rp= >1 MΩ.

Then with $C_o = C_b + C_{load} + C_{par}$ = 10pF and $C_1 = C_2$, with eq.7 the minimum value for $g_m$ should be:

Fundamental: $\omega_o.C_o$= 0.000820 and $g_{m\text{-}min}$ = 0.000153 + 0.000004 + 0.00033= 0.000487 S..

Third overtone: $\omega_o C_o$ = 0.00246 and $g_{m-min}$ = 0.000725 + 0.000004 + 0.00033= 0.001059 S.

Hence for both modes, with $g_{m-min}$= 0.002 S, the circuit will oscillate. To suppress the not wanted fundamental mode, special measures are required, as using an inductive trap filter or using extra damping across the circuit. This subject will be described in more detail in section 5.

From Eq.7 it can be derived, that with given $g_m$ and $R_o$, and with $R_p$>> 4$R_o$ the maximum value of the parallel capacitance $C_o$ of the crystal is inversely proportional with the root value of $R_s$. or

$$C_0^2 \le \frac{g_m - 1/R_o}{4\omega_o^2 R_s} \text{ ... or .... } C_o \le \frac{1}{2\omega_o}\sqrt{\frac{g_m - 1/R_o}{R_s}} \text{ ............................Eq.8}$$

For the crystal above at Fs=39MHz, $R_0$=3000Ω, $R_s$= 30E and $g_m$=1mA/V, we find $C_o$ < 9.6 pF.
With $R_s$=100Ω, $C_0$< 5.2 pF, with $R_s$= 10Ω , the allowed value for $C_o$= < 16.7pF.

From the values shown the conclusion will be, that for a 30MHz overtone crystal, the value of the load capacitance's are rather limited. With $C_0$ being below 10pF, proper values for $C_1$ and $C_2$ are also below 10pF.

## 2.4 Drive level and power dissipation

For most crystals a maximum drive level is specified, e.g.. <5mW. The drive level can be calculated from the power dissipation in the series resistance $R_s$ of the crystal . At resonance, the power dissipation is: Pd= $I_{Rt}^2$.$R_s$., with $I_{Rt}$= $V_x$ .$\omega_o$.$C_o$ and $V_x$ as the effective voltage across the crystal. At resonance the voltages across the crystal at points X1 and X2 are opposite in polarity and the maximum peak to peak value for both is about the supply voltage Vcc. Hence the effective value $V_x$ across $V_{Co}$ is Vcc/v2 or Vx=3.5V. So we find Pd= (3.5 $\omega_o C_o$ )$^2$.Rs, or

$$\text{Drive level .... } P_d = 483 \times f_s^2 \times C_o^2 \times R_s \text{ .........................................Eq.9.}$$

With the crystal from before at $f_s$=39MHz, $C_o$=10pF and $R_s$=30Ω, we get: $P_d$= 0.0022 Watt.

For applications requiring high stability, databooks advise drive levels between 5 µW and 1 mW.

- *Drive levels above 5 mW may seriously affect the frequency stability of the quartz crystal.*

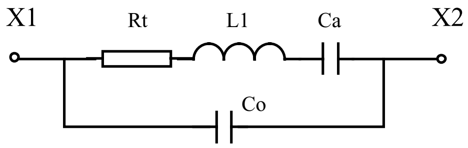
- *Resonators are much less sensitive for overdrive, they can be used at higher drive levels.*

Special attention should be taken with crystals, operating in the overtone mode at high frequencies far above 10MHz, because of the square influence of the resonance frequency on $P_d$, see Eq.9.

E.g.. for the A216 crystal, see section 4.2, nr.10. , with $F_s$= 35.25MHz, $R_s$ = 69 Ω and $C_o$= 20pF, Pd= 16.6 mW. For this case, the load $C_o$ should be reduced to a lower value, e.g. 10pF. Then, Pd= 4.1mW.

## 2.5 Oscillator start-up time

With the fundamental resonance model as shown in Fig.4, the oscillation start-up time can be calculated by assuming an initial noise current through the circuit and $V_{Co}$= Vin at t=0.




Then by using Laplace transformation, for the voltage across Co it can be derived:

$V_{Co} = V_{in} \times e^{-\alpha t} \sin \omega_o t$ , with $\alpha = R_t / 2L_1$ and $\omega_0 \cong 1/\sqrt{(L1Ca)}$ ......................Eq.10

To assure, that the voltage $V_{Co}$ increases, $R_t$ should be negative, with a sufficient high value of $g_m$. Then, for each $\Delta t = 1/\alpha$, $V_{Co}$ increases with a factor e=2.72. Hence, to increase $V_{Co}$ from its initial noise level of e.g.. 1μV to a logic level of 2.5V, for start up it will take:

$T_{start\text{-}up}$= ln(2.5/1e-6) =15 x 1/α sec. ..............................................Eq.11

The value of $R_t$ is given by Eq.5. Neglecting part $1/R_p$ with $4/R_p << 1/R_o$ and C1=C2, it follows:

$$R_t = R_s + \frac{1}{4\omega_o^2 C_o^2}\left(\frac{1}{R_o} - g_m\right)$$ ...........................................................Eq.12

<u>Some examples</u>:

**Crystal nr.7** , Fs=39MHz, Co=10pF, $g_m$=0.002mA/V, Ro=3000Ω, Rs=30Ω, L1=16.8mH.:
$R_t$=30 + 1/0.000024(1/3000- 0.002) = 30 - 69 = -39Ω. Hence α= $R_t$/2L = 1160.sec$^{-1}$.
So the start up time from 1μV to 2.5V amounts $T_{startup}$= 15 x 1/1160 = 0.013 sec.

**Crystal nr.4.** Fs= 32kHz, Co= 20pF, L1=9.3kH, Rs=15 to 50kΩ (from data)
For this type, $g_m$ should be reduced to keep its value below $g_{m.max}$ as given in Eq.7a.
From this equation we get $g_{mmax}$= 1/$R_s$ x (C1/C0)$^2$= < 100μS..
Further $g_{mmin}$= Rs.4$\omega_0^2 C_o^2$ = 15e3.4 = 1μS. Assume $g_m$= 15 μS and Ro=3.8MΩ, as given in the micro controller data handbook, IC20. Hence, $R_t$= 15e3 + (1/64e-12)(1/3.8e6 -15e-6) = 15e3 + 4100 - 234e3 = 215e3 Ω.
So $R_t$/2L=11.6 sec$^{-1}$, and the start-up time $T_{startup}$= 15 x 1/11.6 = 1.3 sec.

## 2.6 Practical hints

a) Testing : Do not use probe at gate input side, this will disturb biasing level.

b) At higher frequencies, the load capacitance's C1 and C2 need to be lower to limit drive level, e.g.. for a 30 MHz overtone crystal, with Rs=30Ω, C1=C2 = <10 pF.

c) With C1<C2, the circuits power consumption will be reduced. Higher input signal means higher dV/dT and shorter operation in threshold region.

d) For most micro controllers, the signal at the input of the oscillator gate is also used for the internal clock. Therefore take C1<C2 to assure that the input level is sufficient high.

e) For a third or fifth overtone crystal, use a tank filter to suppress the fundamental mode.

f) For high frequency ceramic resonators operating in overtone mode, in general no filter is required, these components have build in measures to suppress unwanted frequencies.

g) When calculating the minimum required value of the transconductance $g_m$ for start-up, take care that due to the drive level dependency, the value of the serial resistance Rs of the crystal at start-up may be much higher, from 10% higher up to ten times the specified or measured value at operating condition.

## 3. TRANSCONDUCTANCE MEASUREMENT

The XTAL oscillators, described in this note are of the type Pierce and operate with the internal inverter stage of the microcontroller. For calculations, such a gate amplifier can be replaced in the simulation circuit with one of the simplified diagrams of Fig.5.

In the current source equivalent, the output current $I_o$ is defined by the transconductance $g_m$ of the gate and the input voltage $V_{in}$ as: $I_o = g_m \times V_{in}$. For a CMOS gate as used here the input resistance Ri can be neglected. In most cases, the output impedance $R_o$ is much higher than the output load resistance and the output can be seen as a real current source with $I_o = g_m \cdot V_{in}$.

In the voltage source equivalent, the current source is replaced by a voltage source $e_o = g_m \cdot V_{in} \cdot R_o$. Again, with $R_o \gg R_{load}$, the output behaves as a current source, $g_m \cdot V_{in}$.

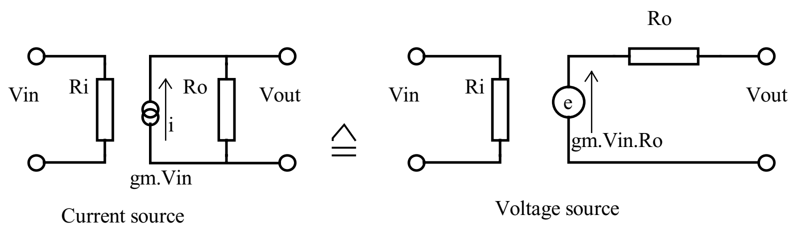



Fig. 5. Gate equivalent circuit

Fig.6 shows a standard test set up to measure the transconductance of the CMOS gate, as used for CMOS products like the HCU04. With a fixed input voltage at 100kHz, $V_{out}$ was measured and then the transconductance can be calculated as:

$$g_m = \frac{I_o}{V_{inp}} = \frac{V_{out}}{R_1 \times V_{inp}} \quad \text{.....................Eq.13.}$$

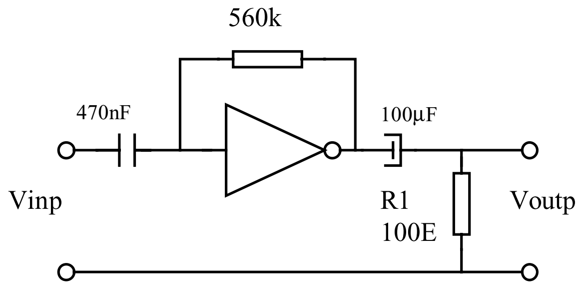



Fig.6 Test circuit transconductance

Test results with some microcontroller devices and the calculated values for the transconductance are listed in the following table.

**TABLE 1 Vinp=400mV at 100kHz, Rl= 100Ω.**

| Device: | Vcc=5V | | Vc=4V | | Vcc=3V | |
|---|---|---|---|---|---|---|
| | $V_{out}$ | $g_m$ | $V_{out}$ | $g_m$ | $V_{out}$. | $g_m$ |
| P87C750, EBFFA,16 | 200 mV | 5 mA/V | 180 mV | 4.5 mA/V | 120 mV | 3 mA/V |
| P87C750, PBFFA,40 | 200 ,, | 5 ,, | 170 | 4.25 ,, | 100 ,, | 2.5 ,, |
| EP87C750-4N | 180 ,, | 4.5 ,, | 150 ,, | 3.75 ,, | 100 ,, | 2.5 ,, |
| P87C750 EBPN | 210 ,, | 5.25 ,, | 170 ,, | 4.25 ,, | 120 ,, | 3 ,, |
| S87C751 4F24 | 130 ,, | 3.25 ,, | 100 ,, | 2.5 ,, | 60 ,, | 1.5 ,, |
| P87C748 EBFFA | 200 ,, | 5 ,, | 160 ,, | 4 ,, | 100 ,, | 2.5 ,, |
| P87C750 PBFFA | 200 ,, | 5 ,, | 150 ,, | 3.75 ,, | 100 ,, | 2.5 ,, |

The table shows, that at Vcc=5V, the transconductance amounts 3 to 5mA/V. At Vcc=3V, a minimum value of $g_m$=1.5 mA/V was found, so for calculation, use $g_{m\text{-}min}$= 1 mA/V..

The value of the output impedance $R_o$ may influence the effective value of $g_m$ if not $R_0$>> $R_{load}$. Therefore the value of $R_0$ was also measured with the test circuit Fig.7.

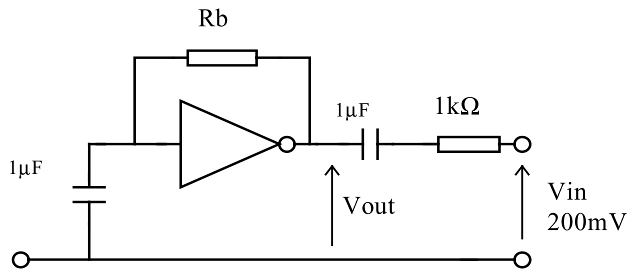



Fig.7 Test circuit output impedance

A signal $V_{in}$ is supplied to the output of the gate via a 1 kΩ series resistance and a decoupling capacitor of 1μF. The gate input is kept quiet by a capacitor to ground to prevent any input signal passing from the output through Rb. With Rb >> 1kΩ it follows:

$$\frac{V_{in}}{V_{out}} = \frac{1000 + R_o}{R_o}, or\ R_o = 1000\left(\frac{V_{out}}{V_{in} - V_{out}}\right) \quad \text{.....................................Eq.14}$$

With $V_{in}$ = 200mV at 100kHz, following values were found:

**TABLE 2 Gate output impedance, Vin= 200 mV.**

| | $V_{out}$ | $R_o$ . |
|---|---|---|
| P87C750, EBFFA,16 | 154 mVolt | 3348 Ω |
| P87C750, PBFFA,40 | 156 ,, | 3545 ,, |
| EP87C750-4N | 160 ,, | 4000 ,, |
| P87C750 EBPN | 150 ,, | 3000 ,, |
| S87C751 4F24 | 172 ,, | 6142 ,, |
| P87C748 EBFFA | 158 ,, | 3760 ,, |
| P87C750 PBFFA | 164 ,, | 4555 ,, |

Note that $R_0$ is between 3 and 6 kOhm, which is sufficient higher than the value of R1=100Ω in fig.6. to have no influence on the transconductance value.

## 4. XTAL CIRCUIT PARAMETERS

### 4.1 Measuring method

The crystals mentioned in this report are tested on a HP 4194A impedance/phase analyser to determine the equivalent electrical data of the crystal, required for simulation of the oscillator circuit.

To carry out the measurements, following short list of test and adjustment procedures of the instruments knobs may be of assistance to start a first measurement. The object is to get an impedance/phase curve as function of frequency around the resonance points and from this to derive the main equivalent circuit parameters at such a point.

Used instrument: HP 4194A Impedance/gain-phase analyser. The equipment should be turned on fifteen minutes before to ensure warming up.

As example, the measurement was done with a 35.25 overtone crystal.

The underlined items are settings by means of pressing the mentioned button of the item block..

1) Check IGPB connection with plotter (Here a HP thinkjet)

2) Check plotting mode: Menu >> more menus >> HPIB define >> talk only >> return.

3) menu >> Function >> impedance >> |Z| - Φ

4) menu >> sweep >> lin sweep >> sweep up.

5) parameter >> start >> (e.g.) 20 MHz >> stop >> 40MHz >> osc level >> 0.1 Volt.

6) menu >> compen >> zeroshrt >> zero open .>> shrtofson >> openofson.

7) Now insert the crystal. Then with sweep mode >> repeat, start testing.

8) menu >> display >> rect X A&B

(sub) menu 1/3 A scale log >> auto scale A
2/3 B scale lin >> auto scale B
3/3 unit on >> grtcl on

9) The display should show now a |Z| and Φ curve from 20 to 40 MHz. Then decrease the frequency range around a resonance point.

10) parameter >> start >> 34 MHz >> stop >> 36 MHz >> start >> 35.2 MHz >> stop >> 35.4 MHz

11) Repeat auto scale A and B, step 8), menu 1/3 and 2/3.

12) further decrease range around Fs=35.25 MHz >> start >> 35.24 MHz >> stop >> 35.26 MHz.
Note: before plotting, pre-set the frequency range to a range of 2, 5 or 10 units for easier read out.

13) Plot both the graphs >> copy

14) Calculating equivalent circuit parameters around the resonance point:
Menu >> more menus >> eqvckt >> CKT E >> calc EQV para >> (plot) >> copy >> display.

15) Both the |Z| and Φ curves as the values of the equivalent circuit components are plotted now on one A4 page, as shown in the appendix 1 for 10 different crystals and resonators.

16) Table3 in next section 4.2 gives a survey of the measured data values of these devices.

## 4.2 Measuring results.

**TABLE 3** Equivalent circuit parameters of some XTALS, see also appendix 1.

| Nr. | Type | Mode | Fs=1/√LC | L | Ca | Rs | Cb |
|---|---|---|---|---|---|---|---|
| 1 | Murata, 3p, CST12.0 T | Fund. | 12 MHz | 45.6 µH | 4.17 pF | 6.10 Ω | 40.3 pF |
| 2 | Murata, 2p, CSA12MTZ | Fund. | 12 MHz | 47.3 µH | 4.04 pF | 5.28 Ω | 27.0 pF |
| 3 | Murata, 2p, CSA16MXZ | Fund. | 16 MHz | 602 µH | 165 fF | 11.1 Ω | 13.1 pF |
| 4 | XTAL, 32.768 kHz | Fund. | 32.78 kHz | 9.3 kH | 2.54 fF | ---- | 1.28 pF |
| 5 | XTAL, 12 MHz, Ph. | Fund. | 12 MHz | 8.47 mH | 20.8 fF | 8.20 Ω | 4.85 pF |
| 6 | XTAL, 16 MHz | Fund. | 16 MHz | 13.05mH | 7.58 fF | 10.9 Ω | 2.14 pF |
| 7a | XTAL 39.13 MHz | Fundam. | 13.06 MHz | 11.9 mH | 12.5 fF | 57.8 Ω | 2.86 pF |
| 7b | ,, overtone | 3rd overt | 39.13 MHz | 16.8 mH | 0.98 fF | 29.6 Ω | 3.24 pF |
| 7c | ,, spurious | 3rd, spur. | 39.24 MHz | 36.6 mH | 0.45 fF | 72 Ω | 2.81 pF |
| 7d | ,, 2nd spurious | 3rd, 2spur | 39.38 MHz | 113 mH | 0.144fF | 290 Ω | 2.79 pF |
| 8a | Murata, CSA36 00MXZ | Fund. ? | 12 MHz | -- | -- | -- | -- |
| 8b | ,, | 3rd overt. | 36.0 MHz | 259 µH | 75.3 fF | 17.4 Ω | 8.70 pF |
| 8c | ,, | 3rd, spur. | 36.4 MHz | 1.64 mH | 11.7 fF | 177 Ω | 3.69 pF |
| 9a | Murata, CSA39.00MXZ | Fund.? | 11.05 MHz | -- | -- | -- | -- |
| 9b | ,, 3rd overtone | 3rd overt. | 39.00 MHz | 209 µH | 80.0 fF | 13.9 Ω | 9.81 pF |
| 9c | ,, spurious | 3rd, spur. | 39.3 MHz | 1.39 mH | 11.8 fF | 124 Ω | 2.78 pF |
| 10a | XTAL, IQD, A216 | Fund.+3rd | | | | | |
| 10b | ,, 35.25 MHz | Fund. | 11.77 MHz | 22.1 mH | 8.28 fF | 302 Ω | 1.78 pF |
| 10c | ,, overtone | 3rd overt. | 35.256MHz | 29.3 mH | 0.695 fF | 69.1 Ω | 2.19 pF |
| 10d | ,, XTAL+ 10pF//. | 3rd overt | 35.251MHz | 29.2 mH | 0.697 fF | 69.6 Ω | 12.24pF |
| 10e | ,, spurious | 3rd, spur. | 35.32MHz | 112 mH | 0.181 fF | 282 Ω | 2.03 pF |

This table includes several test results for a 35MHz, third overtone XTAL from IQD (type A216) also used for the clock oscillator circuit for the 87C750 microcontroller.

After some analysis of the XTAL equivalent circuit parameters of the available XTAL samples and the typical gain and output characteristics of the microcontrolller gate, the next chapter of this application note describes several circuit proposals for the P87C750 circuit to obtain optimum start up action and to prevent oscillation in the undesirable fundamental mode.

## 5. CRYSTAL OVERTONE OSCILLATOR

This chapter gives some application proposals for 3rd overtone XTAL circuits, used for the clock generation section of microcontrollers .

For these applications, precautions should be taken to prevent oscillation in the fundamental mode and to force the overtone mode.

Three proposals are given:

1) Higher damping of the fundamental mode by applying a low ohmic resistor across the gate.

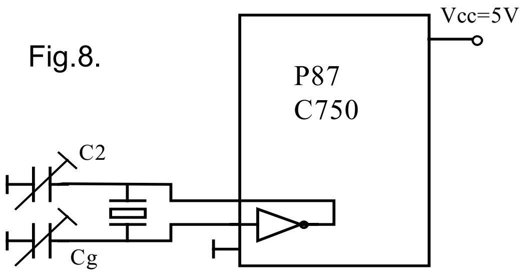
2) Connection of an inductor L between gate output and ground to trap the fundamental mode

3) Connection of such an inductor between the gate input and ground.

For clock frequencies in excess of 15 to 20 MHz, standard XTALs are not preferred or available and the overtone oscillation mode should be used.

Following some circuit possibilities for such a XTAL for 39 MHz clock generation for a P87C750 microcontroller are given.
A circuit diagram of the oscillator with the internal gate of the micro is givens in Fig. 8.

Fig.8.




The circuit above, together with the 3rd overtone XTAL, only oscillates at its fundamental mode. Hence measures are required to force the circuit into the third overtone mode.
The equivalent XTAL circuit data, as shown in Fig.9b, are listed below for the fundamental mode and for the third overtone.

**XTAL 39.13 MHz 3rd overtone**

| Mode | Fseries | L | Ca | Rs | Cb |
|---|---|---|---|---|---|
| First | 13.05 MHz | 11.9 mH | 12.5 fF | 57.6 Ω | 2.84 pF |
| Third | 39.13 MHz | 16.4 mH | 1.0 fF | 30.3 Ω | 3.34 pF |
| Third (Spur.) | 39.24 MHz | 33.6 mH | 0.45 fF | 72 Ω | 2.8 pF |

For this XTAL, the ratio Rs_1/Rs_3 = 57.6 / 30.3 = 1.9.

For the A216, Rs_1/Rs_3= 4.3 See chapter 4
Based upon these results for the XTAL parameters, next section will discuss the results of some practical tests with the XTALs used with the microcontroller circuit.

## 5.1 Forcing overtone mode by frequency dependent damping.

This circuit uses a low value resistance between gate output and input. See Fig.2a

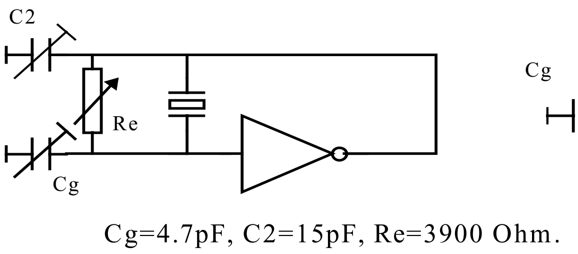



Fig.9a

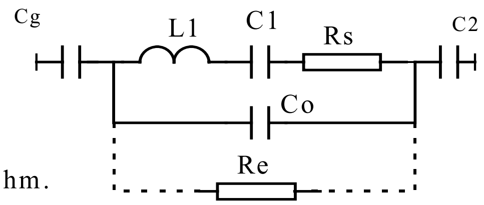



Fig.9b

Forcing the third overtone mode can be achieved by connecting a low ohmic resistor Re in parallel with the XTAL. Fig. 2b shows the equivalent XTAL circuit diagram with Re connected and Cp as the total parallel capacitance to the XTAL, Cp= Co + CgC2/(Cg+C2).
This circuit will oscillate either in fundamental mode or in 3rd overtone, if the gate amplifier compensates for the damping by resistors Rs and external Re. But damping influence of Re is much higher for the fundamental mode, which can be shown by replacing Re into the series loop of L1/C1/Rs and Co as Re_s.

This delivers : $R_{e\_s} = \dfrac{1}{\omega^2 Cp^2 R_e}$

This equation shows that Re has a 9 times lower damping value into the series resonance circuit at the requested overtone frequency.
With the above specified XTAL and the gate of a microcontroller P87C750 (PBFFA), this circuit has been tested and proved to oscillate at the third overtone at all conditions with the following circuit values:

XTAL: 39.13MHz, Cg=4.7pF, C2=15pF, Re= 3900 Ohm.

## 5.2 Connection of a inductive trap filter to the output.

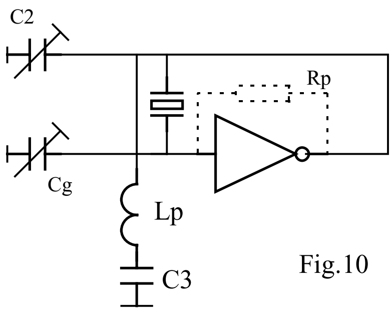



Fig.10

Cg=10 pF
C2=27 pF
Lp= 1.5 microH.
C3= 4700 pF

In this circuit, the fundamental mode is suppressed by connecting an inductance L to the output of the gate amplifier. Together with a part of the capacitance C2 at the output, this inductor will perform a high impedance parallel circuit at the overtone frequency and a low inductive impedance at the fundamental one. The capacitance C3 is a DC decoupling capacitor for the gate bias voltage, sourced by the (internal) resistor Rp. With Lp=1.5 microH, resonance at 39 MHz occurs with C2= $1/(\omega^2 L)$ = 11pF. Hence, the value of C2 should be >11pF. In the practical test, correct overtone oscillation was obtained with the following circuit values:

Cg= 10 pF, C2= 27 pF, Lp = 1.5 microH. and C3= 4700 pF.

### 5.3 Inductive filter at the input.

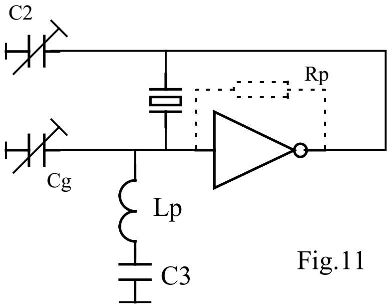



Fig.11

Cg = 10 pF
C2 = 10 pF
Lp = 1.5 microH.
C3 = 4700 pF

Here the inductive trap filter is connected at the input side. Optimum circuit values for this case were: Cg=10pF, C2=10pF, L1=1.5microH and C3=4700pF.
Hence at 39MHz the capacitance Cg is fully tuned out by Lp, the only capacitance left at the input is the input stray and pin capacitance, in the order of 5pF.

**Note.**

The circuit values given above are the optimal values for the applied XTAL as specified above and a typical microcontroller oscillator gate, with a measured transconductance, at Vcc=5V., of around 4.5 mA/V.

Other values may be required with other devices.

For these excersices several measurements have been done to determine the properties of the used XTAL and the current gain (transconductance) of the oscillator gate of the microcontroller. The parameters of the crystal and the inverter-gate together determine the correct oscillation mode of the circuit and its start-up behaviour.

### 5.4 Drive level.

At high frequencies, drive levels are increased due to the low impedance of Co. The drive level is given by the power, dissipated in the series resistance Rs of the XTAL. Hence Pd= $I_S^2$ . Rs. At resonance, the current $I_S$ in the series branch is equal to the current through Co, the total parallel capacitance in the circuit, see Fig.2. At Vcc=5V, the peak to peak voltage at both sides of the XTAL is 5 Volts, but inverted. Hence the peak voltage across the XTAL and Co is 5Volt and the effective voltage Vx is 5V/v2, or Vx=3.5V. Then, $I_S$= Vx.ωCo, or Pd= $(Vx.\omega Co)^2$. Rs.

With Co=$C_{load}$= 18pF, ω= 2π.35e6 and Rs= 69Ω , Pd= $(3.5x2\pi 35e6x18e\text{-}12)^2$.69 = 13 mW. This is far above the recommended drive level as specified for the A216 XTAL, Pdmax=500μW.

Hence Pd should be reduced, by selecting a lower value for $C_{load}$. With C1=C2=4.7pF, $C_{load}$=3pF, and the value of Co is about 5pF. This will reduce Pd to around 1mW, which would be a safe value for Pd to prevent intensified ageing.

### 5.5 Conclusion.

From the practical test with a typical sample of an overtone XTAL and a 87C750 microcontroller, it was found that the specified load capacitance is a too high value to get correct working of the clock oscillator. With the given circuits, a good start up condition in the desired overtone mode was obtained with a reduced load capacitance, e.g. C1= 4.7pF at the input and C2=4.7pF (or up 10pF) at the output side of the XTAL,.

For worst case operation with suppression of the fundamental mode of operation, it may be recommended to use an inductive trap filter for the low frequency, e.g.by connecting L=1.5µH , in series with Cs=4.7nF, from output to ground with C1=4.7pF and C2= 22pF.

## 6. MURATA CERAMIC RESONATORS

An alternative to the traditionally used quartz crystal resonator is the ceramic resonator. The disadvantage of the ceramic resonator is the lower frequency accuracy. If an microcontroller application needs for some reason a very accurate timing then a quartz crystal is usually the only option. For many microcontroller applications timing issues may however be less critical and the ceramic resonator will be an excellent replacement.

A ceramic resonator has several strong advantages:

- lower price

- not sensitive for drive level

- no additional components required for higher frequency (overtone).

- better (mechanical) shock resistance

Microcontrollers are also available for very low cost applications requiring suitable resonators. The muRata company has an excellent reputation in ceramic technology and is offering several ranges of resonators.

For many IC's a suitable resonator can be found in the product programme. Following issues are dedicated to 8-bit microcontroller types.

### 6.1 Resonator types for 8400 and 8051 microcontrollers

Following table lists a number of PHIILIPS SEMICONDUCTOR microcontroller types that were evaluated by muRata with muRata type resonators. These resonator types provide reliable oscillation with the microcontroller types involved.

An external feedback resistor (Rf) that is normally required for an feedback when using an unbuffered CMOS gate can be omitted in most cases because it is integrated in most microcontroller oscillator inverters.

| MICROCONTROLLER | CERALOCK | CL1[pF] | CL2[pF] | Rf[ohm] | Rd[ohm] |
|---|---|---|---|---|---|
| 87C51FA | CSACS24.00MX040 | 5 | 5 | Open | 0 |
| 87C51FA | CSTCS24.00MX0H1 | 5 | 5 | Open | 0 |
| 87C750 | CSTCC6.00MGA0H6 | 0 | 0 | Open | 0 |
| P80C52 | CSA12.0MTZA | 30 | 30 | Open | 0 |
| P80C52 | CST12.0MTWA | 30 | 30 | Open | 0 |
| P80C851FBA | CSTCS12.0MT | 0 | 0 | Open | 0 |
| P80CL51 | CSTCC3.68MG0H6 | 0 | 0 | Open | 0 |
| P80CL51HFT | CSB1000J | 100 | 100 | Open | 5.6k |
| P80CL782 | CSAC6.00MGC | 30 | 30 | Open | 0 |
| P80LC51HFP | CSA10.0MTZ | 30 | 30 | Open | 0 |
| P80LC51HFP | CSA3.58MG | 30 | 30 | Open | 0 |
| P80LC51HFP | CST10.0MTW | 30 | 30 | Open | 0 |
| P80LC51HFP | CST3.58MGW | 30 | 30 | Open | 0 |
| P80LC51HFT | CSA10.0MTZ | 30 | 30 | Open | 0 |
| P80LC51HFT | CSA3.58MG | 30 | 30 | Open | 0 |
| P80LC51HFT | CST10.0MTW | 30 | 30 | Open | 0 |
| P80LC51HFT | CST3.58MGW | 30 | 30 | Open | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | P83C575EHP | CST6.29MGWHA | 30 | 30 | Open | 0 |
| | P83C749EFPN | CSA16.00MXZA040 | 15 | 15 | Open | 0 |
| | P83C750 | CSA12.0MTZ | 30 | 30 | 1M | 0 |
| | P83C750 | CST12.0MTW | 30 | 30 | 1M | 0 |
| | P84C84X | CSA10.0MTZ | 30 | 30 | Open | 0 |
| | P84C84X | CST10.0MTW | 30 | 30 | Open | 0 |
| | P87C52 | CSA24.00MXZ040 | 10 | 10 | 1M | 0 |
| | P87C52EBPN | CSA16.00MXZ040 | 15 | 15 | Open | 0 |
| | P87C52EBPN | CSA20.00MXZ040 | 10 | 10 | 1M | 0 |
| | P87C54IBAA | CSA12.0MTZ | 30 | 30 | Open | 0 |
| | P89CE558EFB | CST12.0MTWA | 0 | 0 | Open | 0 |
| | PCF80C552-4 | CST11.0MT020 | 30 | 30 | Open | 0 |
| | PCF80C562 | CSACS11.0MTA | 30 | 30 | Open | 0 |
| | PCF84C00B | CSA6.00MG097 | 0 | 0 | Open | 0 |
| | PCF84C12 | CSA3.58MG310VA | 0 | 0 | Open | 0 |
| | PCF84C21 | CSA3.00MG | 30 | 30 | 1M | 0 |
| | PCF84C21 | CST3.00MGW | 30 | 30 | 1M | 0 |
| | PCF84C22 | CSA6.00MGA013 | 0 | 0 | Open | 0 |
| | PCF84C270 | CSA3.58MG310VA | 0 | 0 | Open | 0 |
| | PCF84C444 | CSA8.00MTZ | 30 | 30 | Open | 0 |
| | MICROCONTROLLER | CERALOCK | CL1[pF] | CL2[pF] | Rf[ohm] | Rd[ohm] |
| | PCF84C81AP | CST6.00MGW | 30 | 30 | Open | 0 |
| | S87C51FB | CSA12.0MTZ | 30 | 30 | Open | 0 |
| | S87C51FB | CST16.00MXW0C3 | 0 | 0 | Open | 0 |
| | S87C652 | CSA10.0MTZ | 30 | 30 | Open | 0 |
| | S87C652 | CSACS18.43MX040 | 10 | 10 | Open | 0 |
| | S87C654 | CSA12.0MTZ | 30 | 30 | Open | 0 |
| | S87C751 | CSA3.58MG | 30 | 30 | Open | 0 |
| | S87C751 | CSAC11.9MT | 30 | 30 | Open | 0 |
| | S87C751 | CSACS16.00MX040 | 15 | 15 | Open | 0 |
| | S87C751 | CST3.58MGW | 30 | 30 | Open | 0 |
| | S87C751 | CSTCS16.00MX0C3 | 15 | 15 | Open | 0 |

## 6.2 Resonator types for the P87CL884

Recently the P87CL884 was also evaluated by muRata for several frequencies and resonator giving the following results:

### 6.2.1 1...8 Mhz types

| | | | |
|---|---|---|---|
| 1.00MHz CSB1000J | with CL1=CL2 = 100pF | Rd = 4.7kOhm | Rf open |
| 2.00MHz CSA2.00MG | with CL1=CL2 = 30pF | Rd = 0 | Rf open |
| 2.00MHz CST2.00MG | with CL1=CL2 = 30pF(internal) | Rd = 0 | Rf open |
| 3.58MHz CSA3.58MG300ABC | with CL1=CL2 = 30pF | Rd = 0 | Rf open |
| 3.58MHz CST3.58MGW300ABC | with CL1=CL2 = 30pF | Rd = 0 | Rf open |
| 4.00MHz CSA4.00MG | with CL1=CL2 = 30pF | Rd = 0 | Rf open |
| 4.00MHz CST4.00MGW | with CL1=CL2 = 30pF(internal) | Rd = 0 | Rf open |
| 8.00MHz CSA8.00MT093 | with CL1=CL2 = 30pF | Rd = 0 | Rf open |
| 8.00MHz CST8.00MTZ093 | with CL1=CL2 = 30pF(internal) | Rd = 0 | Rf open |

### 6.2.2 12...20 Mhz resonators

With these frequencies the oscillator signal level was so small that no signal could be detected at the clock out pin (pin18).

For this reason it is NOT recommended to use ceramic resonators on these frequencies.

### 6.2.3 3.58 Mhz resonators

Resonator with frequency of 3.58 Mhz are in the 300 series. These series are optimised for use with DTMF IC's. These resonators have smaller tolerances on their frequency to match the DTMF specification requirements.

## 6.3 Resonator types for the P80C54/P87C51RA+

The PHILIPS SEMICONDUCTOR microcontroller products are continually improved by new technologies.

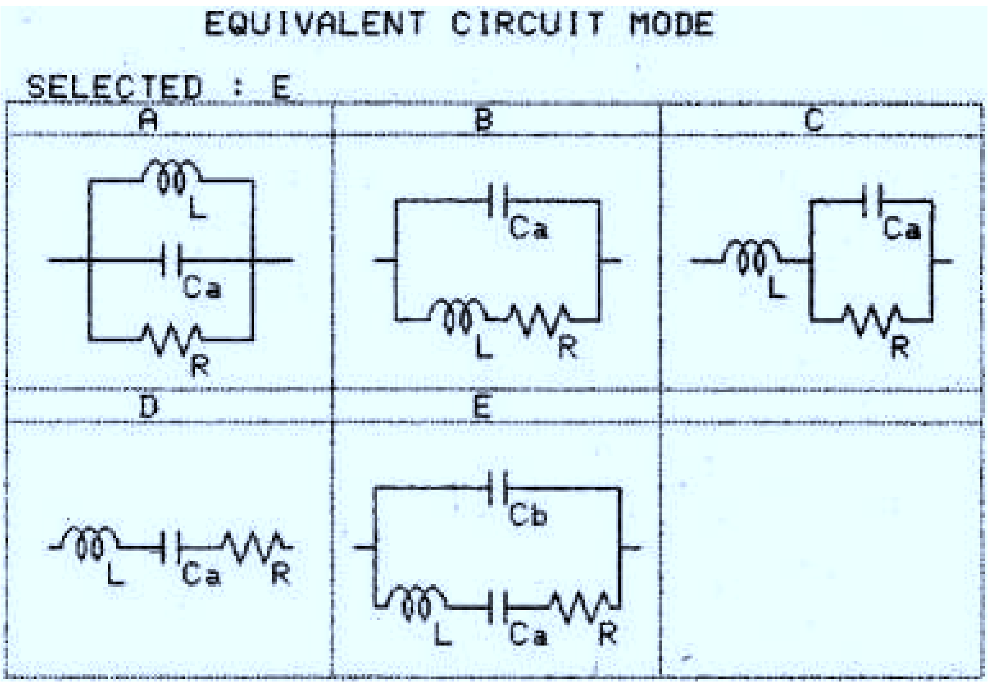
The latest versions of the 80C54 and the 87C51RA+ were also evaluated by muRata with the resonator types: CSA16.00MXZ040 and CST16.00MXW0C3. Results are documented in a report by muRata (see ref. 6)

## 7. REFERENCES

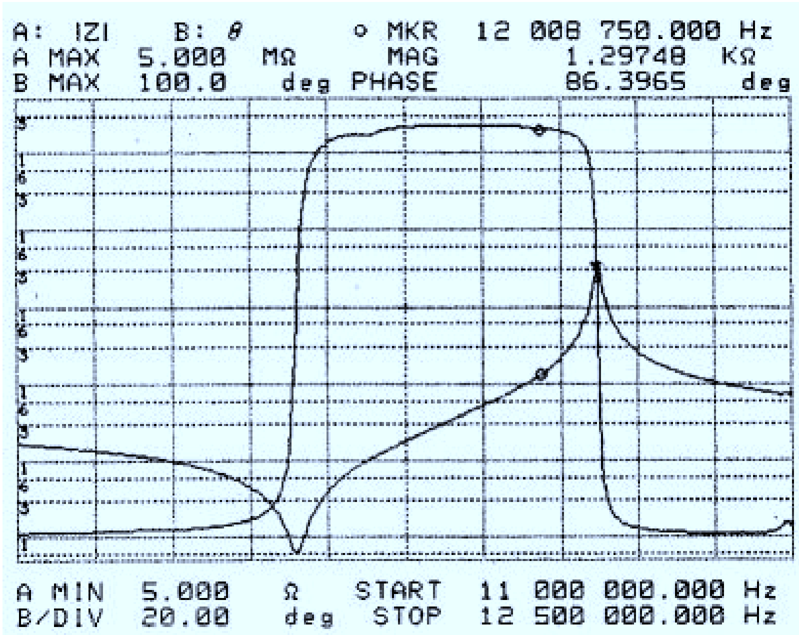
1. AN 96103. XTAL oscillators on 8-Bit microcontrollers. Application note, André Pauptit.
2. ETT8710 Specification of Quartz and ceramic resonators. Lab. report, Jaap Mulder.
3. Techn. note: Start-up conditions for Quartz crystal and PXE oscillators. Nov. 1989. W.Thommen
4. IEEE Tr. on circuits. Start-up condition of CMOS oscillators. march 87, no.3. Andreas Rusznyak.
5. AN 456. Using LC oscillators with Philips microcontrollers. William Houghton.
6. Technical Data of Ceramic Resonator, TCD No.TCD-97-5o04, Toyama muRata manufacturing Co,Ltd.

### 7.1 Appendix

The following equivalent circuit diagrams apply to all figures in the appendix. The relevant values for R, L, Ca and Cb are listed there (R in Ohm, L in µH and C in pF).



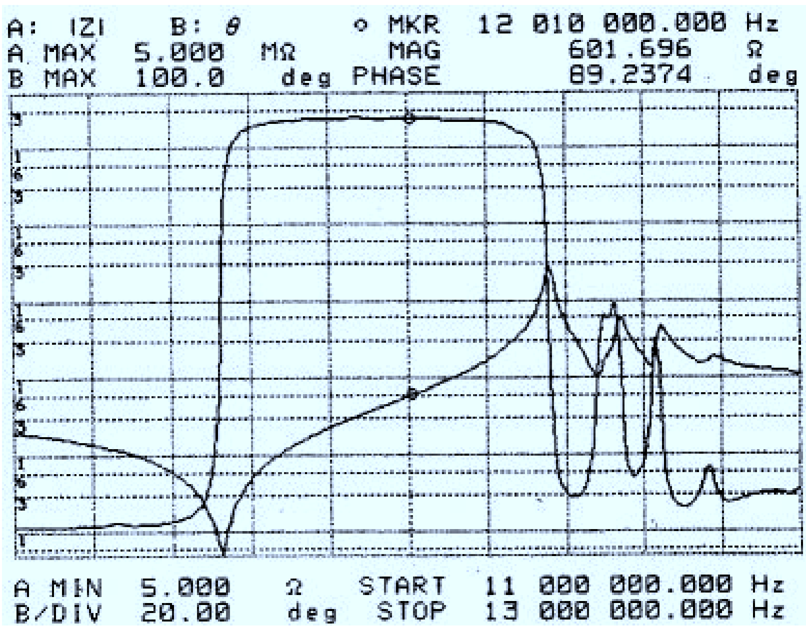

App. 0




App 1 Resonator Murata, 3 pins, CST 12.0T, $F_S$=12.0 MHz

R = 6.10535 Ω Ca = 4.17542 pF

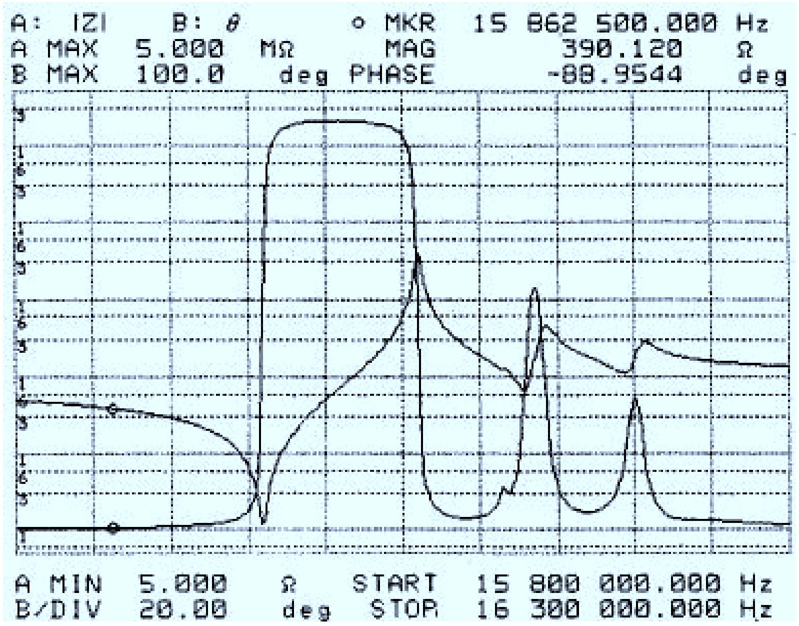
L = 45.5682 µH Cb = 40.2569 pF




App 2 Resonator Murata, 2 pins, CSA 12.0MTZ, $F_S$=12.0 MHz

R = 5.28065 Ω Ca = 4.03804 pF

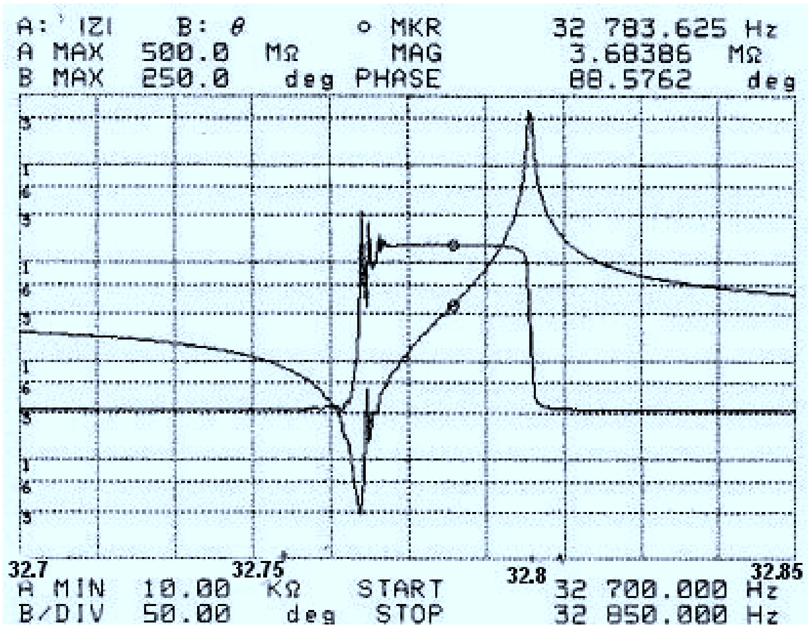
L = 47.2664 µH Cb = 27.0237 pF




App 3 Resonator Murata, 2 pins, CSA 16.0MX, $F_S$=16.0 MHz

R = 11.0840 Ω Ca = 165.139 fF

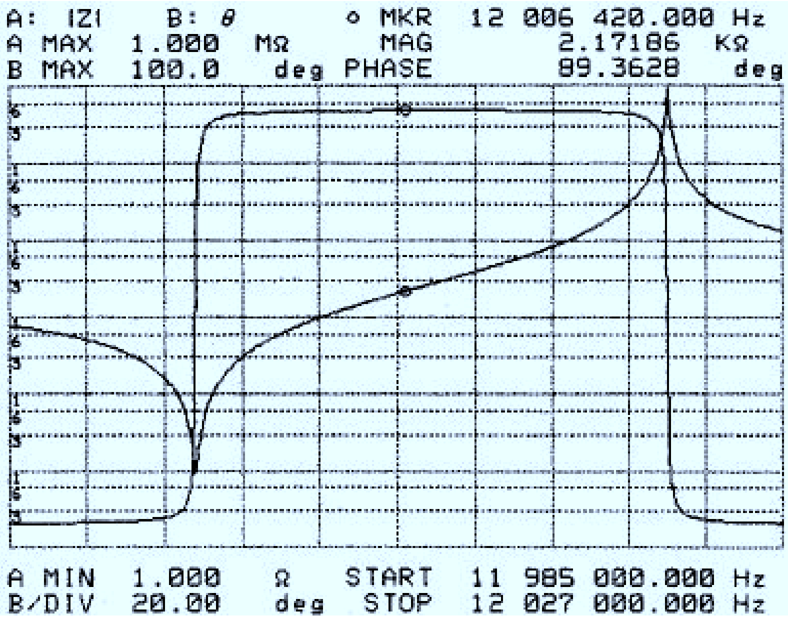
L = 602.177 µH Cb = 13.0631 pF




App 4 Resonator 32.768 kHz

R = 0 Ω Ca = 2.54110 fF

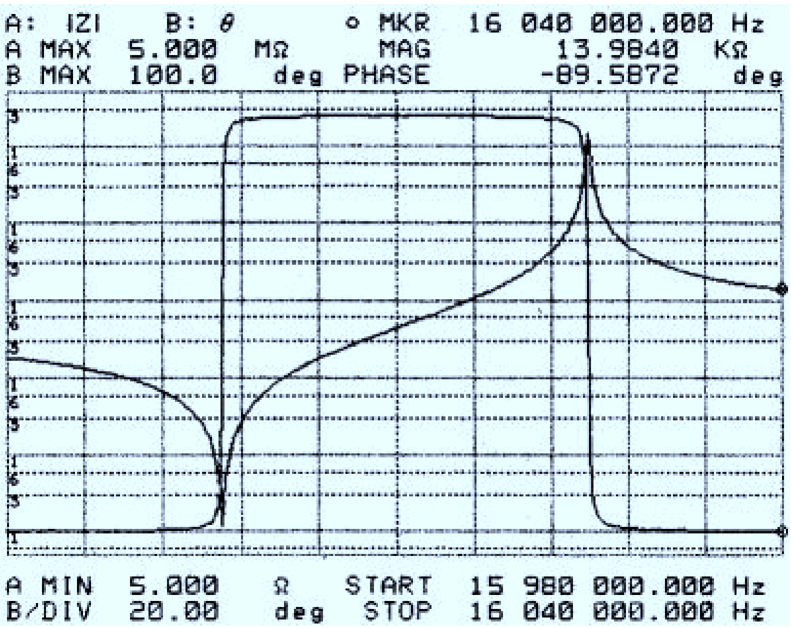
L = 9.28503 kH Cb = 1.27633 pF




App 5 Crystal Philips, 12000.000 code 4631.024, $F_s$=12 MHz

R = 8.19832 Ω Ca = 20.7893 fF

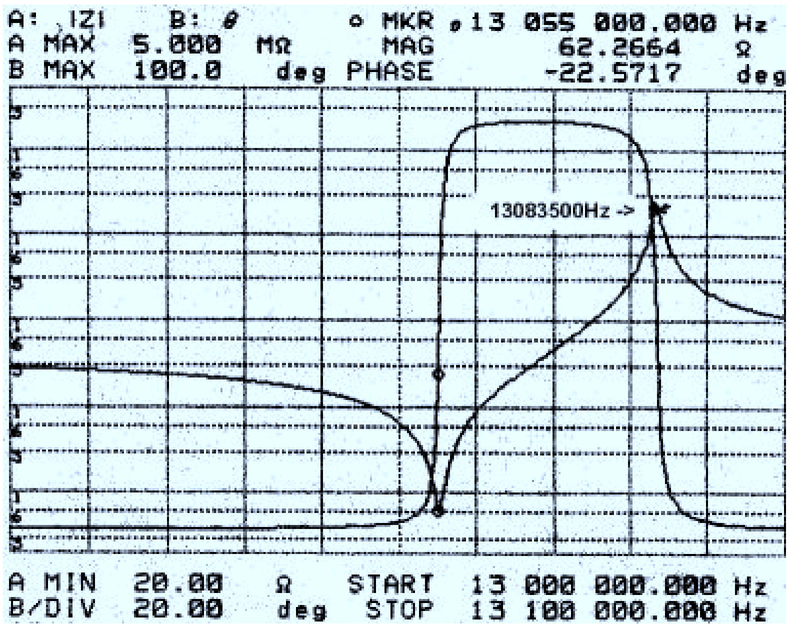
L = 8.46836 mH Cb = 4.85404 pF




App 6 Crystal Philips, 16000.000 code 200002.017, $F_s$=16 MHz

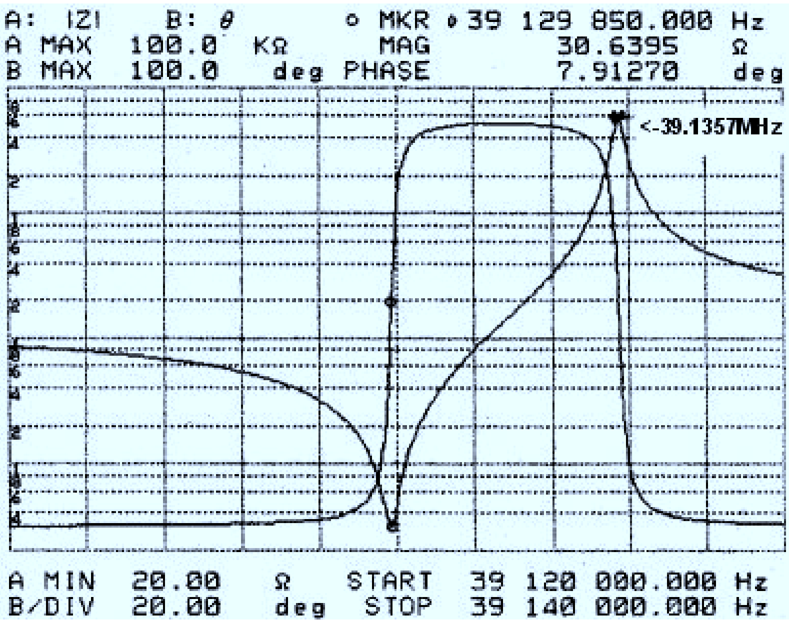
R = 10.8692 Ω Ca = 7.58601 fF

L = 13.0490 mH Cb = 2.13657 pF



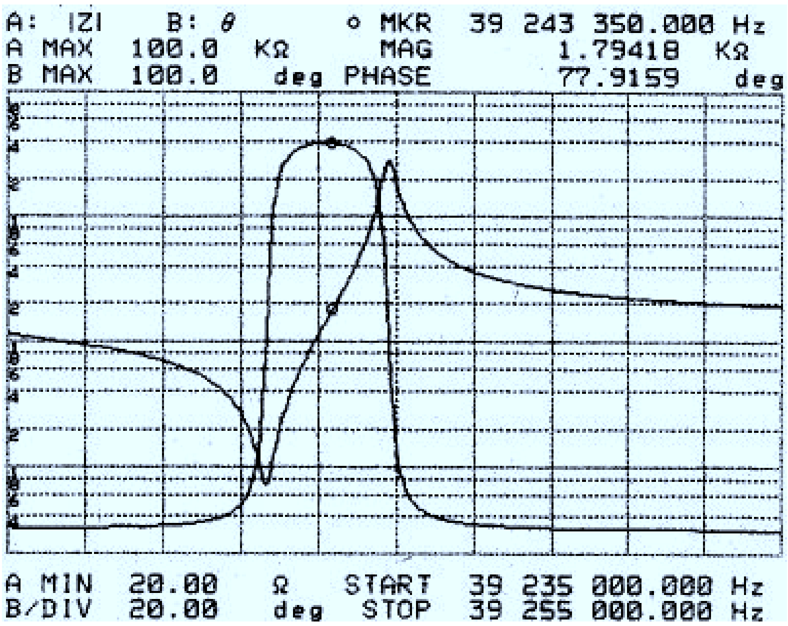

<u>App 7a</u> Crystal Philips 3rd overtone. Code 02370991. $F_s$=39.130000 MHz
Response at fundamental frequency, F=13.05 MHz

| | |
|---|---|
| R = 57.8032 Ω | Ca = 12.4900 fF |
| L = 11.8991 mH | Cb = 2.86327 pF |




<u>App 7b</u> Crystal Philips $3^{rd}$ overtone. Code 02370991. $F_s$=39.130000 MHz
Response at $3^{rd}$ overtone, F=39.13 MHz

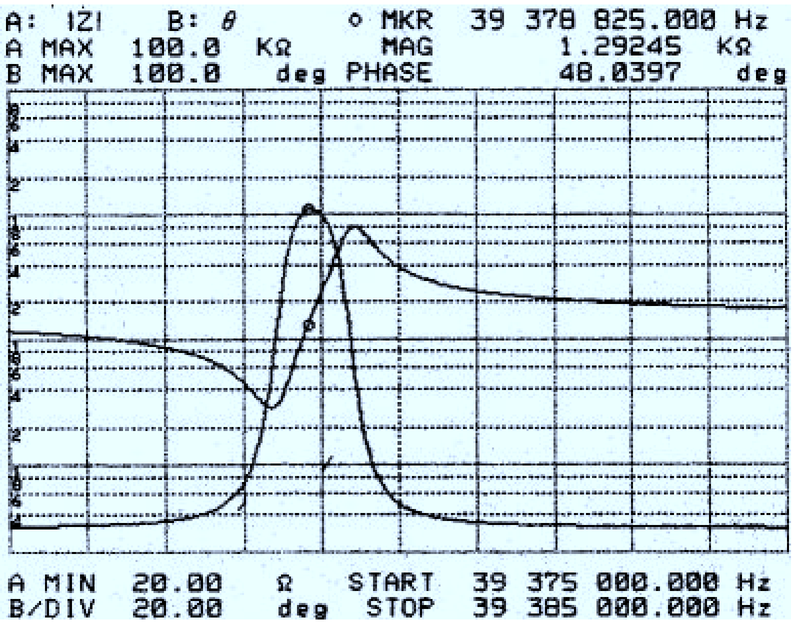
| | |
|---|---|
| R = 29.5671 Ω | Ca = 0.983545 fF |
| L = 16.8202 mH | Cb = 3.24510 pF |




App 7c Crystal Philips 3rd overtone. Code 02370991. $F_s$=39.130000 MHz
Response 3rd overtone frequency, spurious F=39.24 MHz

R = 72.0326 Ω Ca = 0.448987 fF

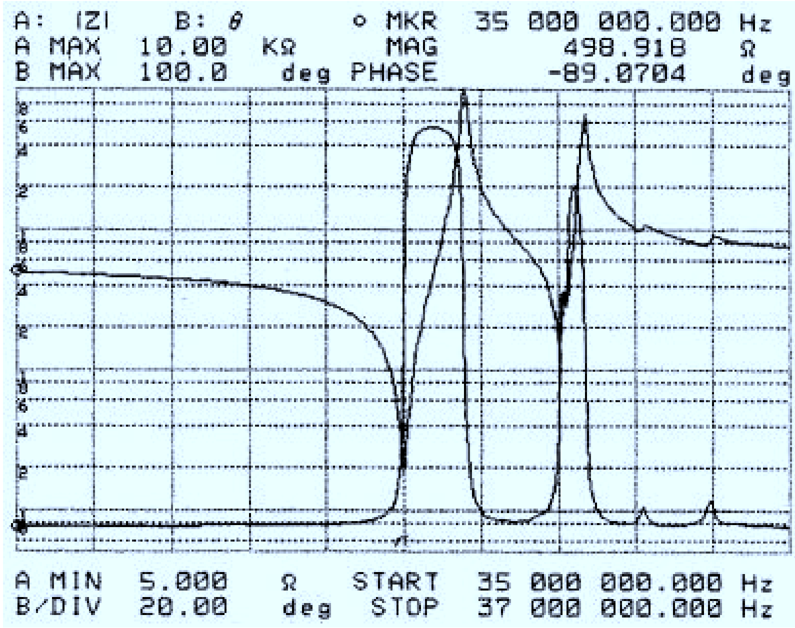
L = 36.6363 mH Cb = 2.80858 pF

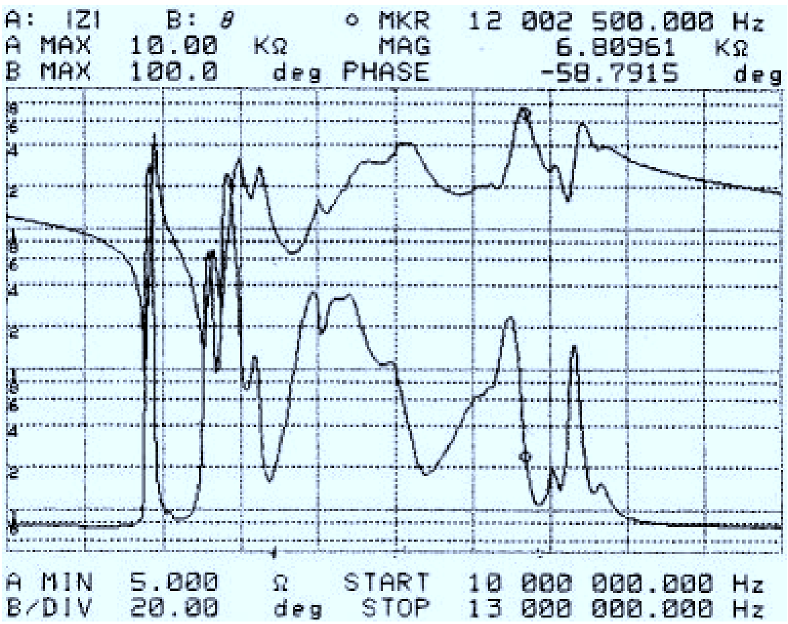



App 7d Crystal Philips 3rd overtone. Code 02370991. $F_s$=39.130000 MHz
Response at 3rd overtone, 2nd spurious F=39.38 MHz

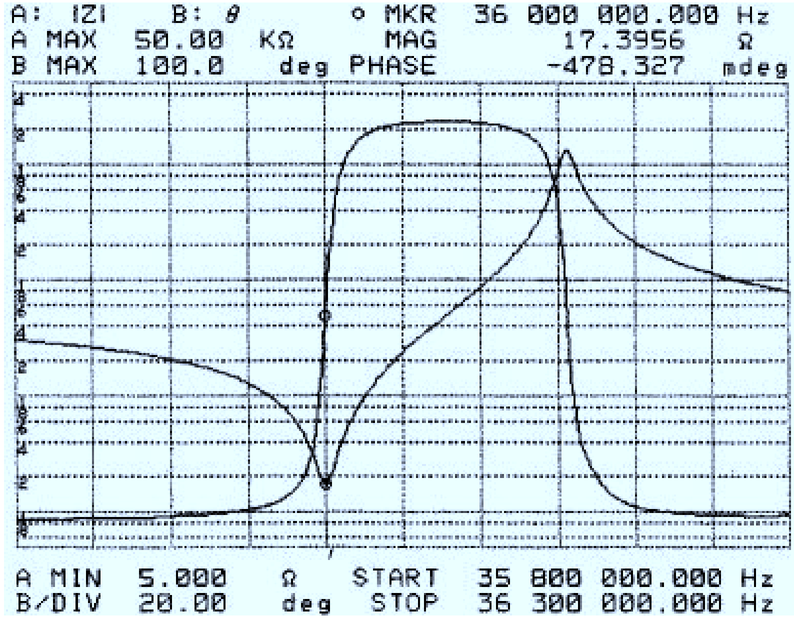
R = 290.131 Ω Ca = 0.144278 fF

L = 113.220 mH Cb = 2.79147 pF



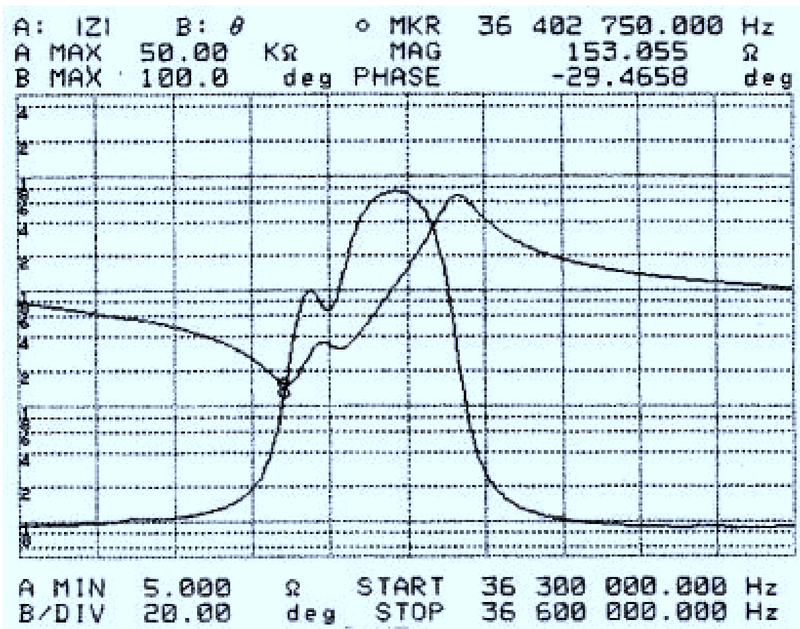

App 8a Resonator, Murata, 3rd overtone, CSA 36.00 MXZ 040, $F_s$=36 MHz.
Response at 3rd overtone and around fundamental, 36 MHz and 12 MHz




App 8b Resonator, Murata, 3rd overtone, CSA 36.00 MXZ 040, $F_s$=36 MHz. Response at 3rd overtone 36 MHz

R = 17.4101 Ω Ca = 75.3167 fF

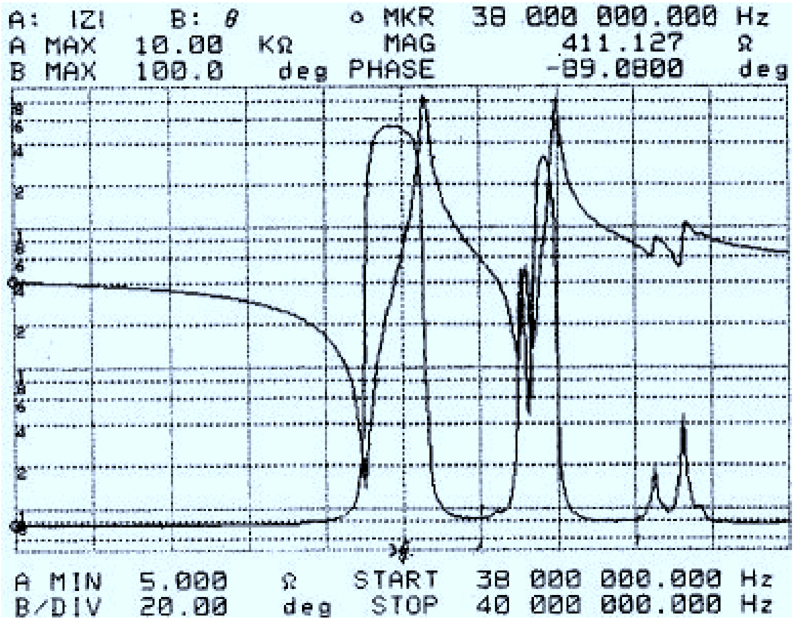
L = 259.506 µH Cb = 8.69794 pF

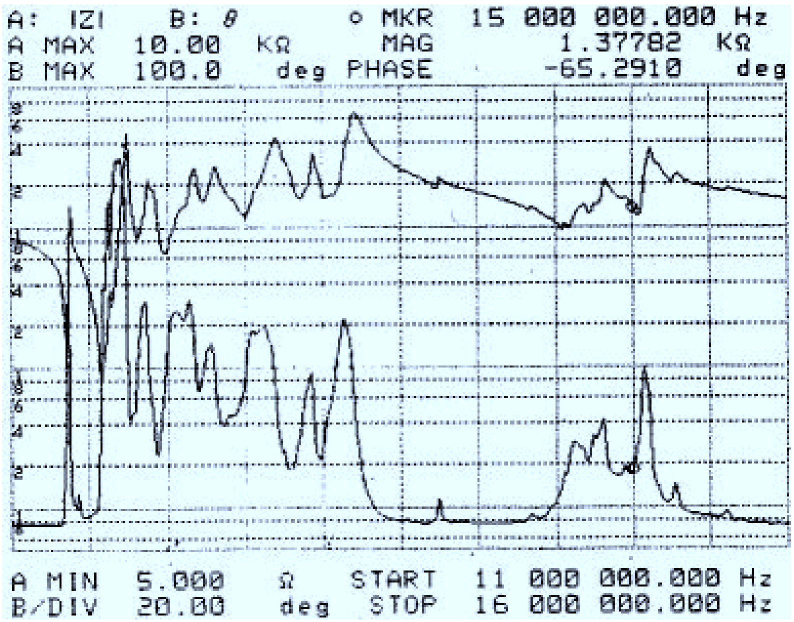



App 8c Resonator, Murata, 3rd overtone, CSA 36.00 MXZ 040, $F_s$=36 MHz. Response at 3rd overtone spurious frequency 36.4 MHz

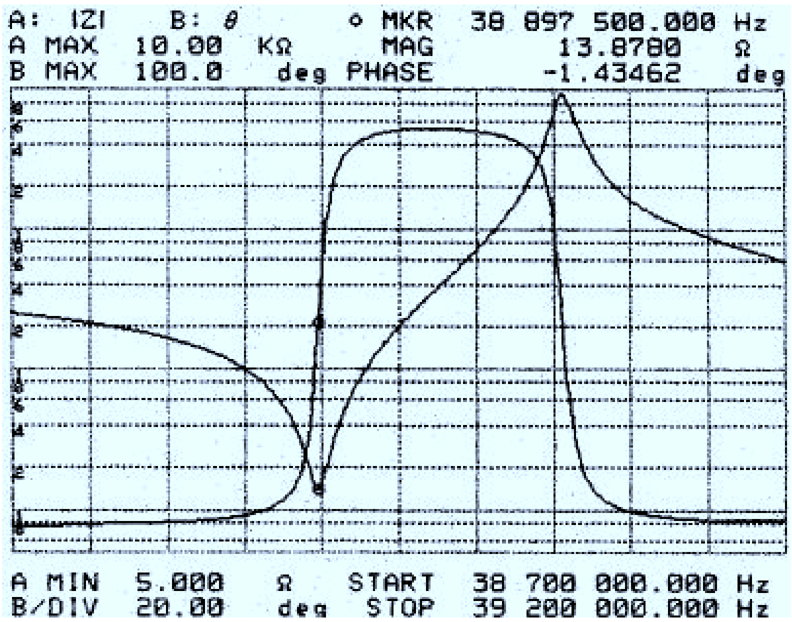
R = 177.476 Ω Ca = 11.6752 fF

L = 1.63697 mH Cb = 3.69068 pF



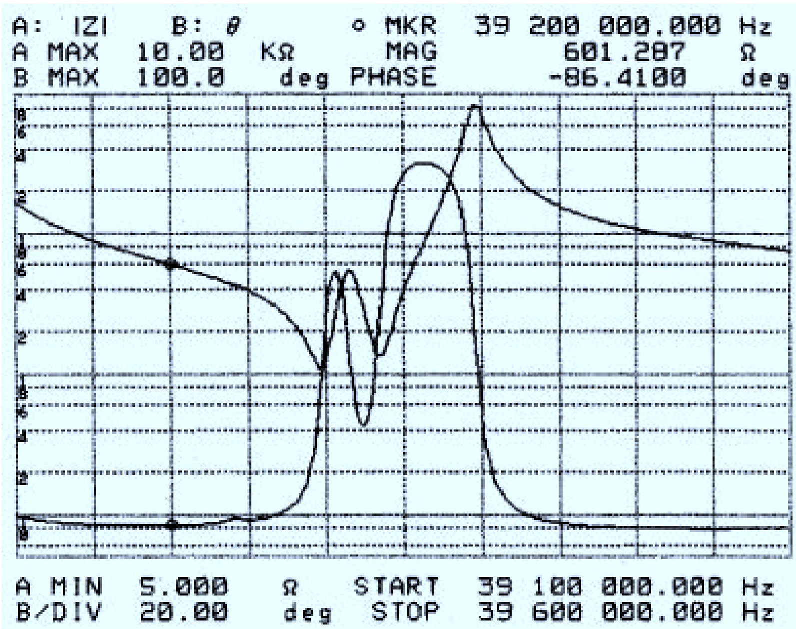

App 9a Resonator, Murata, 3rd overtone, CSA 39.00 MXZ 040, $F_s$=39 MHz. Response at 3rd overtone and around fundamental, 39 MHz and 13 MHz




App 9b Resonator, 3rd overtone, CSA 39.00 MXZ 040, $F_s$=39 MHz. Response at 3rd overtone 38.9 MHz

R = 13.8946 Ω Ca = 79.9597 fF

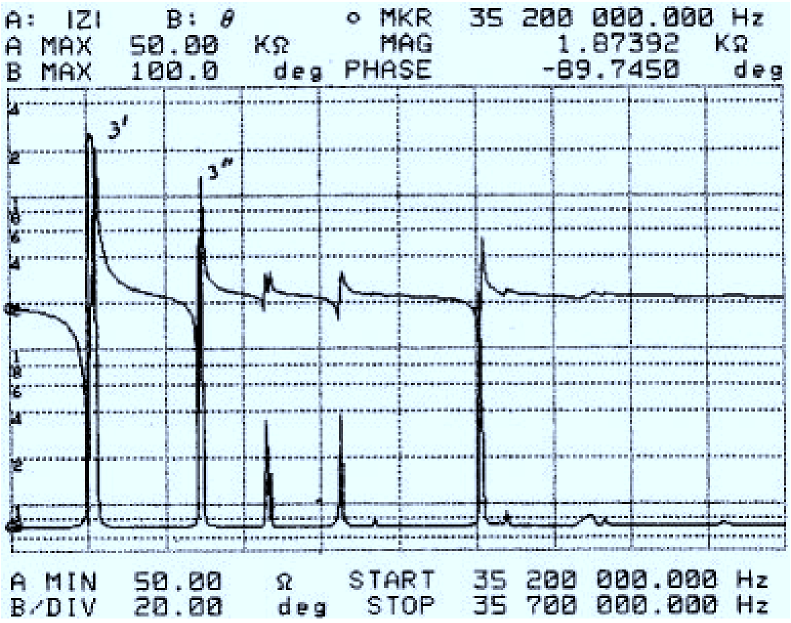
L = 209.376 µH Cb = 9.81582 pF

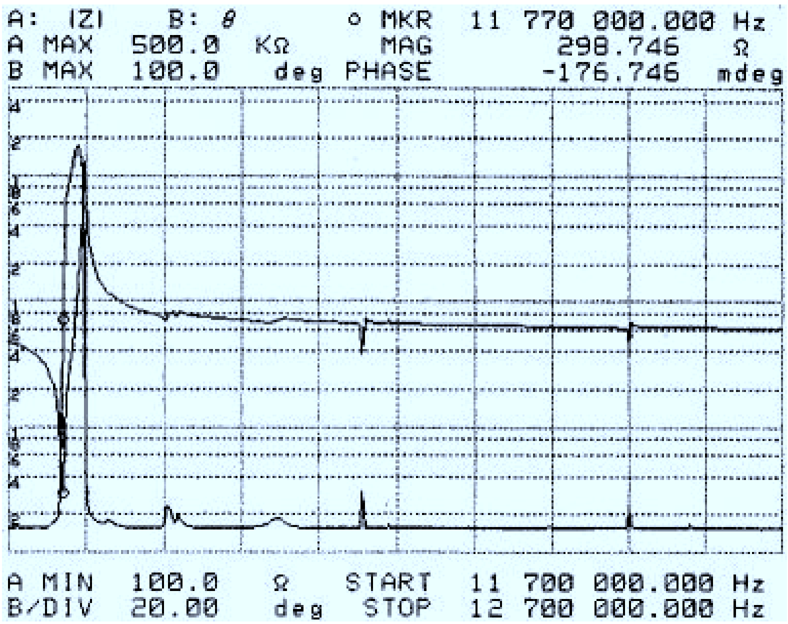



App 9c Resonator, 3rd overtone, CSA 36.00 MXZ 040, $F_s$=39 MHz. Response at 3rd overtone 39.3 MHz

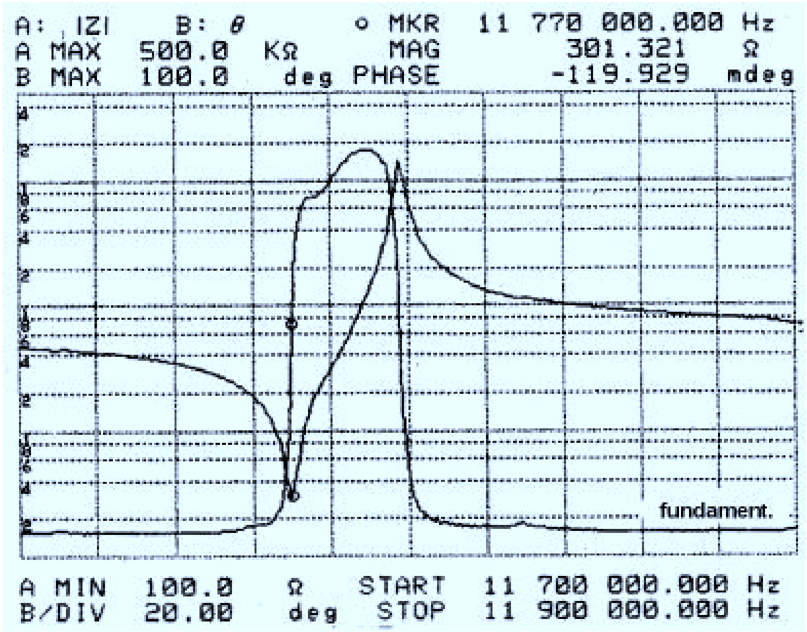
R = 124.243 Ω Ca = 11.7911 fF

L = 1.39105 mH Cb = 2.78760 pF



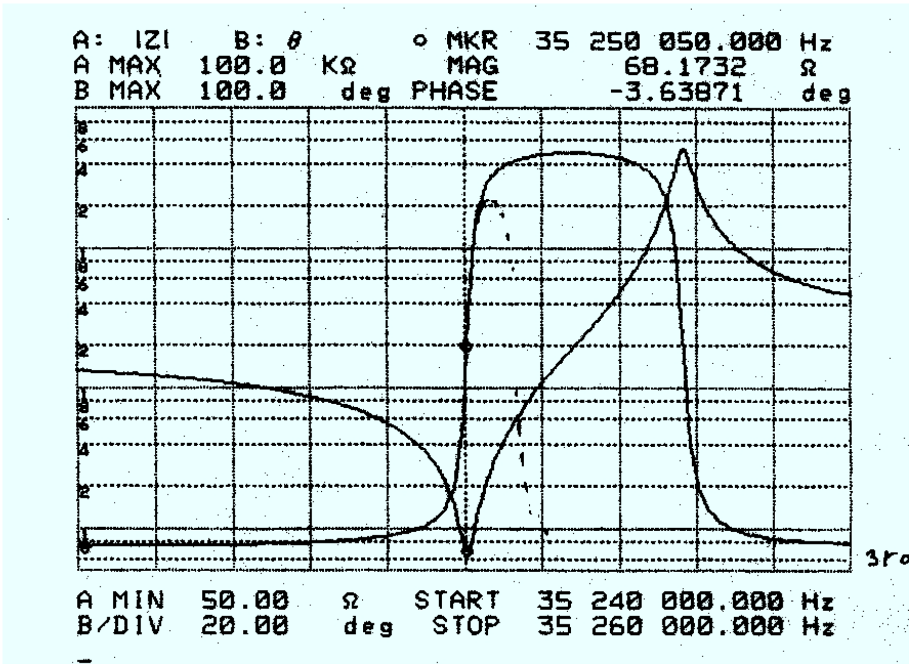

App 10a Crystal IQD. A216, 3rd overtone. $F_s$=35.2512 MHz. Response around overtone and fundamental frequencies, 35.2 MHz and 11.7 MHz




App 10b Crystal IQD. A216, 3rd overtone. $F_s$=35.2512 MHz. Response at fundamental frequency, F= 11.77 MHz

R = 302.660 Ω Ca = 8.28450 fF

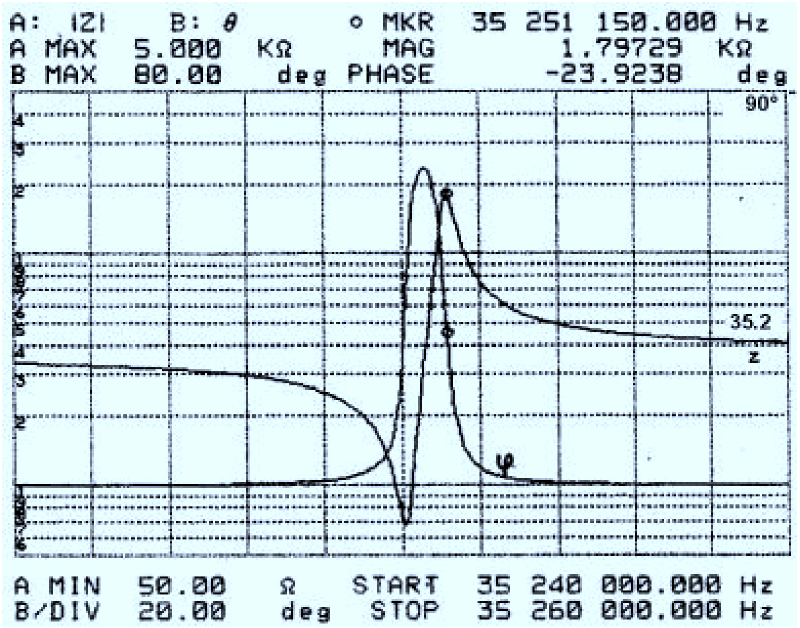
L = 22.0710 mH Cb = 1.78188 pF




App 10c Crystal IQD. A216, 3rd overtone. $F_s$=35.2512 MHz. Response at 3rd overtone, $F_P$= 35.256 MHz

R = 69.0873 Ω Ca = 0.695554 fF

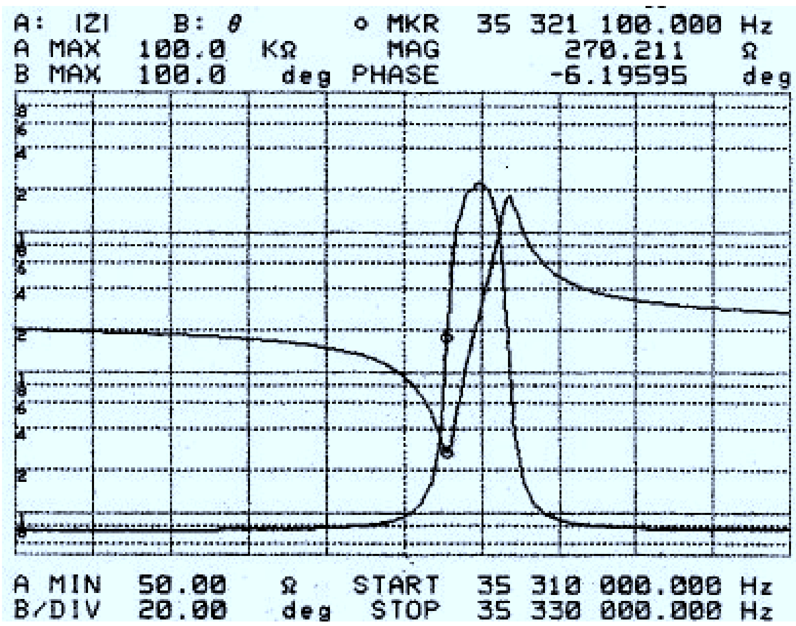
L = 29.3083 mH Cb = 2.19626 pF




App 10d — Crystal IQD. A216, 3rd overtone. $F_s$=35.2512 MHz. Response at 3rd overtone, 10pF load added in parallel to crystal. F= 35.251 MHz

R = 69.6577 Ω — Ca = 0.697244 fF

L = 29.2372 mH — Cb = 12.2397 pF




App 10e — Crystal IQD. A216, 3rd overtone. $F_s$=35.2512 MHz. Response at 3rd overtone, spurious frequency, F= 35.32 MHz

R = 282.210 Ω — Ca = 0.180806 fF

L = 112.295 mH — Cb = 2.02789 pF