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New matching layers to strengthen the metrological characteristics of some ultrasonic transducers

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Abstract

Proper matching layer can increase the energy transmitted efficiency from the transducer's front and it can reduce energy loss due to reflection, so it can improve the transducer's sensitivity. Therefore, the right choice of matching layer is very important. Single and double matching layers - made of copper, silver and silver-nickel - were added on normal transducers' front. The choice of these materials was according to the calculation of their acoustic impedances. The used transducers had frequencies of 2, 4 and 6MHz. The aim was to enhance these transducers, which are the most used in our lab (Ultrasonic measurements lab, NIS, Egypt) for calibration and testing work. Ultrasonic measured different metrological transducers' characteristics such as near field (N), beam diameter (BD), beam directivity (D), transducer sensitivity (S), transducers waves' reflections (R) and transmission (T), signal to noise ratio (SNR) and bandwidth (BW). From the analysis of the obtained results, the effect of matching layers was deduced. Finally, using the modified transducers flaw detection was recorded to know the effect of adding matching layer on the detection of different flat bottom holes in steel specimens.

Keywords: Matching layer; Metrological transducers' characteristics; Flaw

1. *Introduction*

In non-destructive test (NDT), ultrasonic testing (UT) is used to measure thickness and find defects in rolling products like plates and weldments, as well as in components like castings. Consequently, great sensitivity and resolution are required of ultrasonic transducers. By adding a tuned circuit to the transducer, utilizing a suitable backing layer, and positioning a matching layer on the front face of the transducer, transducers with short pulse lengths and high bandwidth can be produced [1].

The active element, baking material, and matching layer make up the majority of an ultrasonic transducer. The piezoelectric element (ceramic, PZT, etc.) that produces the mechanical ultrasonic waves is the active element. The backing material, which lowers reverberation and

energy loss, can be composed of two or more components (e.g., epoxy resin, tungsten, etc.). A matching layer (made of polymer, aluminum, etc.) matches the impedance of the piezoelectric element to the material being tested and shields the element's face.
As acoustic impedance matching transformers, the impedance matching layers on the transducer elements' front surface can increase the transducer's sensitivity [2].

One or more matching layers may be present in the transducers. One to two matching layers are present in the most popular transducers. When a delta function excitation is applied, two quarter wavelength front surface matching layers produce a wide bandwidth with a very brief impulse response. If the impedance of the piezoelectric transducer material is Z_T and the load has impedance Z_L, then for maximum sensitivity the two matching layers would have impedances:

$$Z_1 = 3\surd[Z_T\,(Z_L)^2] \qquad (1)$$

$$Z_2 = 3\surd[(Z_T)^2\,Z_L] \qquad (2)$$

And thicknesses:

$$t_1 = (900/3600)\,(Z_1/\rho_1 f) \qquad (3)$$

$$t_2 = (900/3600)\,(Z_2/\rho_2 f) \qquad (4)$$

Where ρ_i is the density of the i^{th} matching layer and f is the nominal center frequency of operation [3]. The novelty of this study is the designing of new matching layers made of competitive available materials of good properties to enhance the properties of the transducers. The ameliorated transducers with the new matching layers gained new features and they are more able to detect flaws.

2. Research Methodology

2.1 Matching layer

Generally, the transducers are formed of housing, backing material, piezoelectric material and matching layer, Figure 1.

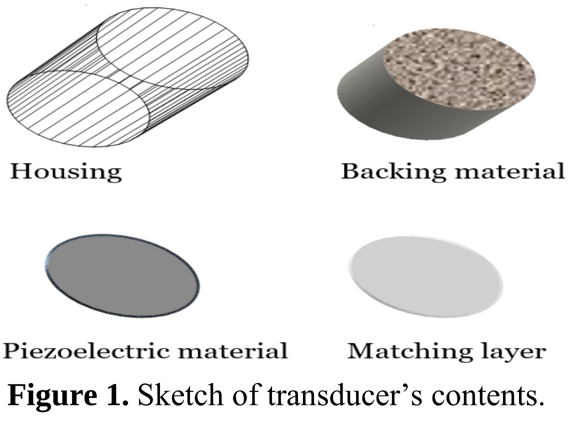


Figure 1. Sketch of transducer's contents.

All of the transducer's components are housed in the housing. The purpose of the backing material is to reduce energy loss and dispersion. The piezoelectric material, the transducer's active component, vibrates in response to an electric signal to generate mechanical ultrasonic waves [4]. Lastly, a matching layer is applied to the piezoelectric material's front. While most transducers only have one matching layer, others include two matching layers for certain applications and purposes. The matching layer's primary functions include matching the impedance of the piezoelectric material to the material being tested and shielding the piezoelectric material's face from external factors like scratches [5].

2.1.1 Choice of matching layer material

In this study, the matching layers were made of copper, silver and silver/nickel. They were added on normal transducers' front of frequencies: 2, 4 and 6MHz. The choice of these materials was according to the calculation of the acoustic impedances (Z_1 and Z_2) (from Eq. 1 and 2). After calculation, the acoustic impedance (Z_1) of the first matching layer was about 41.6MRayls, while the acoustic impedance (Z_2) of the second matching layer was about 38MRayls. Therefore, copper and silver, nickel were used as first matching layers, they have acoustic impedances 41.6MRayls and 40.43MRayls respectively. While, silver was used as second matching layer, it had acoustic impedance 38MRayls. Noting that the acoustic impedance (Z_T) of the transducer was 34.7MRayls and the acoustic impedance (Z_L) of the load specimen (steel 4340) was 45.63MRayls.

2.1.2 Matching layers thicknesses at different frequencies

Matching layer thickness has direct influence on the impedance matching criteria between the transducer and the test specimen [6]. Optimal impedance matching is achieved by sizing the matching layer so that its thickness is one quarter wavelength; also, two quarter can be used [7]. To achieve the two-quarter wavelength front surface matching layers, the thickness of matching layer was calculated according to Eq. 3 and 4, Table 1.

Table 1: Matching layers thicknesses for normal used transducers at different frequencies.

Material of matching layer	**Matching layer thickness, t (mm)** For normal transducers at different frequencies:		
	2 MHz	**4 MHz**	**6 MHz**
Copper	6	3	2
Silver	4.5	2	1.5
Silver-nickel	6	3	2

The thickness measurements were according to ASTM, E797/E797M-21: Standard Practice for Measuring Thickness by Manual Ultrasonic Pulse-Echo Contact Method. The expanded uncertainty for the thickness measurements is ±0.17 mm.

Note that all matching layers had same diameter as the transducers front (12mm). Steel- 4340 was used as load specimen for all measurements. Single matching layer and double matching layer were used. The single matching layers were copper and silver-nickel. The double matching layers were copper + silver and silver + silver-nickel.

2.2 Transducer selection

The ultrasonic measurements were done using a system of measurements, which is consisted of a flaw detector (USIP 20, Krautkramer Branson) to display the echoes, a vector signal analyzer (89441A - hp) to analyze the echoes, an oscilloscope (54615B, hp) to know the time travelled by the echoes, some standards blocks (VI and VII) for thickness calibration, and some normal transducers (2, 4 and 6MHz, 12HB Karl Deutsch) to transmit and to receive echoes.

2.2.1 Transducer frequencies and bandwidth

Using the vector signal analyzer (89441A - hp), the lower (f_l), upper (f_u) and central frequencies (f_o) were determined for all used transducers, Table 2. The bandwidth is the difference between the upper and the lower frequencies.

Table 2: The frequencies and the bandwidth of the used transducers.

Transducer	**f, MHz**	**f_o, MHz**	**f_l, MHz**	**f_u, MHz**	**BW, MHz**
S12 HB 2	2	1.9	1.4	3.1	1.7
S12 HB 4	4	3.8	2.9	5.3	2.4
S12 HB 6	6	5.7	4.2	7.1	2.9

Note:f=Nominal frequency denoted by the factory on the transducer wall and BW=Bandwidth.

As shown in Table 2, the selected transducers' frequencies had different ranges of frequencies that perform best evaluation of matching layers effect on these transducers. In addition, these transducers are the most used in our lab (Ultrasonic measurements lab, NIS, Egypt) for calibration and testing work. Therefore, we aimed to enhance their properties.

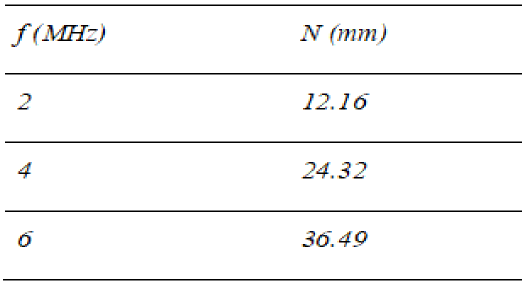
2.2.2 Near field (N)

Ultrasonic waves emerge from several points along the surface of the transducer. The sound field consists of two areas the near field and the far field. The near field is the blind area of the transducer; it is characterized by the numerous interferences between the constructive and the destructive waves. The far field begins directly after the near field; it is the area at which detection can take place because the ultrasonic beam is more uniform and waves' interference diminish [8]. The near field is a function of transducer's frequency and diameter, in addition to the ultrasonic velocity in the tested specimen [9 - 10], Eq. 5.

$$N = (D_{eff})^2 f / 4v \tag{5}$$

Where: D_{eff} = effective diameter of the transducer, f = transducer frequency and v = velocity of specimen under test. NB: the specimen under test was steel-4340 (v =5920 m/s) and the transducers have D_{eff} = 12 mm).

Table 3: Near field values of different used transducers.



f (MHz)	N (mm)
2	12.16
4	24.32
6	36.49

From the near field value, the transducer's sensitivity to detect flaws can be estimated, Table 3. Small near field means high transducer's sensitivity to detect flaws near the surface of the tested specimen [11-12]. From Table 3, the smallest near field value (12.16 mm) is for the transducer of the lowest frequency (2 MHz). Therefore, it is expected that the transducer of 2MHz frequency will have higher sensitivity than the others used.

2.3 Mode of operation

The technique used for all measurements is the pulse echo technique, which is the echo detection by means of a receiver-transmitter transducer. This technique is an easy one that consume time and effort, in addition, it is the most used one for the inspection of different flaws.

3. Results and Discussion

3.1 Influence of matching layers on transducers parameters

3.1.1 Beam diameter (BD)

Beam diameter (BD) can give good information about the influence of matching layer on the transducers [12]. It was calculated according to Eq. 6.

$$BD\ (-6dB) = 1.02Ft / f\ D_{eff} \tag{6}$$

Where: BD = Beam diameter, F = Focal Length, D_{eff} = effective transducer's diameter, f = transducer frequency, t = thickness.

Note: ML=Matching Layer, SML=Single Matching Layer and DML=Double Matching Layer. The test specimen was steel-4340. The effective transducer diameter (D_{eff}) is constant for all used transducers (12mm).

Table 4: Beam diameter (BD) values of transducers with and without matching layer.

F, mm	**t_{steel}, mm**	**$t_{steel+SML}$, mm**	**$t_{steel+DML}$, mm**	**f, MHz**	**BD (without ML), mm**	**BD (with SML), mm**	**BD (with DML), mm**
43	7.3	13.3	17.8	2	13.34	24.31	32.53
86	3.7	6.7	8.7	4	6.76	12.24	15.90
129	2.4	4.4	5.9	6	4.39	8.04	10.78

The beam diameter reflects the transducer's sensitivity for performing a test, i.e. the capability of a transducer to detect different defects. The smaller the beam diameter, the greater the amount of energy is reflected by a flaw, thus it can be said that transducer of small diameter can easily localize flaws [14-15].

From Table 4, the beam diameter of the used transducers increased when using SML and increased more when using DML. This means that the efficiency of the transducers to detect small flaws diminishes as SML or DML were added, but their ability to scan more flaws in more range increased [16].

3.1.2 Beam directivity (D)

Beam directivity (D) can reflect good information for the effect of matching layers on transducers. For a transducer of a conical beam, the directivity (D) calculated as follow [17]:

$$D = 2 / (1-\cos(\theta/2)) \quad (7)$$

Table 5 shows the beam directivity variation when adding the matching layers.

Table 5: Beam directivity (D) of transducers with and without matching layer.

F (MHz)	**D without ML**	**D with SML**	**D with DML**
2	1.17	1.02	1.01
4	1.57	1.17	1.02
6	1.02	1.17	1.01

The divergence angle θ (1/2 the beam spread angle) represents a measure from the center of the acoustic axis to the point where the sound pressure decreased by one half (−3 dB) to the side of the acoustic axis in the far field (M.G. Silk, 1984). The divergence angle θ was from echo signal profile of the used transducers using Vector Signal Analyzer (89441A, HP).

As shown in Table 5, the beam directivity ranged from 1.02 to 1.57 for the transducers without adding new matching layer. While, it ranged from 1.02 to 1.17 for the transducers with single matching layer. But it ranged from 1.01 to 1.02 for the transducers with double matching layers.

3.1.3 Transducer sensitivity (S)

Transducer sensitivity (S) can express the transducer ability to detect flaws [12]. It was obtained from the relationship of the amplitude of voltage applied to the transducer, V_o and the amplitude of the pulse-echo voltage received from the target (steel), V_x (Eq. 8).

$$S(dB) = 20 \log (V_x/V_o) \qquad (8)$$

The transducer sensitivity is also the function of the medium in which the test is performed [18].

Table 6: Sensitivity (S) values of transducers with and without matching layer.

f (MHz)	S without ML	S with SML	S with DML
2	1.19	2.54	2.97
4	1.99	3.01	4.38
6	2.91	4.46	6.25

From Table 6, we noted the increment in sensitivity of transducers with SML from about 1.5 to 2 times those without addition of matching layer, while, the increment in sensitivity of transducers with DML from about 2 to 2.5 times those without addition of matching layer. Therefore, the addition of matching layers enhanced the transducer sensitivity [19]. DML was more efficient to increase sensitivity than SML.

3.1.4 Transducers waves' reflections (R_1) and transmission (T_1)

Ultrasonic waves are reflected at boundaries, where there are differences in acoustic impedance, Z.

The transducers waves' reflections (R_1) and transmission (T_1) are important to estimate the amount of energy entering and exiting from the specimen under test. They are given as follow [1]:

$$T_1=4/\{2+[((Z_3/Z_1)+(Z_1/Z_3))\cos^2 k_2 d]+[((Z_3)^2/Z_1Z_3)+(Z_1Z_3/Z_2))\sin^2 k_2 d]\} \qquad (9)$$

$$R_1 = 1-T_1 \qquad (10)$$

Where: Z_1 = acoustic impedance of first medium (transducer=34.7MRayls),

Z_2 = acoustic impedance of second medium (Z_2 will vary according to the used matching layer i.e. Z_2 for different matching layers will be as follow:

Z_2 when using SML copper = 41.61MRayls,

Z_2 when using SML silver - nickel = 40.43MRayls,

Z_2 when using DML copper + silver = 79.61MRayls,

Z_2 when using DML silver – nickel + silver = 78.43MRayls),

Z_3 = acoustic impedance of tested specimen (steel = 45.63MRayls),

k_2 = the wave number in medium,

d = the matching layer (s) thickness.

The transducers waves' reflections (R_1) and transmission (T_1) are affected by matching layer, which is considered as second boundary before reaching the test specimen surface, which is the third medium [20], Table 7.

Table 7: Reflections (R_1) and transmission (T_1) of transducers with SML and with DML matching layer.

Transducer with	**T_1%**			**R_1%**		
	At frequency, f (MHz)			**At frequency, f (MHz)**		
	2	**4**	**6**	**2**	**4**	**6**
SML: copper	27%	57%	16%	73%	43%	84%
SML: silver-nickel	26%	57%	15%	74%	43%	85%
DML: copper+silver	23%	41%	32%	77%	59%	68%
DML: silver-nickel+silver	23%	41%	32%	77%	59%	68%

Table 7 shows the increment of reflection coefficient (R_1) in 2 and 4MHz transducers with SML than in those with DML but the transmission coefficient (T_1) do the contrast. While, there was a decrement of reflection coefficient (R_1) in 6MHz transducers with SML than in those with DML but the transmission coefficient (T_1) increased. We can say that these ameliorated transducers with new added matching layers may have many applications that need high reflection coefficient.

3.1.5 Signal to noise ratio (SNR)

After the transducer fabrication, SNR is an important factor to be calculated, because it may affect the purchase of the transducer or it may affect its usage in one or more of its applications. Signal to noise ratio (SNR) was obtained from the relationship between the received signal amplitude in volts, V_x and the noise floor in volts, V_n [21].

$$SNR\ (dB) = -20 \log (V_x/V_n) \tag{11}$$

There are many factors affect the SNR, like: the probe size, frequency, bandwidth, efficiency, etc., in addition to the inherent noisiness in tested specimen e.g. cracks, surface curvature or roughness, etc. Matching layer in transducer may affect the transducer's bandwidth or its efficiency, so it can be said that the addition of matching layer/s may have influence on the SNR, Table 8.

Table 8: Signal to noise ratio (SNR) values of transducers with and without matching layer.

f (MHz)	SNR without ML	SNR with SML	SNR with DML
2	-10.36	-14.22	-16.83
4	-10.87	-14.46	-17.95
6	-11.52	-15.99	-19.43

From Table 8, The SNR was decreased by a factor of about 1.4 when using transducer of SML, while it was decreased by a factor of about 1.6 to 1.7 when using transducer of DML. This means the DML transducers have less SNR, so they had high pulse width and less ability to detect small flaw [22].

3.1.6 Bandwidth (BW)

After measuring the bandwidth of the transducers of added SML and DML, we noticed the increment in the bandwidth, i.e. the bandwidth became broader in the transducers of added SML and DML [22]. Vector signal analyzer (89441A - hp) was used to analyze the transducers echo to get the BW. The increment in BW was about 35% for transducers of added SML and about 50% for transducers of added DML, Table 9.

Table 9: Bandwidth (BW) for transducers with and without adding matching layer.

Bandwidth (BW), without adding ML, MHz	Bandwidth (BW), with adding SML, MHz	Bandwidth (BW), with adding DML, MHz
1.7	2.295	2.55
2.4	3.24	3.6
2.9	3.915	4.35

As per Table 9, SML (Copper or Silver-nickel) and DML (Copper + Silver or Silver-nickel + silver) were effective to increase the BW of the used transducers.

3.2 Flaw detection using the modified transducers

It was important to test the efficiency of the modified transducers with the new single matching layers (SML) or the new double matching layers (DML). Therefore, steel specimens with flat bottom holes were designed to be tested using these modified transducers.

To know where we will drill the flat bottom holes in the steel specimens, the shortest possible flaw distance for every used transducer must be calculated. From the specimen's surface, the shortest possible flaw distance, which can be detected by the direct pulse-echo contact method, is given by the following equation [20].

$$N < 1.4 * \text{shortest possible flaw distance} \quad (12)$$

The calculated shortest possible flaw distance for every used transducer is shown in Table 10.

Table 10: The shortest possible flaw distance for the used transducers.

Transducer's frequency, f (MHz)	Shortest possible flaw distance (mm)	Near field, N (mm)
2	8.7	12.16
4	17.4	24.32
6	26.1	36.49

Therefore, we cannot detect sub-surface flaws, which will be located at a distance less than that calculated in Table 10. Therefore, the designed steel test specimens had FBH at 9mm for 2MHz transducer, at 20mm for 4MHz transducer and at 27mm for 6MHz transducer. Steel test specimens' dimensions were 45*45*30mm^3. They had same flat bottom holes (FBH) of same diameter (0.95mm) and same depth (5mm) but they located at different distances from the specimen's surface (9, 20 and 27mm), Figure 2. Thus, the steel specimens were detected using these different transducers, Figure 3.

Figure 2. Steel specimen with FBH at about 9 mm from the specimen's surface.

The equipment of the ultrasonic measurement was adjusted on the same conditions (the gain, filter coarse, time base, rectifier, etc.) for all measurements, and then the echo height was recorded see example in Fig. 4. In addition, the temperature and the humidity were kept constant during all measurements (temperature = 23^{0}C and humidity = 45%).

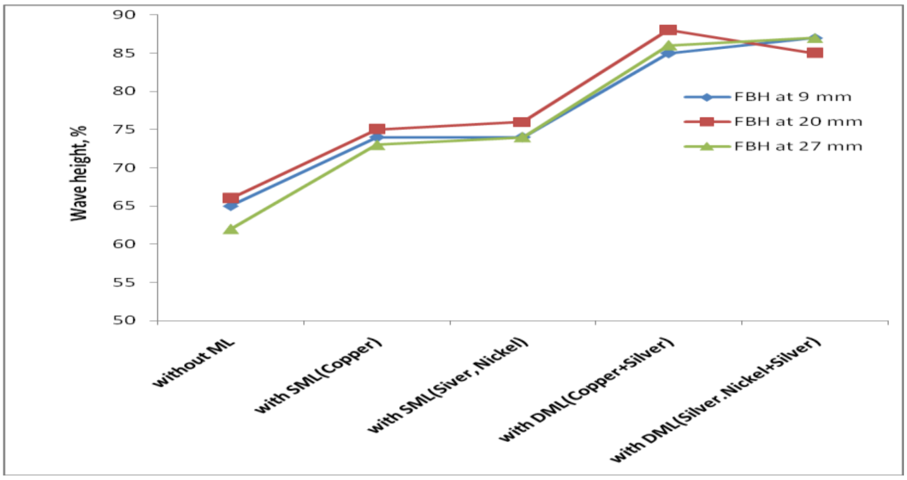
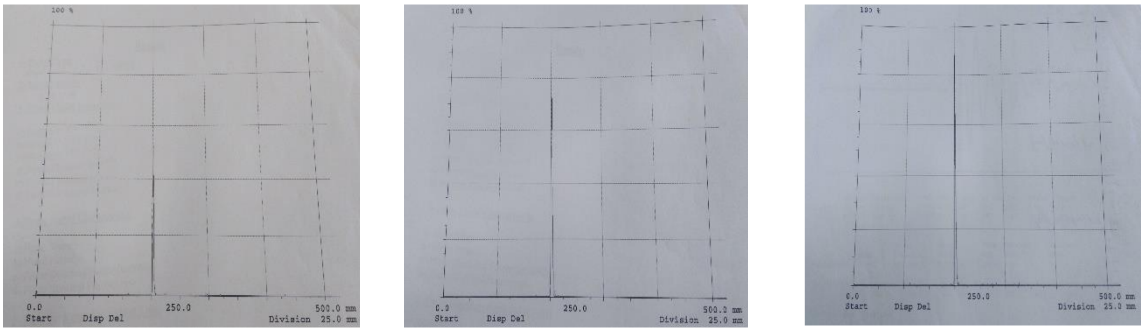


Figure 3. Echo height detection from different FBH (with respect to specimens' surface, 30 mm) in steel specimens using different transducers (without adding ML, with adding SML and with adding DML).



(a) (b) (c)

Figure 4. Detection of echo height from FBH at 20 mm from the steel surface specimen (photos were taken from Flaw detector USIP 20, Krautkramer Branson.

(a) Using 4MHz transducer without adding matching layer. The echo height is about 66%.

(b) Using 4MHz transducer with adding single matching layer (Copper). The echo height is about 74%.

(c) Using 4MHz transducer with adding single matching layer (Copper). The echo height is about 74%].

From Figures 3 and 4, we noticed the increment in wave height with respect to the test mode. The echo height was about 62% to 66% when using transducers without adding matching layer, it was about 73% to 75% when using transducers with single matching layer, and it was about

85% to 88% when using transducers with double matching layer. Thus, it can be said that the adding of matching layers enhanced the transducer echo height [21]. Therefore, the added matching layers improved the capability of the transducer to detect flat bottom holes [22]. These ameliorated transducers can be used in our lab. to make calibration and testing of more flaws in different materials. Future research work can be done to increase the detection capability of the recent of transducers in the lab. That have different frequencies, bandwidth, near field, etc.

Conclusions

In this study, SML and DML were made of copper, silver and silver-nickel. They were added on normal transducers' front. These matching layers had influence on the transducer's parameters: beam diameter, beam directivity, transducers' sensitivity, reflection and transmission coefficients, signal to noise ratio and bandwidth. We concluded the following: - The efficiency of the transducers to detect small flaws diminished but their ability to scan more flaws in more range increased. The transducer sensitivity increased. The reflection coefficient (R_1) in transducers with SML increased than in those with DML but the transmission coefficient (T_1) do the contrast. The DML transducers have less SNR, so they had high pulse width and less ability to detect small flaw. The bandwidth became broader in the transducers of added SML and DML.

Finally, when FBH were detected using SML transducers or DML transducers, we noticed that the added matching layer enhanced the capability of the transducer to detect flat bottom holes. The advance technology of this study is the innovation of these matching layers.

Therefore, we can conclude that the new modification of the transducers was efficient and give good benefit results, i.e. the modified transducers – by the new matching layers – became improved to do calibration and test works in our lab. (Ultrasonic measurements lab., National Institute of Standards, Egypt).

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