# Function Matching Design of Wide-Band Piezoelectric Ultrasonic Transducer

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## Abstract

The matching design in wide-band piezoelectric ultrasonic transducer is studied in theory in the following aspect: the choice of piezoelectric wafer; the acoustic impedance match between the back layer and the piezoelectric wafer; the matching circuits of the transducer; the matrix matching layer. According to theoretical analysis, an ultrasonic transducer is designed. Test result shows that it has a good bandwidth and high sensitivity.

## Keywords

Matching Design, Piezoelectric Wafer, Back Layer, Matching Circuits, Matrix Matching Layer.

## 1. Introduction

Ultrasonic transducer is a key component during the nano-particles ultrasonic testing. An idealized ultrasonic transducer depends on its high sensitivity and wide bandwidth, but you can't have it all at the same time, so you should only select one aspect or lower your sights. In this article, an ultrasonic transducer has been designed and manufactured with the 20MHz mid-frequency LiNbO3 and the mixture of tungsten particles and epoxy resin. The following aspects are listed to increase bandwidth of it.

## 2. The construction and principle of the transducer

The transducer is composed of piezoelectric wafer, back layer, acoustic impedance matching layer, matching circuits, matrix matching layer, external connector, inner shell and outer shell. (Fig.1)

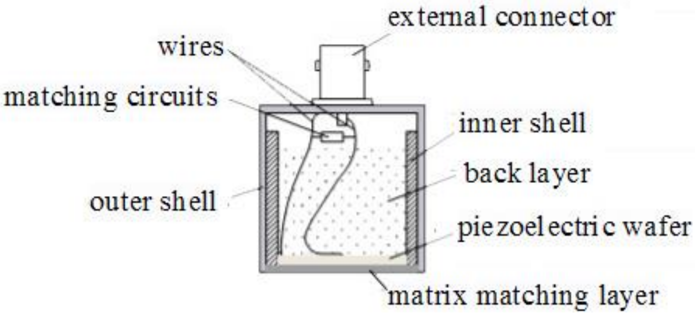

Fig.1 The construction of the transducer

Piezoelectric wafer is a major component of transducer, which could complete the conversion between mechanical energy and electric energy. An acting force on the proper direction of piezoelectric wafer may be about to change its electric polarization state with positive and negative electric charges proportional to the force appearing on opposite surfaces of the piezoelectric wafer. This phenomenon is called piezoelectric effect which is the principle of the ultrasonic transducer to receive ultrasonic signals by converting mechanical signals into electrical signals. Conversely, with the change of electric polarization state in piezoelectric wafer by an effect of electric field on the surfaces, the strain generated in proportion to the electric field intensity. This phenomenon is called inverse piezoelectric effect which is the principle of the ultrasonic transducer to transmit ultrasonic signals by converting electrical signals into mechanical signals.

## 3. Function matching design

### 3.1 The piezoelectric wafer

Piezoelectric wafer is a kind of anisotropic materials, with the fundamental performance parameter such as electro-mechanical coupling coefficient ($K$), dielectric constant ($\varepsilon$) and mechanical quality factor ($Q_{\mathrm{m}}$).

Electro-mechanical coupling coefficient ($K$) is the ratio between mechanical energy and electric energy in piezoelectric wafer, expressed as flowing:

$$K_t = \frac{the\ output\ mechanical\ energy}{the\ input\ power} \times 100\% \qquad \text{(Emitting state)} \quad (1)$$

$$K_s = \frac{the\ output\ power}{the\ input\ mechanical\ energy} \times 100\% \qquad \text{(Accepting state)} \quad (2)$$

There are two different vibration modes in piezoelectric wafer, one is longitudinal electrostriction and the other is lateral electrostriction. $K_{\mathrm{t}}$ is the longitudinal electrostrictive coefficient and $K_{\mathrm{s}}$ is the lateral electrostrictive coefficient. The longitudinal electrostriction is usually used in piezoelectric wafer, and a higher $K_{\mathrm{s}}$ of piezoelectric material is often demanded in the transducer

Dielectric constant ($\varepsilon$) is a physical quantity to describe the dielectric properties of piezoelectric wafer which is related to electrical impedance. In order to realize appropriate impedance matching, $\varepsilon$ of the piezoelectric wafer is usually not be too big.

Mechanical quality factor ($Q_{\mathrm{m}}$) is defined as following:

$$Q_{\mathrm{m}} = \frac{the\ mechanical\ energy\ stored\ inpiezoelectric\ wafer}{the\ loss\ of\ \ mechanical\ energyin\ onevibration\ period} \qquad (3)$$

From the formula 3 we could see that the loss of mechanical energy is smaller with a bigger $Q_{\mathrm{m}}$ ($Q_{\mathrm{m}} > 1$) and the pulsed-signal width would widen. So the back layer is always used behind the piezoelectric wafer to reduce the value of $Q_{\mathrm{m}}$ and to add bandwidth of the transducer.

In this study, we took the choice of $LiNbO_3$ as piezoelectric wafer which is a kind of synthetic single-crystal material with strong piezoelectric properties and stable physical and chemical properties. $LiNbO_3$ doesn't dissolve in water, meanwhile, its curie point and melting point is 1210℃ and 1240℃. The longitudinal electrostrictive coefficient ($K_{\mathrm{t}}$) of $LiNbO_3$ cut along the direction of 36°y is nearly to 55%, so the energy loss of ultrasonic propagating in $LiNbO_3$ is less than 0.05dB/cm with 500MHz high frequency ultrasound. At the same time, LiNbO3 is very perfect for high-frequency transducer because of the frequency constant of it is up to 3.62MHz·mm.

### 3.2 The acoustic impedance match between the back layer and the piezoelectric wafer

The basic requirement to the back layer is that the acoustic impedance of back layer as same as possible to piezoelectric wafer. And the attenuation coefficient of back layer is must bigger enough so the backward ultrasonic generated by piezoelectric wafer could be absorbed and an ideal test waveform may be gained.

In our study，the mixture of tungsten particles and epoxy resin is used for back layer of transducer. In order to make impedance matching well, the theoretical calculation and experiment validate about acoustic impedance of composite materials transducer back layer is required to identify the relationships between volume concentration of particle and its impedance.

Other studies have shown that the acoustic impedance and the attenuation coefficient could be changed by controlling the particle size and quantity in back layer.

### 3.3 The matching circuits of the transducer

The matching circuits of the transducer is an important method to add bandwidth. The impedance characteristic has been demonstrated by equivalent circuit in Fig.2.

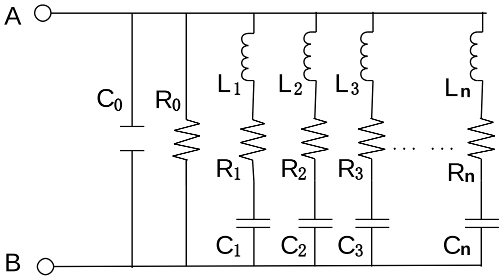

Fig.2 Equivalent circuit

In Fig.2, L1, R2 and C3 are equivalent inductance, equivalent resistance and equivalent capacitance, C0 is static capacitance, R0 is dielectric loss.

$$R_0 = \frac{1}{\omega C_0 \tan\delta} \tag{10}$$

Where $\omega$ is angular frequency, $\tan\delta$ is tangent of dielectric lose angle. Different circuit branch with different L, R and C correspond to different resonance frequency.

If the thickness of the piezoelectric wafer is certain, a fixed frequency $f_0$ existed as formula 11.

$$f_0 = \frac{V}{2d} \tag{11}$$

Where $V$ is speed of sound in piezoelectric wafer, $d$ is thickness of piezoelectric layers.

As can be seen from Fig.2: only the dynamic impedance of L1-R1-C1 branch is caused by piezoelectric effect.

When ultrasonic frequency is just equal to $f_0$ in piezoelectric wafer, the electric resonance and mechanical resonance is compatible which lead L1-R1-C1 circuit branch to pure resistance state. At this moment, the equivalent circuit of Fig.2 with ignoring the influence of R0 can be simplified as shown in Fig.3

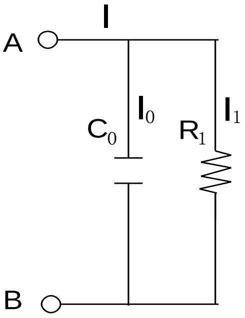

Fig.3 The equivalent circuit when frequency is $f_0$

As can be seen from Fig.3: When frequency is $f_0$, the source current (I) could not flow hundred -percent into R1 branch because of the static capacitance (C0). That is to say the branch current (I0) reduces the power factor of the transducer. For general piezoelectric wafer, C0 is defined as:

$$C_0 = \frac{\varepsilon S}{d} \tag{12}$$

Where $\varepsilon$, $S$ and $d$ are dielectric constant , area and thickness of the piezoelectric wafer. The transmit power of the transducer could be greatly improved by a parallel inductance ($L_0$) to cancel out the capacitive reactance of $C_0$. $L_0$ is calculated by:

$$L_0 = \frac{1}{\omega_0^2 C_0} \tag{13}$$

### 3.4 The matrix matching layer

The matrix matching layer outside of the transducer is another method to add bandwidth. This matching layer could be regarded as dielectric between the transducer and the measured material. Considering from the field of physics, it is a series circuit with the relationship of impedance conversion as following:

$$Z_{in} = Z_l \frac{Z_m \cos\frac{2\pi l}{\lambda} + jZ_l \sin\frac{2\pi l}{\lambda}}{Z_l \cos\frac{2\pi l}{\lambda} + jZ_m \sin\frac{2\pi l}{\lambda}} \tag{14}$$

Where $Z_{in}$ is the input impedance of transducer, $Z_l$ is the impedance of the matrix matching layer, $Z_m$ is the impedance of the measured material, $l$ is the thickness Of the matrix matching layer and $\lambda$ is the wavelength in the matrix matching layer.

The transmission characteristic of the regenerator is discussed in three particular cases:

(1) If $l \ll \lambda$, the effect of the matrix matching layer is only to protect the transducer, without any impedance matching function;

(2) If $l = \lambda/2$, it has no effect to change the relative phase relation because the matrix matching layer could only offer a resonance layer. On the contrary, it increases the reflection loss;

(3) If $l = \lambda/4$, from formula 14 we can see, $Z_{in} = Z_l^2/Z_m$. And then, the best impedance matching optimization is realized as soon as $Z_l = \sqrt{Z_{in} Z_m}$. You could get the same effect. When $l$ is odd time of $\lambda/4$ to thicker-layer or multi-layer.

## 4. Experimental tests and conclusion

According to the above theoretical analysis，a transducer has been designed with 20MHz center frequency $LiNbO_3$, tungsten particles and epoxy resin back layer, appropriate thickness matching layer, etc.

In order to test performance of the transducer, the analysis of the spectrum with a high frequency ultrasonic signal (Fig.4) is obtained by spectrum analyzer, which is shown in Fig.5

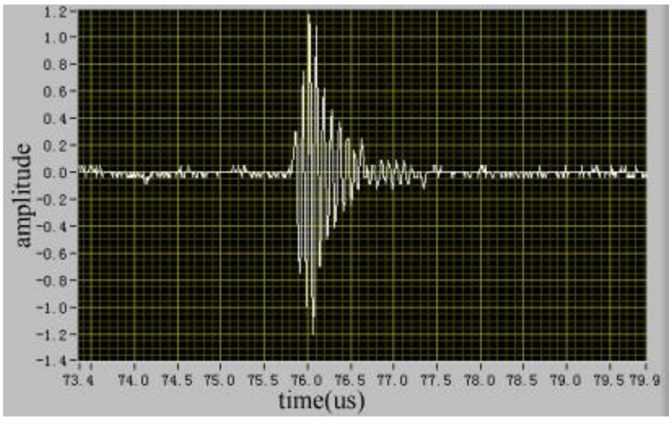

Fig.4 Ultrasonic signal

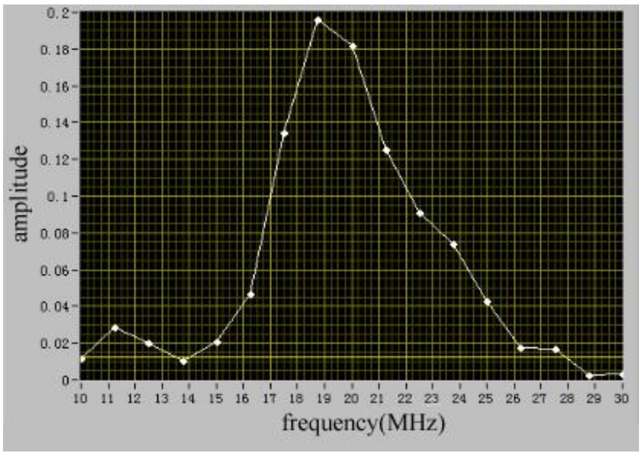

Fig.5 Ultrasonic spectrum curve

As can be seen from Fig.5, the transducer in this study has 18.5MHz center frequency and 5.5MHz band width the power received by 6 dB. So, the relative bandwidth is 30%, and all these are enough evidence to the good bandwidth and high sensitivity of our transducer.

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