DRIVING A CAPACITIVE LOAD J.Sortor, E&I 30 August 2005

INTRODUCTION:

A problem that is often encountered is devising a method of generating a high AC voltage across the terminals of a piezo electric crystal or a capacitive load. There are three factors that contribute to the loss in such a system when using a RF power amplifier or signal source to drive the capacitive load: reactive loss, return loss, and dielectric loss. This paper will discuss these losses and three main approaches to overcoming them.

REACTIVE LOSS:
Reactive loss is a function of the value of the capacitor.

$$Xc = \frac{1}{2 * \Pi * F * C}$$

where:

Xc = reactance measured in -j Ohms
F = Frequency in Hz
C = Capacitance in Farads

As frequency increases, the reactance decreases. Most crystals are driven as an unbalanced load (One terminal is RF hot and the other is connected to ground.) At very low frequencies (DC - 1 MHz) the reactance is high compared to the impedance of the signal source. (50 Ohms) At frequencies >30 MHz (depending on the value of the capacitance) the reactance could be less than the impedance of the source. As you continue to increase the frequency, the crystal under test will begin to look more and more like a short circuit to the output terminal of the RF generator or signal source.

RETURN LOSS:
Return loss or reflection coefficient is a function of impedance. Most RF amplifiers and signal sources have an output impedance of 50 Ohms. It is possible to deliver all of the energy from the amplifier to the device under test if you use 50 Ohm coax and the load you are driving is also 50 Ohms. If the load impedance is >50 Ohms or < 50 Ohms then a portion of the energy will be reflected or returned back toward the signal source.

$$\text{Voltage Reflection Coefficient} = \frac{Z\ load - Z\ source}{Z\ load + Z\ source}$$

Where both Z load and Z source are complex vector values.

Return loss in (–dB) = 20 * LOG (ABS (Voltage Reflection Coefficient))

Forward Power in (%) = 100 * (1- Voltage Reflection Coefficient ^ 2)

Reflected Power in (%) = 100 * Voltage Reflection Coefficient ^ 2

Eg. if the crystal or capacitor with an impedance of 50.0 – j 50.0 Ohms is connected directly to the output of the RF amplifier, (50.0 + j 0.0 Ohms) 20% of the power will be lost due to the reflected power caused by the complex impedance of the crystal or capacitor..

DIELECTRIC LOSS:
Dielectric loss is a function of the capacitor or crystal material properties and is the most difficult to quantify. Factors that contribute to dielectric loss such as dielectric constant, dielectric strength, frequency, power factor, and velocity factor are not normally published as the mixture of the ceramic material is proprietary. Only a few of the manufactures of high quality ceramic and porcelain capacitors list dielectric loss data. Dielectric loss is the most important factor since this loss will turn into heat generated in a very small volume.

"The RF Capacitor Handbook" is a good reference on this subject and is available from American Technical Ceramics.
http://www.atceramics.com/technicalnotes/order_capacitor_handbook.asp

There are also facilities that specialize in measuring dielectric properties of any type of material.
http://www.damaskosinc.com/

COMPLEX CRYSTAL IMPEDANCE:
A simple method of determining the loss of an unknown crystal or capacitor is to measure the complex impedance using a vector network analyzer. This instrument will measure the voltage and phase through a component under test and return the complex impedance in several different formats. (scalar or polar plots, reflection coefficient, VSWR, real & imaginary Ohms, Voltage magnitude & angle)

It is preferable to view the real and imaginary impedance data since these vector values can be used to calculate the voltage reflection coefficient and in turn the percentage of forward power that is delivered to the crystal. The real and imaginary numbers that are returned by the network analyzer represent a series equivalent circuit. (Series C, Shunt R)

Actual data measured on an NaCl crystal is given below as an example:

Complex Impedance of a NaCl Crystal:

Freq MHz	Re Ohm	Im jOhm	C pF
1	300	-7557	21.1
2	47	-3622	22.0
5	17	-1817	21.0
10	10.7	-915	21.4
15	4.7	-460	21.4
30	3.5	-229	21.3
60	2.8	-112	23.7
125	1.9	-50	25.5
250	0.47	-12	53.1
300	0.34	-0.4	1330

Refer to the table of complex impedances above:

At 1 MHz both the real part (Re = 300 Ohms) and the reactance (Im = Xc = -j 7557 Ohms) is high. In a 50 Ohm system less than 1% of the power will be delivered to the terminals of the crystal. The capacitance is calculated using the equation given in the first part of this paper. The ratio of these 2 numbers gives the quality factor or "Q" of the crystal.

$$Q = \frac{Xc}{Re} = \frac{\text{energy stored}}{\text{energy dissipated}}$$

At 2 MHz the real part has already decreased to 47 Ohms. Let's assume that a conjugate match was designed to resonate the capacitive reactance (-j3622 Ohms) with a lossless inductor. (+j3622 Ohms) The resulting RLC network would look like a pure 47 Ohm resistor. This network will provide a good load for a 100 Watt RF power amplifier. The problem is that the salt crystal is not capable of dissipating 100 Watts of energy which results in failure of the crystal structure due to thermal overload.

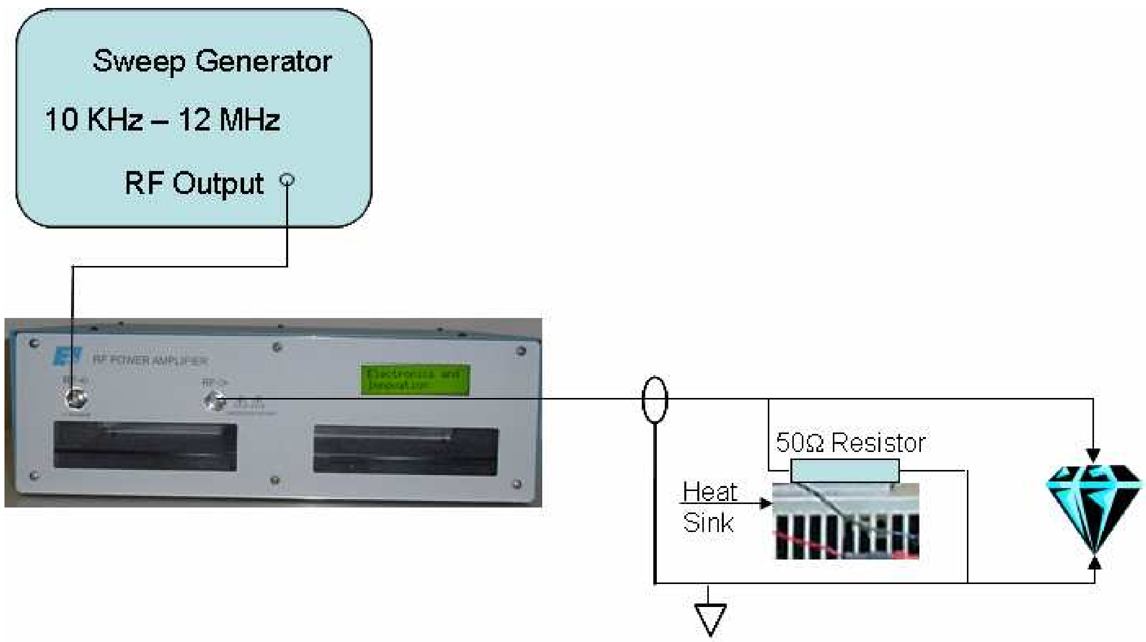
At 250 MHz the real part is less than an Ohm and the imaginary part has dropped to the point where the effective value of the capacitance has doubled. The decreased reactance (Xc = -j12 Ohms) will give additional unwanted reactive loss. A RLC circuit could be designed to efficiently match the energy from the 50 Ohm amplifier output to the crystal at 250 MHz but generally it is desired to provide a high AC voltage potential across the terminals of the crystal. Driving this particular crystal with a 200 volt RMS signal at 250 MHz would require a RF power amplifier with an output power of:

$$Pout = \frac{200 \text{ volts}^2}{0.47 \text{ Ohms}} = 85{,}106 \text{ Watts}$$

This of course is not a practical solution since generating 85 kWatts is not a trivial matter. Plus there is still the thermal management problem inherent with the crystal structure. In this unusual example it is important to note that the crystal must also be designed to dissipate 85 KWatts.

If the frequency is increased beyond 300 MHz the crystal will go through a series resonance where the RLC network would look like a short circuit causing the voltage across the crystal to go to zero. Above the series resonance point the complex impedance data would show that the crystal now looks like an inductor. (+j Ohms)

50 OHM TERMINATION:
A simple broadband solution to this problem is to place the crystal and a 50 Ohm load in parallel. The voltage developed across the resistor can be used to drive the crystal.



The complex impedance of the same NaCl crystal and a 50 Ohm resistor was measured and is shown below.

Complex Impedance of a NaCl Crystal and 50 Ohm Load in Parallel:

freq	Re	Im	C pF
1	50	-0.08	1989440
2	50	-0.2	397887
5	50	-0.5	63662
10	50	-1.0	15915
15	50	-2.0	5305
30	49	-4.2	1263
60	47	-8.0	332
125	35	-11.7	109
250	21	-16.2	39.3
300	18	-35.0	15.2

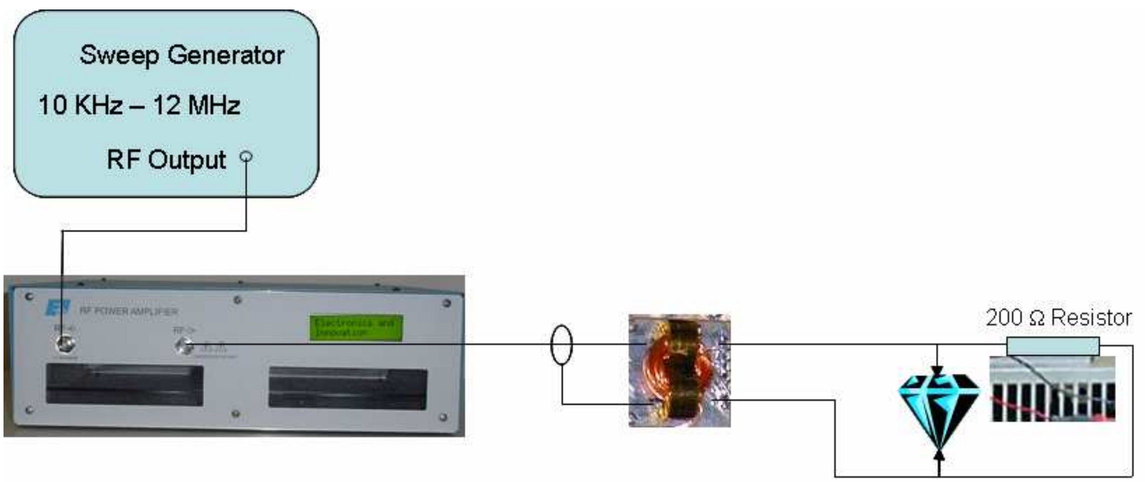
This network would provide a good termination for the RF power amplifier up to 60 MHz. The reactive loss starts to becomes a factor at 125 MHz (Im = -j 11.7 Ohms).

There is a thermal issue to consider with this solution. The termination resistor must dissipate most of the energy from the RF power amplifier and the resistor must be located as close to the crystal under test as possible. 50 Ohm coax cable must be used to efficiently transfer the energy from the amplifier to the crystal / resistor network. A low inductive RF type flange mount resistor with the power rating de-rated by 50% must be mounted to a heat sink and either cooled by natural convection or by forced air.

STEP UP TRANSFORMER:

A problem with the 50 Ohm termination is that the characteristic impedance of the system limits the magnitude of the voltage that can be generated across the 50 Ohm resistor. A 200 Watt RF power amplifier will only provide:

Voltage = Sqrt (200 Watts * 50 Ohms) = 100 Volts RMS across the crystal.



A broadband auto transformer can be employed to step the voltage up by a factor of 2, 3, or 4 depending on the transformer topology that is selected. The same salt crystal was terminated with a low inductance 200 Ohm resistor and the complex impedance was tabulated.

Complex Impedance of a NaCl Crystal and 200 Ohm Load in Parallel:

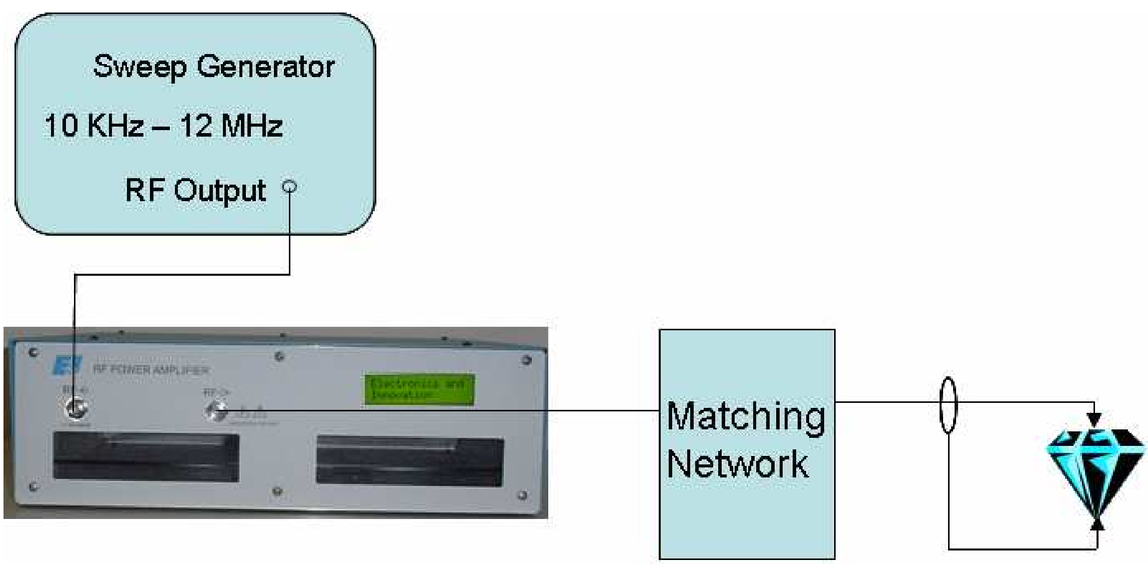
freq	Re	Im	C pF
1	203	-12	13263
2	203	-21	3789
5	200	-41	776
10	191	-77	207
15	162	-131	81.0
30	100	-161	32.9
60	39	-125	21.2
125	11	-66	19.3
250	2	-17	37.4
300	1	-3	177

The output impedance of the RF power amplifier is 50 Ohms. The autotransformer is a 1:2 voltage transformation but this equates to a 1:4 impedance transformation. 50 Ohm in = 200 Ohms out. This network will present a good load to the RF amplifier up to 10 MHz. A 200 Watt RF power amplifier will now provide:

Voltage = Sqrt (200 Watts * 200 Ohms) = 200 Volts RMS across the crystal.

Transformer theory states that power in = power out so a high power, 200 Ohm, low inductance resistor with a heat sink will be required.

IMPEDANCE MATCHING NETWORK:
An impedance match is a network of inductors and capacitors. It is possible to design a circuit using only these basic elements to match any complex impedance to another complex impedance.



Refer to the chart labeled "Complex Impedance of a NaCl Crystal" At a frequency of 1 MHz a series inductor can be selected to have an inductive reactance (Xl) of +j 7557

Ohms to cancel the capacitive reactance (Xc) of –j 7557. An additional series inductor terminated with a shunt capacitor can be used to transform the 50 Ohm output of the RF power amplifier to the 300 Ohm resistance of the crystal. A 200 Watt RF power amplifier will now provide:

Voltage = Sqrt (200 Watts * 300 Ohms) = 245 Volts RMS across the crystal.

This matching network is a narrow band solution since the inductors and capacitors in the matching network increase the "Q" of the circuit. If a frequency change is desired it will be necessary to select different value inductors and capacitors since the complex impedance of the crystal changes over frequency.

There are manual match networks that can be purchased which include variable inductors and capacitors which can be tuned for each frequency and impedance. Automatic match networks are also available which use motor driven inductors and capacitors. Samples of the forward and reflected RF power is used as feedback signals to a microprocessor.

CONCLUSION:

There are low loss crystals that have been conjugate matched and driven with 20 Watts of RF energy at 10 MHz to produce more than 1,800 Volts pk-pk across a 40 pF capacitive load. At the other end of the spectrum there are high loss crystals when matched produce only mVolts across the terminals using 200 Watts of RF power. In both cases the result was satisfactory.

When in the design stage consider the construction of the crystal. Copper loss (I^2*R) can be responsible for a large portion of the overall loss. If a crystal is sputtered with only a few Angstroms of metal the copper loss will be high at high frequencies due to the skin effect.

Be cautious when driving a crystal with high levels of energy. If the conjugate match into the crystal is efficient the result will cause a large portion of the generated energy to be delivered directly to the crystal under test resulting in failure of the crystal due to thermal overload.

Sometimes it is difficult to know exactly what is needed to bring an experiment to a successful conclusion. If a high power RF amplifier is already available there are several options you can investigate under $500 that will help direct you towards your eventual goal.

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