L-Matching the Output of a RITEC Gated Amplifier to an Arbitrary Load

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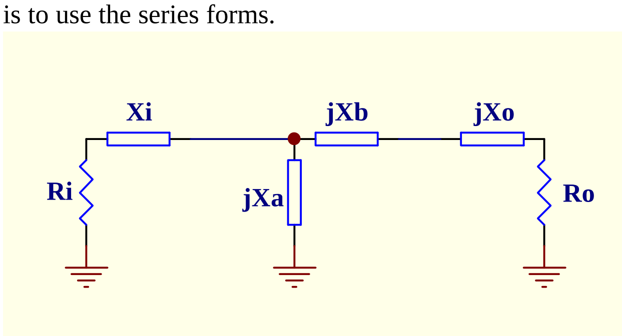
Historically, matching transmitter impedances to high impedance transducers such as Quartz was important when reasonable signal-to-noise ratios were to be achieved. This process becomes much less important when using lower impedance ceramic piezoelectrics. In most cases it was enough to add an inductor in parallel with the active element to resonate the capacitance and raise the impedance. However, there is normally a large impedance mismatch between EMATs and the transmitters that drive them, and the inefficiency of these devices requires that everything be done to maximize the transfer of energy into the sound beam. Nonlinear ultrasonics uses single crystal piezoelectrics such as Lithium Niobate which can also benefit from more sophisticated matching techniques.

Probably the most useful LC matching network for transducers is the “L-Matching Network”. Two reactive elements (X_a and X_b) are placed between the amplifier and the transducer in an effort to maximize the power transfer to the transducer. This requires that the impedance of the transducer and the output impedance of the gated amplifier be known. Even though the actual output impedance may be somewhat lower, for the purpose of calculating matching circuits, the gated amplifier can be assumed to be 50 Ohm resistive. Thus R_i =50 and X_i=0.

The transducer impedance must be measured or estimated. Some care must be taken when using an impedance meter to measure the transducer. The readings will be affected by the acoustic loading of the transducer as well as the cable connected to it. If the transducer is connected to a sample during measurement, there may be sample resonant effects that are highly sensitive to the frequency and spoil the reliability of the readings. It may be necessary to use a highly attenuative acoustic load with the correct acoustic impedance or a large sample with damping on the far side to minimize these resonant effects.

The usual way of representing the impedances for this network is to use the series forms.



The output impedance of the source is, therefore, given by:

$$Z_i = R_i + jX_i \quad (1)$$

and the load impedance (transducer) by:

$$Z_0 = R_0 + jX_0 \quad (2)$$

where j = $(-1)^{1/2}$

The applicable equations for obtaining the matching impedances are:

$$X_a = \frac{-(R_i^2 + X_i^2)}{QR_i + X_i} \quad (3)$$

$$X_b = QR_0 - X_0 \quad (4)$$

where Q is defined by:

$$Q = \pm\sqrt{\left(\frac{R_i\left[1+\left(\frac{X_i}{R_i}\right)^2\right]}{R_0} - 1\right)} \quad (5)$$

If the transducer impedance is given in parallel form, it can be converted to series form using equations 6 and 7. Conversions from series to parallel are also valuable when examining the networks and are given by equations 8 and 9.

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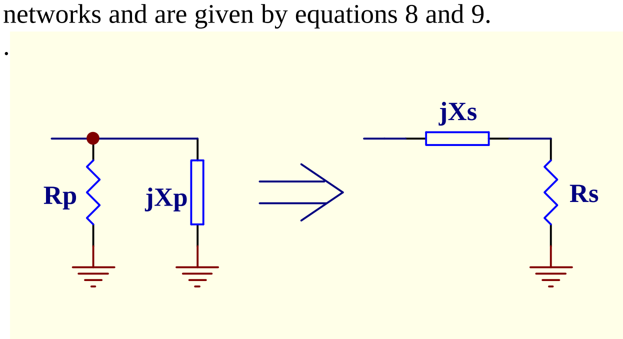


$$R_s = R_p \frac{1}{1+\left(\frac{R_p}{X_p}\right)^2} \quad (6)$$

$$X_s = X_p \frac{\left(\frac{R_p}{X_p}\right)^2}{1 + \left(\frac{R_p}{X_p}\right)^2} \quad \textbf{(7)}$$

$$R_p = R_s \left[1 + \left(\frac{X_s}{R_s}\right)^2 \right] \quad \textbf{(8)}$$

$$X_p = X_s \frac{1 + \left(\frac{X_s}{R_s}\right)^2}{\left(\frac{X_s}{R_s}\right)^2} \quad \textbf{(9)}$$

Note that this formalism assumes that the shunt element of the *L Matching circuit* is in parallel with the transmitter. If one exchanges the values of Z_i for those of Z_0 and vise-versa, another solution is obtained in which the shunt element is in parallel with the transducer. One also obtains separate solutions for positive and negative values of Q giving a total of 4 possible matching networks.

This may seem confusing but in many real situations the number of possibilities may be easily reduced. Q may be imaginary for one of the positions of the "L" network and, therefore, in this case two of the solutions are non-physical. It also common that some of the solutions are physically unrealizable because one of the components can not be obtained or constructed easily. One or more solutions may also be rejected because they have unwanted characteristics. For example: one solution may give a high-pass filter characteristic and a low-pass one is preferred.

Voltage Step-up Ratio

It is always interesting to know the Voltage step-up or step-down from the output of the gated amplifier to the transducer. If the matching network is properly designed, the power output of the gated amplifier is given by

$$Power = \frac{E_{out}^{\,2}}{50} \quad \textbf{(10)}$$

The power applied to the transducer is given by

$$Power = \frac{E^2_{transducer} \;\; R_o}{|\, Z_o \,|^2} \quad \textbf{(11)}$$

where E_{out} and $E_{transducer}$ refer to the rms Voltage levels at gated amplifier output and at the transducer contacts.

When equations 10 and 11 are equated, the solution for the ratio of the transducer and transmitter Voltages (step-up ratio) is given by

$$\frac{E_{transducer}}{E_{out}} = \frac{|\, Z_o \,|}{\sqrt{50 \;\, R_o}} \quad \textbf{(12)}$$

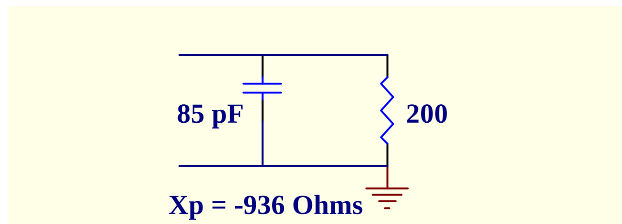
where $|\, Z_o \,|$ is the absolute magnitude of the complex transducer impedance.

Example No 1
Lithium Niobate Piezoelectric Transducer

2 MHZ, 2.54 cm diameter 36^0 Y-cut compressional mode
Thickness = d= 0.1575 cm
Area = A = 5.07 cm^2, dielectric constant = ε = 30

$$C = 0.08842 \; \frac{A}{d} \; \epsilon \;\; pF$$
$$= 85 \;\; pF$$

Assume an equivalent circuit for the transducer at resonance of



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This assumes that the transducer is loaded. The 200 Ohms will change depending on the acoustic impedance of the sample and the character of the bond. Therefore, 200 Ohms is only an educated guess. Back loading will also change the impedance.

The first step is to change the parallel form of the transducer impedance into a serial form using equations 6 and 7.

$$R_0 = R_s = 200 \frac{1}{1 + \left(\frac{200}{-936}\right)^2} = 191\,\Omega$$

$$X_0 = X_s = -936 \frac{\left(\frac{200}{-936}\right)^2}{1 + \left(\frac{200}{-936}\right)^2} = -40.9\,\Omega$$

The results can then be used to calculate Q, X_a, and X_b using equations 3, 4, and 5.

$$X_i = 0 \; ; \quad R_i = 50$$

$$Q = \pm \sqrt{\left(\frac{50\left[1 + \left(\frac{0}{50}\right)^2\right]}{191.26} - 1 \right)} = \pm\sqrt{-0.738}$$

An imaginary value of Q represents a nonphysical situation and therefore, two of the solutions are rejected and the positions of the source and load must be reversed to calculate the second two matching networks.

$X_o = 0$; $R_o = 50\ \Omega$; $X_i = -40.87\ \Omega$; $R_i = 191.26\ \Omega$

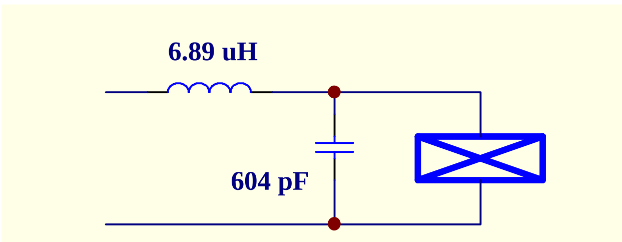
$$Q = \pm\sqrt{\left(\frac{191\left[1+\left(\frac{-40.9}{191}\right)^2\right]}{50} - 1\right)} = \pm 1.73$$

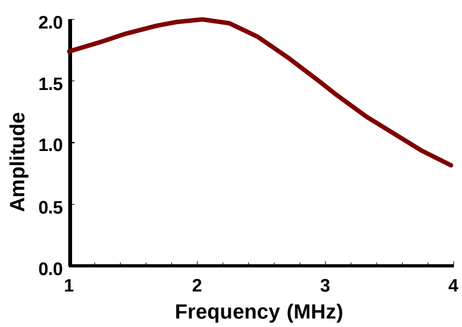
Using Q = +1.732

$$X_a = \frac{-\left(191^2 + (-40.9)^2\right)}{1.73\ x\ 191\ -\ 40.9} = -132\Omega;$$

C_a=604 pF

$$X_b = 1.73\ x\ 50\ - 0 = 86.6\Omega\ ;\ L_b = 6.89\mu H$$





Matching Network Output

Solution No.1 (Low-pass)

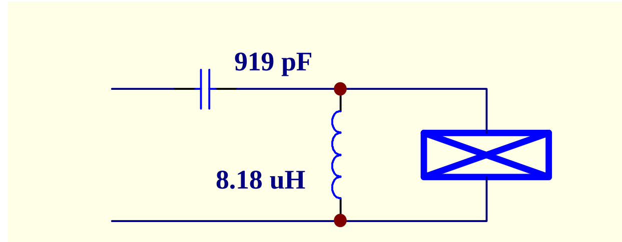
The matching network output shown above and the ones that follow were created using a circuit simulation program (SPICE). They give the network's output as a function of frequency assuming the generator driving the network has an output of one Volt into 50 Ohms. The output impedance of the generator is taken to be 50 Ohms.

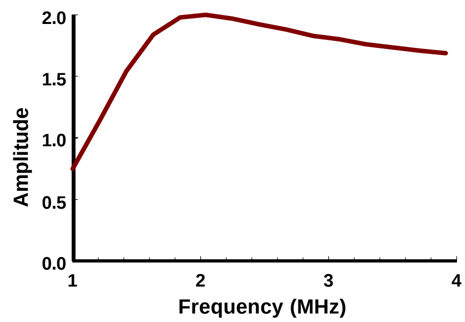
Using Q = -1.732

$$X_a = \frac{-\left(191^2 + (-40.9)^2\right)}{-\ 1.73\ x\ 191\ -\ 40.9} = -103\Omega\ ;$$

L_a=8.18µH

$$X_b = -\ 1.73\ x\ 50 = -\ 86.6\Omega\ ;\ C_b = 919 pF$$





Matching Network Output

Solution #2 (High-pass)

When working in nonlinear acoustics solution #1 is preferred because it becomes a low-pass filter and any harmonics in the driving source which may excite the transducer will be attenuated. Solution #2 is a high pass filter and will not attenuate any harmonic distortion that may be present.

The step-up ratio is calculated from equation 12.

$$\frac{E_{transducer}}{E_{out}} = \frac{|\ 191\ -\ j\ 40.9\ |}{\sqrt{50\ x\ 191}} = 2.00$$

The inductors must be air core types rather than ferrites to avoid saturation effects and probably will have to be hand wound. Roller adjustable inductors are also valuable but somewhat difficult to obtain. The capacitors must be high voltage, high Q types such as mica or high voltage variable air units. In this example, the voltage step-up was only 2. Very large voltage increases may be expected when working with quartz transducers, but only around 2 or 3 can be expected with Lithium Niobate.

At this point the question arises, "Why don't I use a transformer and then I won't have to tune the circuit?". Normally this would be correct. However, experience has shown that the transformer may cause distortion at these high levels and the value of the low-pass filter is lost. Thus, for nonlinear applications, the LC network may be preferred.

It should also be pointed out that any coaxial cable impedances that may be present and affect the circuit have been neglected in this example. This is a reasonable procedure providing the matching elements are placed very close to the transducer. If this is not done, the impedance of the transducer including the cable should be measured or calculated using transmission line theory.

Example No. 3
Commercial PZT Transducer

The transducer chosen for this matching exercise is a one inch diameter 1 Mhz unit. The back loading and the parallel matching inductor normally included in transducers of this type were purposely left out. The purpose of the back loading is to make the bandwidth as wide as possible and is not desired in a narrow band system where signal-to-noise ratio is of the utmost importance. The matching inductors that are usually installed in commercial units may not stand the high power RF bursts from a RITEC gated amplifier. They either fail completely and burn out or they saturate and distort the signal.

The actual best operating frequency is typically less than the resonant frequency of the active element. We were operating this transducer at 0.9 Mhz. The results of the impedance bridge measurement with the transducer loaded are:

F=0.9 Mhz; R_o=18.14 Ω; X_o= -103 Ω
R_i=50 Ω; X_i= 0

These values are then used to calculate Q, Xa, and Xb using equations 3, 4, and 5.

R_i= 50 Ω; X_i= 0.

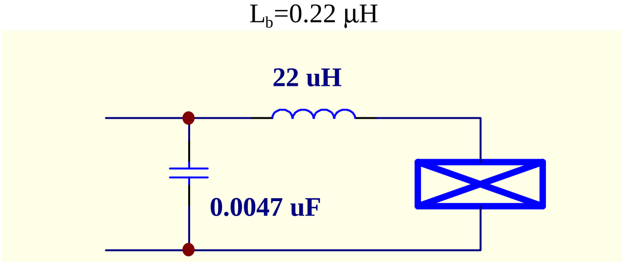
$$Q = \pm\sqrt{\left(\frac{50}{18.14} - 1\right)} = \pm\ 1.325$$

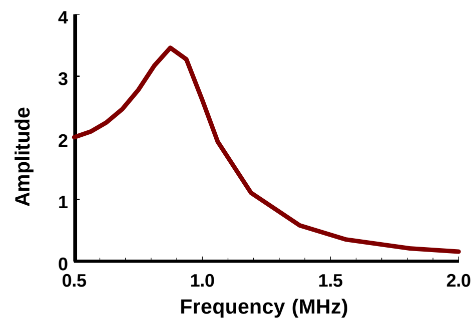
Using Q= +1.325

$$X_a = \frac{-50^2}{1.325\ x\ 50} = -37.73\ \Omega; \quad C_a = 0.0047\ \mu F$$

$$X_b = 1.325\ x\ 18.14 + 103 = 127\ \Omega$$

L_b=0.22 µH





Matching Network Output

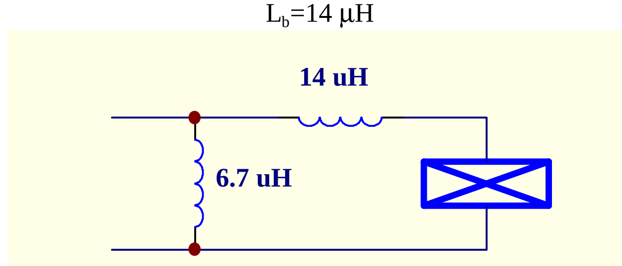
Solution No. 1

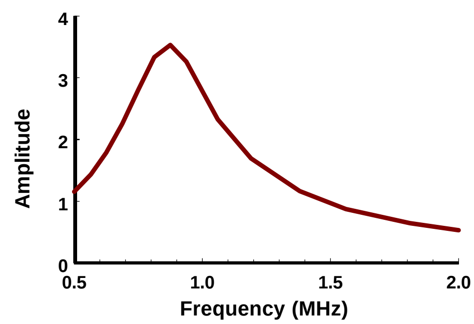
Using Q= -1.325

$$X_a = \frac{-50^2}{-1.325\ x\ 50} = 37.73\ \Omega; \quad L_a = 6.67\ \mu H$$

$$X_b = -1.325\ x\ 18.14 + 103 = 78.96\ \Omega$$

L_b=14 µH





Matching Network Output

Solution No. 2

After reversing the positions of transmitter and transducer, the parameters for two more matching networks are calculated.

R_i =18.14 Ω; X_i=-103 Ω; R_o=50 Ω; Xo=0

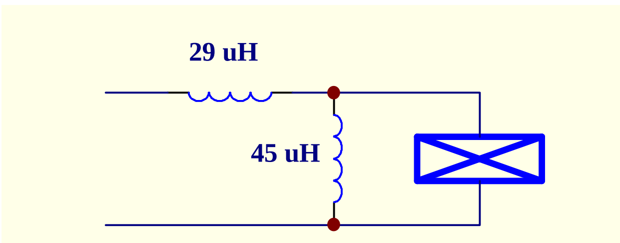
$$Q = \pm\sqrt{\left(\frac{18.14\left[1 + \left(\frac{-103}{18.14}\right)^2\right]}{50} - 1\right)} = \pm\ 3.32$$

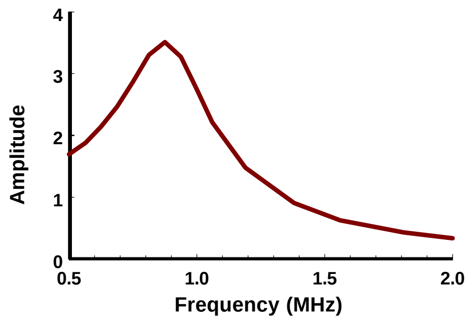
Using Q = +3.32

$$X_a = \frac{-\left(18.14^2 + 103^2\right)}{3.32 \ x \ 18.14 \ - \ 103} = 256\Omega;$$

L_a=45 μ H

$$X_b = 3.32 \ x \ 50 \ - 0 = 166\Omega \ ; \ L_b = 29\mu H$$





Matching Network Output

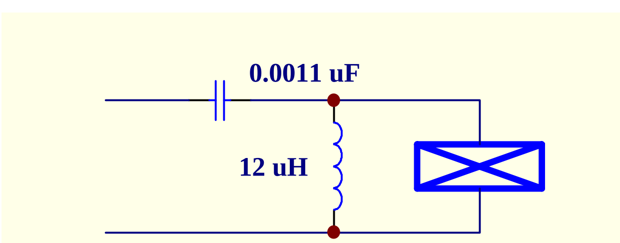
Solution No. 3

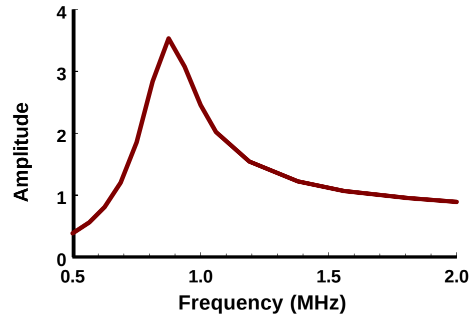
Using Q = -3.32

$$X_a = \frac{-\left(18.14^2 + 103^2\right)}{-3.32 \ x \ 18.14 \ - \ 103} = 66.7\Omega;$$

L_a=11.8 μ H

$$X_b = -3.32 \ x \ 50 \ - 0 = -166\Omega \ ; \ C_b = 0.0011 \ \mu F$$





Matching Network Output

Solution No. 4

The step-up ratio is calculated from equation 12

$$\frac{E_{transducer}}{E_{out}} = \frac{|\ 18.14 \ - \ j \ 103 \ |}{\sqrt{50 \ x \ 18.14}} = 3.47$$

A step-up factor of 3.47 indicates that there is a considerable advantage for matching to this transducer. Some advantage can be obtained by simply placing a high power 18 μH coil in parallel with the device. This will transform the impedance into a pure resistance of ~ 600 Ω and allow the use of a transmission line transformer.

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Example No. 3
Meander-line Surface Wave EMAT

The impedance of the EMAT was measured at 1.5 Mhz. with a vector impedance meter.

R_o = 0.512 Ω; X_o =0.844 Ω

Because the impedance was so low special care was taken to include the EMAT twinax cable and to compensate for the impedance meter coax cable. The matching network components are calculated using equations 3, 4, and 5.

R_i=50 Ω; X_i=0

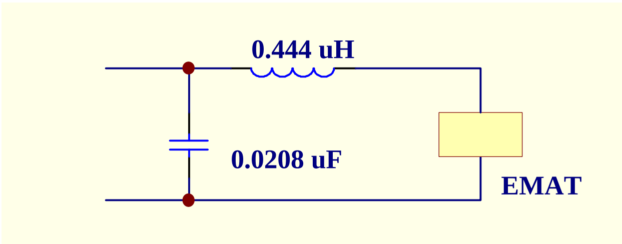
$$Q = \pm \sqrt{\left(\frac{50}{0.512} - 1\right)} = \pm \ 9.83$$

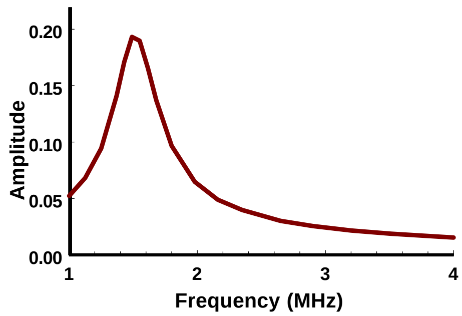
Using Q= +9.83

$$X_a = \frac{-50^2}{9.83 \ x \ 50} = -5.09 \ \Omega; \quad C_a = 0.0208 \ \mu F$$

$$X_b = 9.83 \ x \ 0.512 \ - \ 0.844 = 5.88 \ \Omega$$

L_b=0.444 μH





Matching Network Output

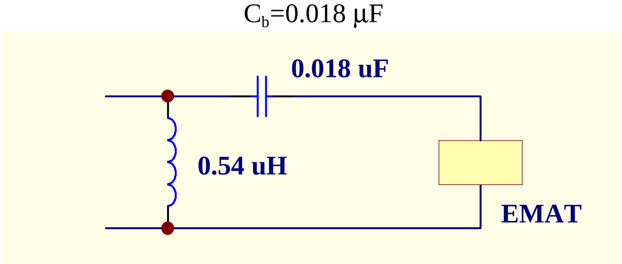
Solution No 1 (low-pass)

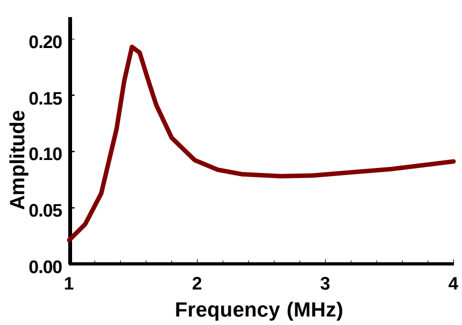
Using Q=-9.83

$$X_a = \frac{-50^2}{-9.83 \; x \; 50} = 5.09 \; \Omega; \qquad L_a = 0.54 \; \mu H$$

$$X_b = -9.83 \; x \; 0.512 - 0.844 = -5.88 \; \Omega$$

C_b=0.018 μF





Matching Network Output

Solution No. 2 (high-pass)

We now reverse the positions of Z_i and Z_o and attempt to find two more solutions.

R_i = 0.512 Ω; X_i=0.844 Ω; R_o=50 Ω; Xo=0

The value of Q is given by

$$Q = \pm \sqrt{\left(\frac{0.512 \left[1 + \left(\frac{0.844}{0.512} \right)^2 \right]}{50} - 1 \right)} = \pm\sqrt{-0.96}$$

which is imaginary and, therefore, there are only two solutions for this transducer at 1.5 MHz.

The step-up ratio is calculated from equation 12

$$\frac{E_{transducer}}{E_{out}} = \frac{| \; 0.512 \; + \; j \; 0.844 \; |}{\sqrt{50 \; x \; 0.512}} = 0.195$$

which is expected because such low impedances are involved.

In this particular case solution no. 1 may be preferred because it will attenuate the harmonics and produce a better spectrum.

Example No. 4
Pancake Coil Lorentz Force EMAT

The impedance of the EMAT was measured at 1.5 Mhz. with a vector impedance meter.

R_o = 1.549; X_o = 9.295

Again, because the impedance was so low special care was taken include the EMAT twinax cable and compensate for the impedance meter coax cable. The matching network components are calculated using equations 3, 4, and 5.

R_i=50 Ω; X_i=0

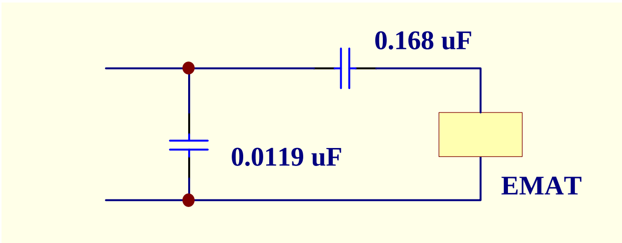
$$Q = \pm \sqrt{\left(\frac{50}{1.549} - 1 \right)} = \pm \; 5.59$$

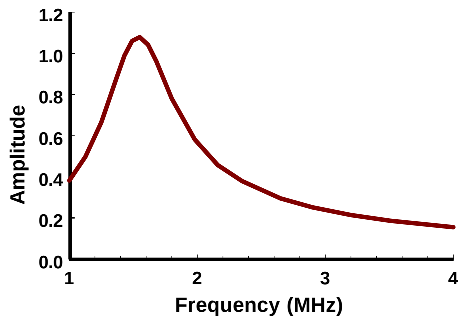
Using Q = +5.59

$$X_a = \frac{-50^2}{5.59 \; x \; 50} = -8.94 \; \Omega \; ; \qquad C_a = 0.0119 \; \mu F$$

$$X_b = 5.59 \; x \; 1.549 - 9.295 = -0.632 \; \Omega$$

C_b = 0.168 μF





Matching Network Output

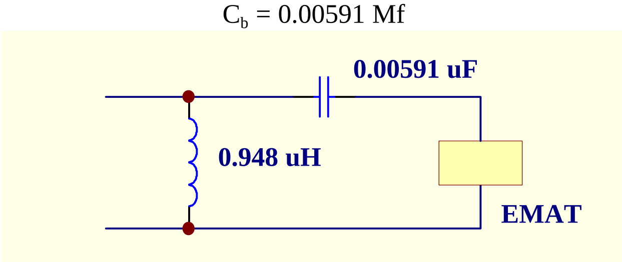
Solution No. 1

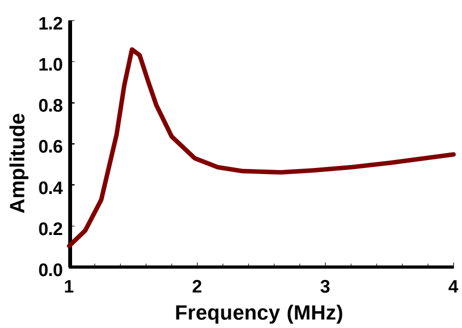
Using Q = -5.59

$$X_a = \frac{-50^2}{-5.59 \ x \ 50} = 8.94 \ \Omega \ ; \quad L_a = 0.948 \ \mu H$$

$$X_b = -5.59 \ x \ 1.549 - 9.295 = -17.958 \ \Omega$$

C_b = 0.00591 Mf





Matching Network Output

Solution No. 2

After reversing the positions of transmitter and transducer, the parameters for two more matching networks are calculated.

R_i =1.549 Ω; X_i=9.295 Ω; R_o=50 Ω; Xo=0

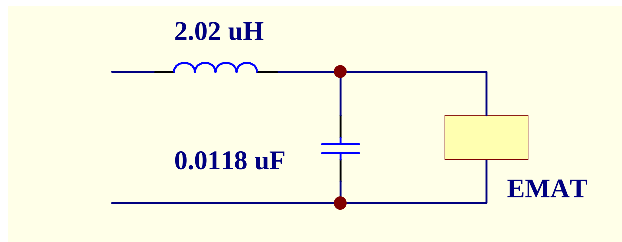
$$Q = \pm \sqrt{\left(\frac{1.549\left[1+\left(\frac{9.295}{1.549}\right)^2\right]}{50} - 1 \right)} = \pm \ 0.38$$

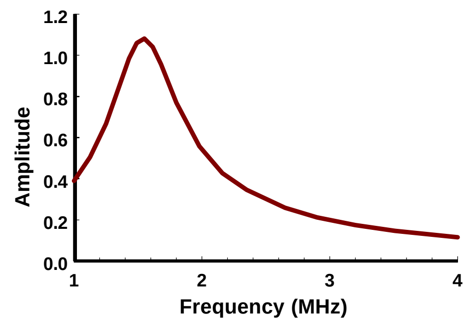
Using Q = +0.38

$$X_a = \frac{-\left(1.549^2 + 9.295^2\right)}{0.38 \ x \ 1.549 + 9.295} = -8.98\Omega;$$

C_a=0.0118 μ F

$$X_b = 0.38 \ x \ 50 - 0 = 19\Omega \ ; \ L_b = 2.02\mu H$$



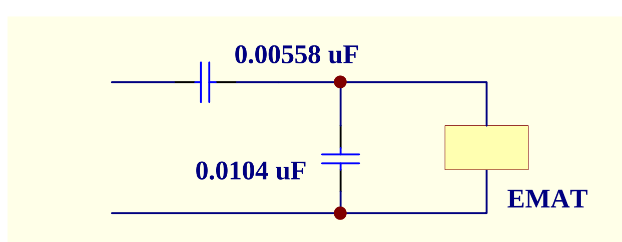


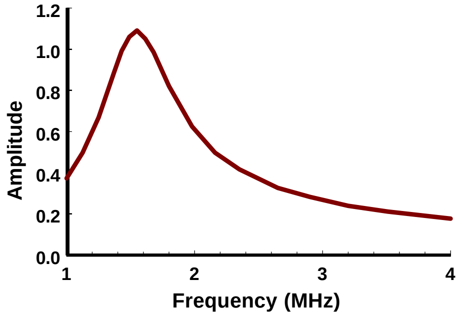
Solution No. 3

Using Q = -0.38

$$X_a = \frac{-\left(1.549^2 + 9.295^2\right)}{-0.38 \ x \ 1.549 + 9.295} = -10.2\Omega; \ C_a = 0.0104\mu F$$

$$X_b = -0.38 \ x \ 50 - 0 = -19\Omega \ ; \ C_b = 0.00558 \ \mu H$$





Matching Network Output

Solution No. 4

The step-up ratio is calculated from equation 12

$$\frac{E_{transducer}}{E_{out}} = \frac{|\ 1.549 + j\ 9.295\ |}{\sqrt{50 \ x \ 1.549}} = 1.07$$

The fact that the step-up ratio is so close to one indicates that there is no significant voltage drop across the series matching element and it may be possible to eliminate one of the components. Equations 8 and 9 are used to calculate parallel form of the transducer impedance.

$X_p = 9.55\ \Omega$ and $R_p = 57.3\ \Omega$

When a 0.0111 μF is used to parallel resonate the inductance, the impedance becomes 57.3 Ω resistive. The difference between this and 50 is completely trivial. Solution no. 5 is the obvious choice.

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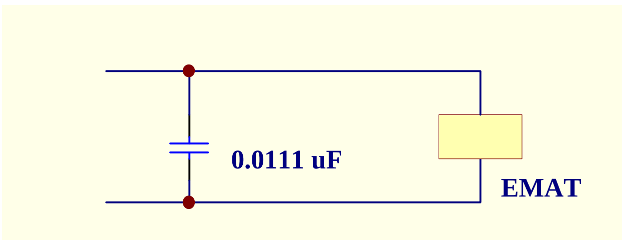
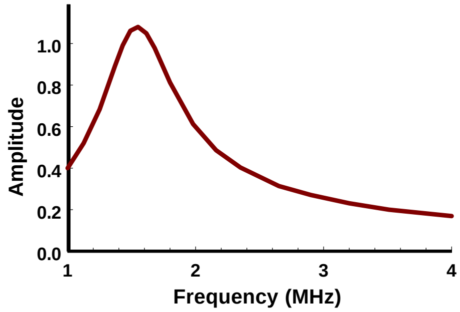


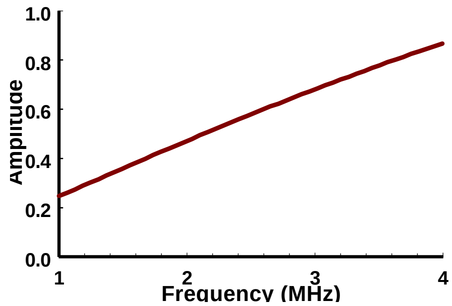


Matching Network Output

Solution No. 5

Simple parallel capacitance has been used with success for some time to improve the impedance match to EMATs.

When broadband operation is desired, it is also valuable to examine the possibility of driving the transducer directly without any matching.



Voltage on EMAT with no matching

In this example it may be useful to consider using a transmission line transformer to obtain a wider bandwidth than is possible using LC networks. There are also more complicated LC matching networks than the simple ones discussed in this work and they can be designed for wider bandwidths.

The high voltage tuning capacitors and inductors may be obtained from:

Cardwell Condenser Corporation
80 East Montauk Highway
Lindenhurst, New York 11757
(516) 957-7200

RITEC Inc., 60 Alhambra Rd. Suite 5, Warwick, RI 02886
(401)738-3660, FAX: (401)738-3661, email: gary@RitecInc.com, Web: www.RitecInc.com