Proceedings of the 10th WSEAS International Conference on CIRCUITS, Vouliagmeni, Athens, Greece, July 10-12, 2006 (pp148-153)

Simulation of Balanced Surface Acoustic Wave (SAW) Devices Incorporating a Modified Four-port Mason's Equivalent Circuit Model

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Abstract: - In the present work, a four-port model for inter-digital transducer was developed. This model was modified from Mason's equivalent circuit and was ideal for the simulation of balanced mode surface acoustic wave devices. Inheriting the virtues of Mason's model, this model included the energy storage effect and was capable to fit arbitrary polarity configuration of transducers. Simulation results for an unbalanced-balanced longitudinal coupled double mode SAW filter compared well, the experimental results showed, validating the proposed model.

Key-Words: - Surface acoustic wave, Equivalent circuit model, Balanced longitudinal coupled double mode SAW filter.

1. Introduction

Because of the nature of circuit topology, symmetry and virtual ground, balanced circuits are robust to poor radio-frequency (RF) ground, eliminate electromagnetic interference (EMI), suppress the even mode harmonics and possess excellent immunity from variety of noise sources such as those from power supplies, adjacent circuits, and other external sources. These virtues support balanced devices and circuits, such as balanced surface acoustic wave (SAW) filters, differential mode amplifiers, balanced mixers and etc., to be widely applied in modern communication systems. SAW filters, which have the merits of low insertion loss, excellent shape factor and compact size, are key components in many communication systems served as an intermediate-frequency (IF) or RF stage filter [1-6]. Previous techniques used-- like Mason's equivalent circuit, coupling-of-modes (COM), and P-matrix--in modeling SAW devices were originally for unbalanced circuit structure for all these techniques model the inter-digital transducer (IDT) as a three-port device [7-11]. And there were many publications [12-15], in which the model for IDT was further developed and modified based on original Smith model developed in 1972 [8], most of them either focused on equivalent circuit parameters of IDTs derived from SAW in periodic metal gratings [12] or equivalent networks for SAW gratings [13], and some applied in one-port resonator or unbalanced SAW filters [14][15]. Although unbalanced devices may be converted to balanced circuitry by inserting a baluns as adapters between balanced and unbalanced ports, the expanse is increasing circuit complexity and cost. In spite balanced SAW filter becomes more and more popular and various types of balanced SAW filters have come to the market, such as balanced lattice-ladder filters [4][16], five-IDT type longitudinal multi mode SAW (LMMS) filter [17] and longitudinal coupled double mode SAW (DMS) filter [2][3][18][19], few of these papers detailed on simulation techniques but emphasized on structures and performances. For SAW filters that directly operate in balanced mode, it is more convenient to treat IDT as a four-port device. Hence, a modified Mason's equivalent circuit model with four ports-- two acoustic ports and two electrical ports-- was essential in this paper. As inherited from Mason's model, the effect of energy storage and arbitrary polarity configuration of transducers were taken into account in this work. Simulation results for an unbalanced input and balanced output DMS SAW filter showed good agreement with experiments.

2. Simulation of Balanced SAW Devices

2.1 Review of Mason's Circuit Model and Simulation of SAW Devices

On simulation of SAW devices, one of commonly employed technique is to decompose the devices into several building blocks and then use any circuit software to obtain the entire performance of the devices. As illustrated in Figs. 1 and 2, a simple SAW filter and a one-port SAW resonator can be decomposed in to blocks of IDT (S_{IDT}), transmission path (S_G), reflection greeting (S_R), and boundary block (or absorber) (S_B). By knowing the characteristics of each block and circuit topology, the entire performance of the filter is readily obtainable.

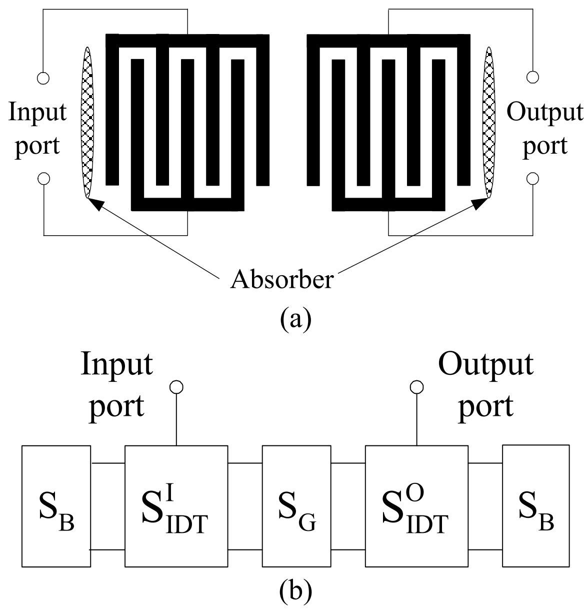


Fig. 1 A simple SAW filter: (a) The geometric structure, (b) The building blocks.

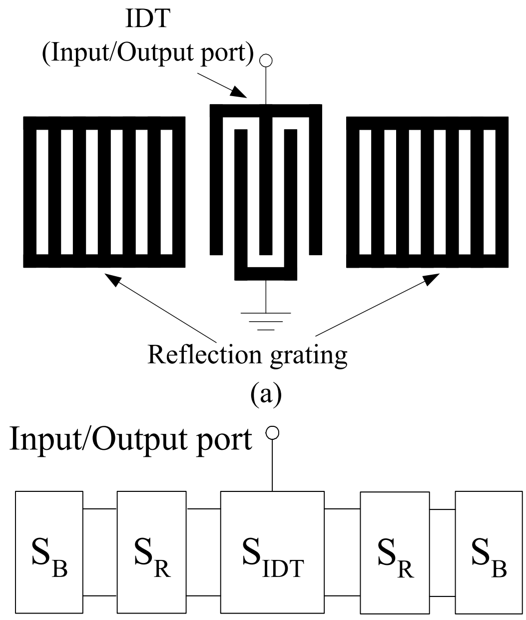


Fig. 2 A one-port SAW resonator: (a) The geometric structure, (b) The building blocks.

Several methods can be applied to model IDT and reflection grating among them COM and Mason's equivalent circuit are most commonly used. In Mason's equivalent circuit model, the single electrode is described as a three-port network as shown in Fig. 3. The network consists of three regions, one metallized region and two unmetallized regions transversally which are both modeled as a section of transmission line T-network. The notations used in Fig. 3 are listed as follows: $Z_{1m} = Z_m \tanh(\psi_n/2)$, $Z_{2m} = Z_m \operatorname{csc}h(\psi_n)$, $Z_{1o} = Z_o \tanh(\phi_n/2)$ and $Z_{2o} = Z_o \operatorname{csch}(\phi_n)$. $\psi_n = \gamma_m L_s$, $\phi_n = \gamma_o L_g/2$. L_s and L_g are the lengths of the metallized and unmetallized portions, γ_m and γ_o are propagation constants under metallized and unmetallized portions, and Z_m and Z_o are characteristic impedances for metallized and unmetallized region, respectively. The energy storage effect at the junction of metallized and unmetallized regions is expressed by adding a radiation susceptance jB. The capacitor C_s is the static capacitance of IDT. The transformer ratio R_n models the excitation efficiency. To determine the characteristics of a single electrode one can solve the three-port equivalent circuit and the results are given as a 3×3 admittance matrix in reference [8]. Once the admittance parameters of single electrode are known, the admittance parameters of entire IDT can be further calculated by cascading each electrode in proper polarization [8]. The equivalent circuit model of single electrode for reflection grating is similar to the one used in IDT, except the acoustic port is either short- or open-circuited for short or open reflection grating. Therefore, instead of three-port network, the reflection grating is simply a two-port circuit.

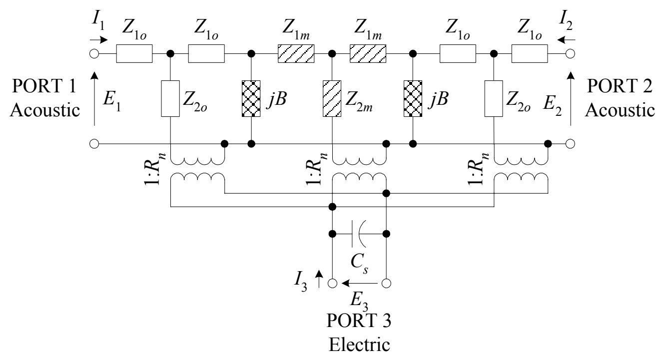
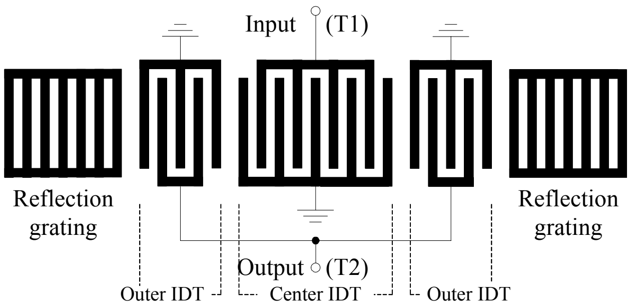


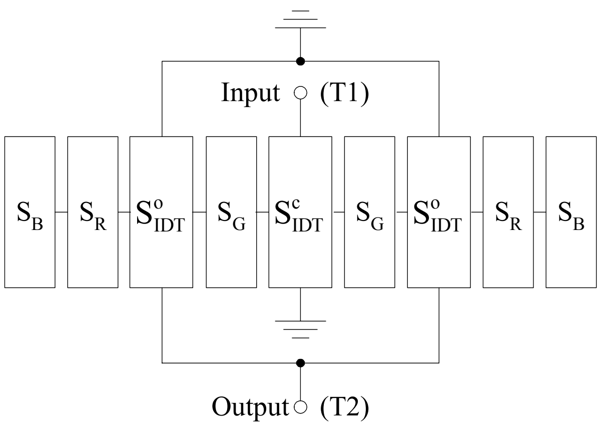
Fig. 3 Three-port Mason's equivalent circuit of a single electrode including an acoustic impedance discontinuity.

2.2 Limitation of Three-Port IDT Model on Simulation Balanced SAW Devices

Generally, the techniques mentioned in section 2.1 that use the three-port IDT model can be applied to simulate the performance of unbalanced input to unbalanced output SAW devices without any difficulty. However, for devices in which balanced ports are involved, one may encounter difficulties in constructing the circuitry. Fig. 4(a) illustrates a one-track unbalanced input and unbalanced output DMS filter. Three-port IDT model can be applied to construct the circuitry of this filter successfully, as shown in Fig. 4(b). As balanced output is required, as shown in Fig. 5(a), constructing the filter circuit becomes unrealizable. Unfortunately, the market demanding for such devices are increasing for various reasons such as noise reduction purpose and different impedance requirement at each terminal balanced port. In Fig. 5(a), the unbalanced input is applied to the electrical ports of the outer IDTs and the balanced output is applied to two sides of the center IDT. Apparently, equivalent circuit for IDT that contains only one electrical port is not able to model the output of the filter. It is necessary to treat the center IDT as a four-port circuit with two acoustic ports and two electrical ports. With an extra electrical port of the center IDT, modeling the balanced output port becomes an easy task as shown in Fig. 5(b).

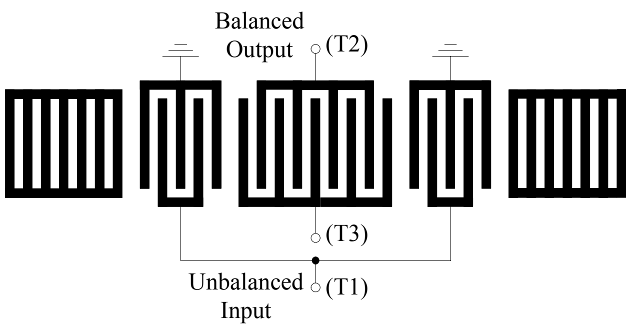


(a)

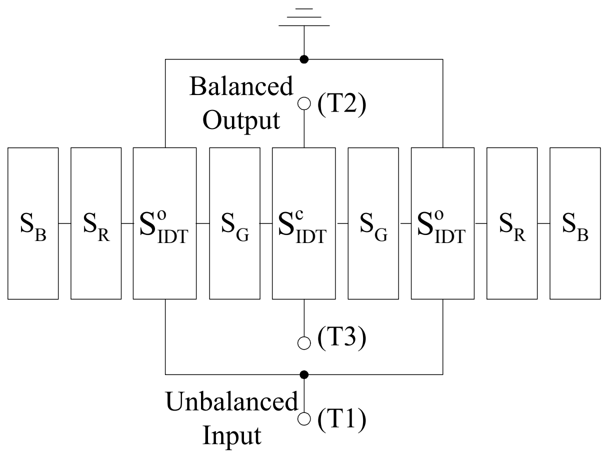


(b)

Fig. 4 A typical one-track unbalanced input and output DMS filter: (a) The geometric structure, (b) The building blocks.



(a)



(b)

Fig. 5 A typical one-track unbalanced input and balanced output DMS filter: (a) The geometric structure, (b) The building blocks.

2.3 Derivation of Four-Port IDT Model

Fig. 6 shows a modified four-port IDT network and the equivalent circuit of a single electrode. Unlike the original Mason's model, this modified circuit includes two electrical ports, port 3 and 4. Exactly like the Mason's model, metallized and unmetallized regions of a single electrode are described as transmission line T-networks. The energy storage effect due to the discontinuity between metallized and unmetallized regions and the static capacitance of single electrode are modeled by a susceptance jB and capacitor C_s, respectively. The transformer ratio R_n models the excitation efficiency. As inheriting from Mason's model, this four-port model is capable of handling various metallization ratio and most of the second order effects such as attenuation, energy storage effect, and reflection at junction of metallized and unmetallized regions. Applying the definition of admittance parameters [20] and solve the circuit, the 4×4 admittance matrices of the unmetallized and metallized regions are derived as:

$$
\begin{aligned}
y_{11o} &= y_{22o} = \frac{1}{Z_{1o} + Z_{12o}} \\
y_{12o} &= -\frac{Z_{12o}}{Z_{1o}\left(Z_{1o} + Z_{12o}\right)} \\
y_{13o} &= y_{23o} = -\frac{R_n}{Z_{1o} + 2Z_{2o}} \\
y_{14o} &= y_{24o} = \frac{R_n}{Z_{1o} + 2Z_{2o}} \\
y_{33o} &= y_{44o} = -\frac{R_n}{Z_{1o} + 2Z_{2o}} \\
y_{34o} &= -\frac{2R_n^2}{2Z_{2o} + Z_{1o}} - j\omega C_n
\end{aligned}
\qquad (2)
$$

$$
\begin{aligned}
y_{11m} &= y_{22m} = \frac{1}{Z_{1m} + Z_{12m}} + jB \\
y_{12m} &= -\frac{Z_{12m}}{Z_{1m}\left(Z_{1m} + Z_{12m}\right)} \\
y_{13m} &= y_{23m} = -\frac{R_n}{Z_{1m} + 2Z_{2m}} \\
y_{14m} &= y_{24m} = \frac{R_n}{Z_{1m} + 2Z_{2m}} \\
y_{33m} &= y_{44m} = -\frac{R_n}{Z_{1m} + 2Z_{2m}} \\
y_{34m} &= -\frac{2R_n^2}{2Z_{2m} + Z_{1m}} - j\omega C_n
\end{aligned}
\qquad (3)
$$

In Equations (2) and (3),

$$Z_{12o} = \left(Z_{1o} Z_{2o}\right) / \left(Z_{1o} + Z_{2o}\right) \quad (4)$$

$$Z_{12m} = \left(Z_{1m} Z_{2m}\right) / \left(Z_{1m} + Z_{2m}\right) \quad (5)$$

y_{ijo} and y_{jim} are the admittance parameters of unmetallized and metallized regions, respectively. Other notations are the same as in section 2.1.

Once the admittance matrices of unmetallized and metallized regions are obtained, the admittance parameters of a single electrode of an IDT are readily known by cascading networks according to Fig. 6(b). Similarly, one can determine the admittance matrix of the entire IDT by cascading each electrode in proper position and polarization as shown in Fig. 7, that is the terminal 1 of n^{th} section is cascaded to terminal 2 of $(n+1)^{\text{th}}$ section and all set of terminals 3 and 4 are connected in parallel, respectively. For four-port networks cascaded together, the cumulative admittance parameters of n electrodes connected together can be calculated by:

$$\tilde{y}_{ij}^{(1)} = y_{ij}^{(1)} \quad (6)$$

for $n > 1$,

$$
\begin{aligned}
\tilde{y}_{11}^{(n)} &= y_{11}^{(n)} - \frac{\left[y_{12}^{(n)}\right]^2}{A} \\
\tilde{y}_{12}^{(n)} &= -\frac{y_{12}^{(n)} \cdot \tilde{y}_{12}^{(n-1)}}{A} \\
\tilde{y}_{13}^{(n)} &= y_{13}^{(n)} - \frac{y_{12}^{(n)} \cdot B}{A} \\
\tilde{y}_{14}^{(n)} &= y_{14}^{(n)} - \frac{y_{12}^{(n)} \cdot C}{A} \\
\tilde{y}_{22}^{(n)} &= \tilde{y}_{22}^{(n-1)} - \frac{\left[\tilde{y}_{12}^{(n-1)}\right]^2}{A} \\
\tilde{y}_{23}^{(n)} &= \tilde{y}_{23}^{(n-1)} - \frac{\tilde{y}_{12}^{(n-1)} \cdot B}{A} \\
\tilde{y}_{24}^{(n)} &= \tilde{y}_{24}^{(n-1)} - \frac{\tilde{y}_{12}^{(n-1)} \cdot C}{A}
\end{aligned}
\qquad (7)
$$

$$
\begin{aligned}
\tilde{y}_{33}^{(n)} &= \tilde{y}_{33}^{(n-1)} + y_{33}^{(n)} - \frac{B^2}{A} \\
\tilde{y}_{34}^{(n)} &= \tilde{y}_{34}^{(n-1)} + y_{34}^{(n)} - \frac{B \cdot C}{A} \\
\tilde{y}_{44}^{(n)} &= \tilde{y}_{44}^{(n-1)} + y_{44}^{(n)} - \frac{C^2}{A}
\end{aligned}
\qquad (7)
$$

where,

$$
\begin{aligned}
A &= y_{22}^{(n)} + \tilde{y}_{11}^{(n-1)} \\
B &= y_{23}^{(n)} + \tilde{y}_{13}^{(n-1)} \\
C &= y_{24}^{(n)} + \tilde{y}_{11}^{(n-1)}
\end{aligned}
\qquad (8)
$$

$y_{ij}^{(n)}$ and $\tilde{y}_{ij}^{(n)}$ are the admittance parameters of the n^{th} electrode and n-connected electrodes, respectively.

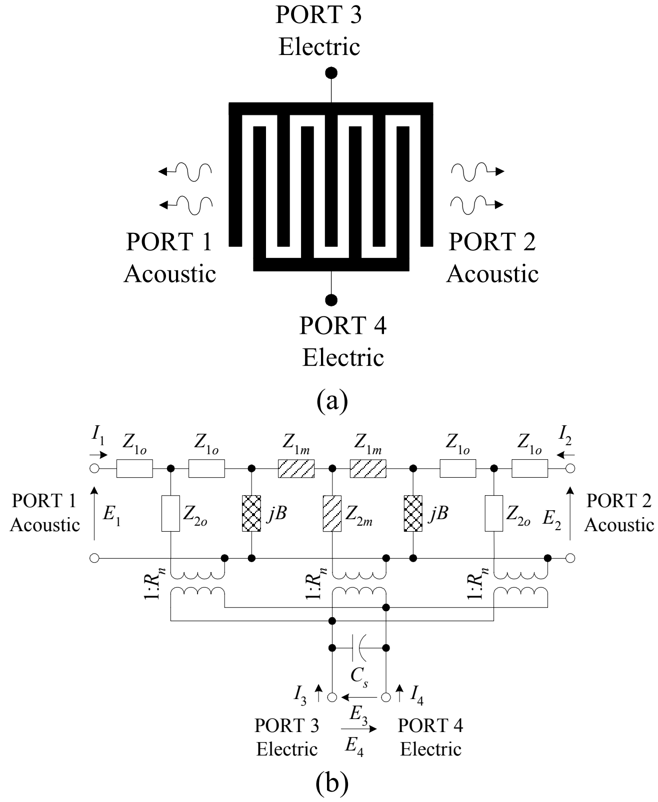


Fig. 6 (a) Representation of the SAW IDT as a four-port network, port 1 and 2 are the "acoustic" ports and port 3 and 4 are the "electric" ports. (b) A modified equivalent circuit model of a single electrode of the SAW IDT.

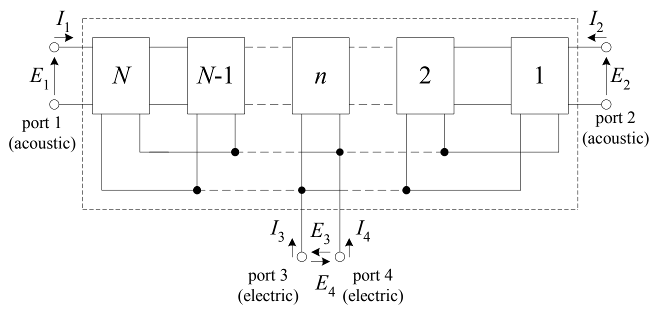


Fig. 7 Cascaded model for N electrodes of a balanced SAW IDT.

3. Experimental Results

To demonstrate the usage of the four-port IDT model, a one-track unbalanced-balanced DMS filter as illustrated in Fig. 5 was fabricated. The geometrical parameters of the fabricated filter are listed in Table 1.

3.1 Passband Characteristics

Since the amplitude and the phase difference between balanced terminals affect the passband ripple and stopband attenuation of balanced SAW devices [3], it is of importance to know these characteristics. Figs. 8 and 9 show the simulation and experiment performances of amplitude and phase differences between S21 and S31 in passband. In the two figures, S21 is measured between terminals T1 and T2 with terminal T3 grounded. S31 is measured between terminals T1 and T3 with terminal T2 grounded. The measured different amplitude is small about within 0.75 dB in the passband (f0 +/-6 MHz) and the phase is inverted. The phase imbalance (∠S21-∠S31-180 degree) is +/-5 degree.

Table 1 Geometrical parameters of the fabricated unbalanced-balanced DMS filter.

IDT period	3.67 μm
Number of center IDT fingers	22.5 pairs
Number of outer IDT fingers	15.5 pairs
Aperture of IDT	107 μm
Number of reflectors	150 strips
Al electrode thickness	2520Å (h/λ~7%)
Substrate	Y42°-X $LiTaO_3$

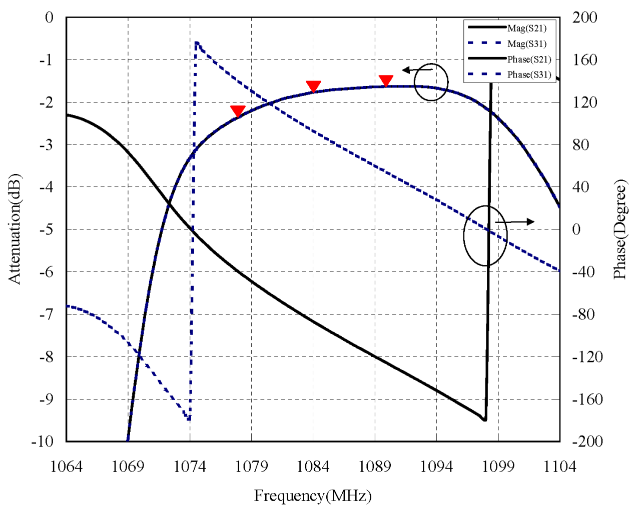


Fig. 8 Simulated characteristics of the unbalanced-balanced DMS filter, where S21 is in solid line and S31 is in dot line.

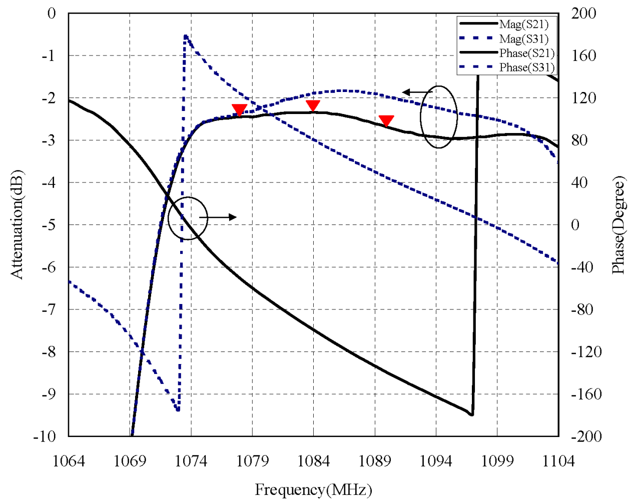


Fig. 9 Experimental characteristics of unbalanced-balanced DMS filter, where S21 is in solid line and S31 is in dot line.

3.2 Unbalanced-Balanced DMS Filter Performance

The simulation and experiment performances of the one-track unbalanced-balanced DMS filter are shown in Fig. 10. The center frequency of the filter is at 1084MHz and the input/output impedance is 50Ω/50Ω. As seen from Fig. 10, the overall performance obtained from simulation well matched with experimental results. The slight disagreement on pass band insertion loss is caused by redundant testing layout so that the device can fit in the test set of probe station.

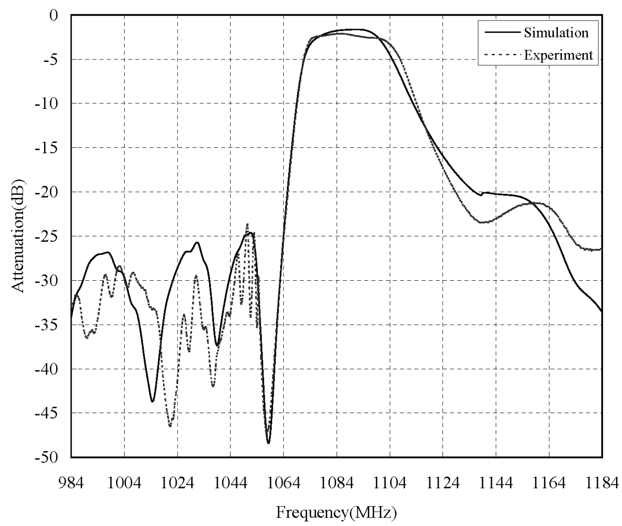


Fig. 10 Overall performance of the unbalanced-balanced DMS filter, where simulated in solid line and experimental in dot line

4. Conclusions

A modified Mason's equivalent circuit with four independent ports for single electrode of IDT was derived. Based on this model, a four-port IDT admittance parameters were obtained by cascading each electrode in proper position and polarization. The model was verified with experimental results of an unbalanced-balanced DMS SAW filter. By employing the four-port model of IDT, the performances of most balance type SAW filters can be easily simulated.

Acknowledgments

The authors would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 94-2213-E-214-016 and ftech Corporation for technique support.

References:

[1] S. N. Kondratiev, V. P. Plessky and M. A. Schwab, Compact Low Loss IF Balanced Bridge Filters, *1995 IEEE Ultrasonics Symposium*, 1995, pp. 55-58.

[2] Y. Taguchi, S.I. Seki, K. Onishi and K. Eda, A New Balanced-Unbalanced Type RF-Band SAW Filter, *1996 IEEE MTT-S Digest*, 1996, pp. 417-420.

[3] G. Endoh, M. Ueda, O. Kawachi and Y. Fujiwara, High Performance Balanced Type SAW Filters in the Range of 900MHz and 1.9GHz, *1997 IEEE Ultrasonics Symposium*, 1997, pp. 41-44.

[4] V. Plessky, Balanced Lattice Filter with Acoustically Interacting Resonators, *2002 IEEE Ultrasonics Symposium*, 2002, pp. 143-145.

[5] Application note 1373-1, Agilent Technoligies, Inc., 2002.

[6] Application note 1EZ53, Rohde & Schwarz, 2004.

[7] G. Tobolka, Mixed Matrix Representation of SAW Transducers, *IEEE Transactions on Sonics and Ultrasonics*, Vol.26, No.6, 1979, pp. 426-428.

[8] W. Richard Smith, Henry M. Gerard and William R. Jones, Analysis and Design of Dispersive Interdigital Surface Wave Transducers, *IEEE Transaction on Microwave Theory and Techniques*, Vol. 20, No. 7, 1972, pp.458-471.

[9] K. Hirota and K. Nakamura, Equivalent Circuit of Interdigital Transducers Based on Coupling-of-Modes Theory Considering Electrode Resistivity and Propagation Loss, *Japanese Journal of Applied Physics*, Vol.33, 1994, pp. 2972-2975.

[10] K. Ibata, T. O,ori, K. Hoshimoto and M. Yamaguch, Polynomial Approximation of SAW Reflection Characteristics for Fast Devices Simulation Tools, *Japanese Journal of Applied Physics*, Vol.38, 1999, pp. 3293-3296.

[11] K. Hoshimoto, *Surface Acoustic Wave Devices in Telecommunications*, Springer-Verlag, Berlin Heidelberg, 2000.

[12] T. Aoki and K. A. Ingebrigtsen, Equivalent Circuit Parameters of Interdigital Transducers Derived from Dispersion Relations for Surface Acoustic Waves in Periodic Metal Gratings, *IEEE Transactions on Sonics and Ultrasonics*, Vol.24, No.3, 1977, pp. 167-178.

[13] M. Koshiba and S. Mitobe, Equivalent Networks for SAW Gratings, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol.35, No.5, 1988, pp. 531-535.

[14] T. Kojima and R. Yabuno, Equivalent Four-Port Networks Force Factors for SAW Interdigital Transducers, *1994 IEEE Ultrasonics Symposium*, 1994, pp. 227-232.

[15] T. Kojima, N. Kawai and H. Obara, Equivalent Four-Port Networks for Series Connected SAW-IDT and Their Application, *1997 IEEE Ultrasonics Symposium*, 1997, pp. 49-54.

[16] H. K. J. Dolle, J. W. Lobeek, A. Tuinhount and J. Foekema, Balanced Lattice-Ladder Bandpass Filter in Bulk Acoustic Wave Technology, *2004 IEEE MTT-S Digest*, 2004, pp. 391-394.

[17] S. Ichikawa, H. Kanasaki, N. Akahori, M. Koshino and Y. Ebata, Mode Analysis of Longitudinal Multi Mode SAW Resonator Filter, *2001 IEEE Ultrasonics Symposium*, 2001, pp. 101-106.

[18] M. Koshino, H. Kanasaki, T. Yamashita, S. Motobe, M. Kawase and Y. Ebata, Simulation Modeling and Correction Method for Balance Performance of RF SAW Filters, *2002 IEEE Ultrasonics Symposium*, 2002, pp. 301-305.

[19] G. Kovacs, A Generalised P-matrix Model for SAW Filters, *2002 IEEE Ultrasonics Symposium*, 2002, pp. 707-710.

[20] D. M. Pozar, *Microwave Engineering*, John Wiley & Sons, Inc., New York, USA, 1998.