Operation Mechanism of Double-Mode Surface Acoustic Wave Filters with Pitch-Modulated IDTs and Reflectors

Ken-ya Hashimoto, Tatsuya Omori and Masatsune Yamaguchi

Dept. of Electronics and Mechanical Eng., Chiba University, 1-33 Yayoi-cho, Inage-ku, Chiba-shi, Chiba 263-8522, Japan
E-mail: {k.hashimoto, omori, masa} @faculty.chiba-u.jp

Abstract—One of the authors (KH) previously proposed pitch-modulated IDTs and reflectors for developing low-loss and wideband longitudinally coupled double-mode SAW (DMS) filters. This paper discusses how a wide and flat passband is realised by applying the pitch-modulated IDTs and reflectors to DMS filters. It is shown that the pitch-modulated structure enables to adjust the location of multiple resonance frequencies simultaneously by varying an effective reflective position with frequency. That is, the IDTs are pitch-modulated so that the outer portion has slightly larger pitch than the inside, and the pitch of the outermost reflectors is made largest. Accordingly, higher-order SAW resonances occur between the two pitch-modulated IDTs; the outer portion of each IDT acts as a reflector, while the inner portion is mainly responsible for SAW excitation. Lower-order SAW resonances occur between the two reflectors.

I. Introduction

Presently, because of their features like embedded balun- and transformer-functions in addition to their low insertion loss and wide passband width, the longitudinally-coupled double-mode SAW (DMS) filters [1] are widely used in the RF section of modern mobile phones.

The DMS filter is designed to support multiple resonance modes in its passband. Since interdigital transducers (IDTs) are placed in the resonance cavity and their internal reflection is not negligible, the device design is quite complex.

In the traditional DMS filter design, the location of resonance frequencies is adjusted by the IDT acoustic length and pitch, and the gap between two IDTs. Since the degree of freedom (the number of design variables) is not large enough in the design, the number of adjustable resonances is rather limited. Accordingly, the cavity length must be sufficiently short to enlarge the frequency separation between resonances for wideband applications. In order to place in the cavity and impedance match with peripheral circuitry, this needs the IDT with small acoustic length and increased aperture. The increased aperture results in relatively large ohmic loss of the IDT, though. In addition, the centre gap causes the SAW scattering into bulk acoustic waves. For these reasons, traditional DMS filters exhibit relatively larger insertion loss than ladder-type SAW filters [2].

The authors showed that the number of adjustable resonances can be increased by simply increasing the number of design variables [3]. As a practical technique to increase the degree of freedom, one of the authors (KH) proposed the pitch-modulated IDT and reflector to show how they work effectively in DMS filters [4].

It was also shown that the pitch-modulated IDT and reflector also offer the following two distinctive features:

1) Because of the extended IDT length, the IDT aperture can be made short.

2) The increased degree of freedom makes the centre gap unnecessary, and structural discontinuities become avoidable.

For their excellent performance, the pitch-modulated IDT and reflector have already been applied to the development of Rx filters in the PCS Antenna duplexer [5].

This paper discusses how a wide and flat passband shape is realised by the pitch-modulated IDT and reflector in DMS filters.

It is shown that the location of multiple resonance frequencies is adjusted simultaneously by varying an effective reflective position with frequency. That is, the IDTs are pitch-modulated so that the outer portion has slightly larger pitch than the inside, and the pitch of the outermost reflectors is made largest. By this pitch-modulation, the inner portion acts as a waveguide at lower-order resonances, while the outer portion is responsible for SAW excitation. On the other hand, at the highest-order resonance, the outer portion acts as a reflector, while the inner portion is responsible for SAW excitation.

II. Operation of conventional DMS filters

This section discusses for comparison how a flat passband shape has been realised in conventional DMS filters.

For the discussion, let us assume a two-port DMS structure shown in Fig. 1.

Because of structural symmetry, resonance modes in the structure are categorised into two types: one is the even-order mode having symmetrical field distribution, and the other is the odd-order mode with antisymmetrical one (see Fig. 1).

The electrical equivalent circuit of the DMS filter is given by Fig. 2 [6]. In the figure, C_0 is the IDT static capacitance, and Y_{me} and Y_{mo} are the motional admittances, respectively, for the symmetrical and antisymmetrical modes.

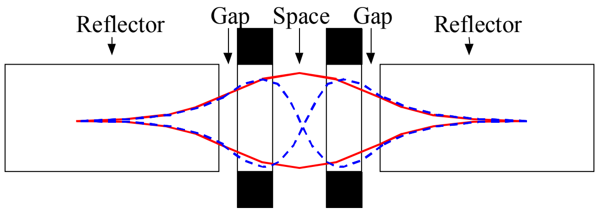


Fig. 1 Two-port DMS resonator.

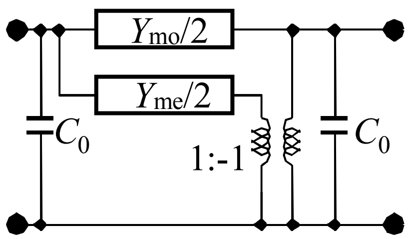
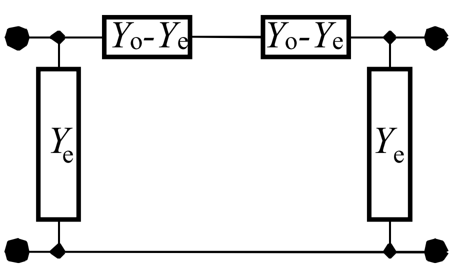
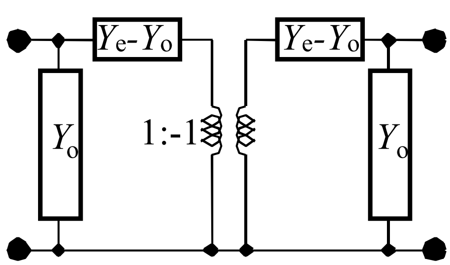


Fig. 2 Equivalent circuit for two-port DMS filter.

This circuit can be modified into π-type circuits shown in Figs. 3 (a) and (b), where $Y_o=2(Y_{mo}+j\omega C_0)$ is the input admittance of an equivalent one-port resonator when the two IDTs are parallel-connected, whereas $Y_e=2(Y_{me}+j\omega C_0)$ is the admittance when the two IDTs are parallel-connected, their polarity being inverted.



(a) Equivalent circuit A



(b) Equivalent circuit B

Fig. 3 Modified equivalent circuit for two-port DMS filter.

It is clear from the circuits that the lossless transmission is realised when the following condition is satisfied:

The antiresonance frequency ω_a^o giving $Y_o=0$ coincides with the resonance frequency ω_r^e giving $Y_e^{-1}=0$, or the antiresonance frequency ω_a^e giving $Y_e=0$ coincides with the resonance frequency ω_r^o giving $Y_o^{-1}=0$.

It is known that the transmission peak becomes broad and the insertion loss is minimised when $(\omega C_0)^{-1}$ is equal to the characteristic impedance R_0 of the peripheral circuit.

In multi-mode resonators, ω_r^e and ω_r^o appear alternately in general, and ω_a^e and ω_a^o are larger than ω_r^e and ω_r^o, respectively. So, provided that the lossless transmission condition is satisfied at multiple frequencies successively, the transmission peaks overlap with each other, by which a flat and wide passband can be obtained without sacrificing the insertion loss.

In the conventional DMS filter design, three resonance modes are used for the synthesis of the filter passband. Two of them resonate between the two reflectors (see Fig. 1), and the location and separation of the frequencies are adjusted mainly by the IDT length L_I and gap length L_T between the two IDTs. On the other hand, the remaining third mode resonates between the IDTs (see Fig. 4). Since the IDT acts as a reflector at its resonance, the location of the resonance frequency is scarcely influenced by L_I and mainly determined by L_T.

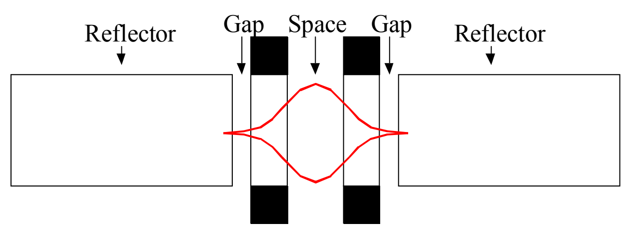


Fig. 4 Higher-order resonance mode.

For this operation, the IDT pitch p_I is chosen so that the reflection of the IDTs may be weak at the first and second resonances, while the reflection may get significant at the third resonance [3]. On the other hand, the reflector pitch p_r and the electrode thickness h are determined properly so that the reflector stopband includes only these three resonances.

A DMS filter was designed by this principle. The coupling-of-modes theory [7] was employed for the device modelling, and the excitation efficiency[7] ζp_I was assumed to be $(0.02\omega C p_I)^{0.5}$. The specifications were as follows: $|S_{21}|=1$ at F=[-0.025:0.025] and $|S_{21}|=0$ at F=[-0.07:-0.04] and F=[0.04:0.07], where F is the frequency normalised by the centre frequency of the filter passband.

The designed results are listed in Table. 1.

Fig. 5 shows the admittance of the designed DMS filter. It is seen that the lossless transmission condition is mostly fulfilled at F=-0.02 and F=+0.01.

Table 1 Parameters of designed conventional DMS filter

Reflection coefficient	$\kappa_{12}p_I=0.0824\pi$
IDT length	$L_I=13.5p_I$
Reflector length	$L_r=55p_r$
Gap length	$L_T=0.36\lambda$
IDT pitch	$p_r=1.03p_I$
Characteristic impedance	$R_0=(0.93\omega CL_I)^{-1}$

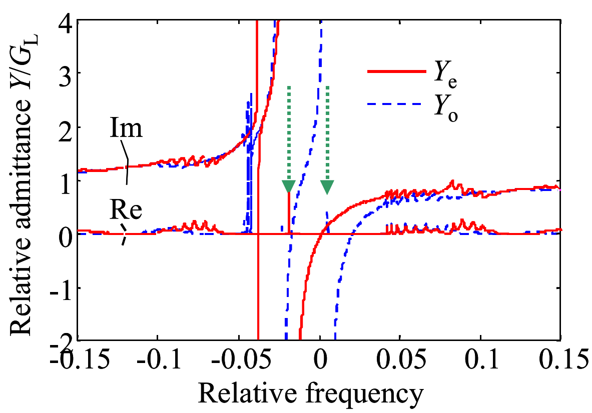


Fig. 5 Input admittance of conventional DMS filter.

Fig. 6 shows the transmission characteristics of the filter when two stages are cascade-connected. Comparison of Figs. 5 and 6 indicates that the flat passband is realised between two frequencies satisfying the lossless transmission condition.

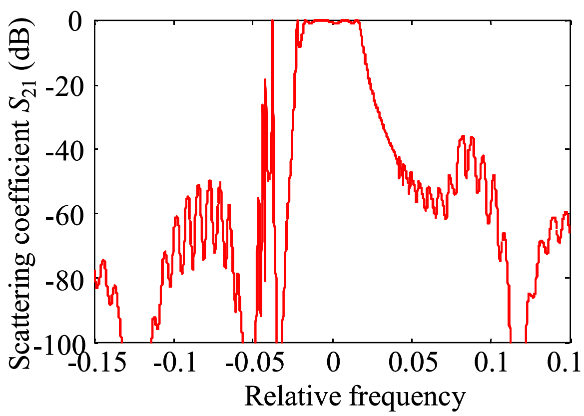


Fig. 6 Transmission Characteristics of designed DMS filter (two stage cascaded).

The relatively strong transmission is seen at F=[0.03,0.1]. This is called the transversal response and caused by the direct SAW transfer between the two IDTs. Accordingly, the bandwidth of the transversal response is almost determined by L_I.

A null is seen at $F\approx$-0.04, where Y_e and Y_o resonate simultaneously (see Fig. 5). Namely, the resonance occurs in a half section composed of an IDT and a reflector, which means that SAW signals are not transferred from one IDT to another.

The strong spurious responses are seen in the lower rejection band. This is due to sidelobes in the reflector response, and can be suppressed efficiently by tapering off [8] the outer portion of the reflectors.

III. Pitch-Modulated IDTs

The IDT-pitch modulation allows not only to adjust the frequency location of multiple modes simultaneously, but also to optimise the IDT characteristics for the efficient excitation provided that there is the sufficient number of design variables.

A pitch-modulated IDT was designed by subdividing it into four blocks and optimising their periodicities and lengths (see Fig. 7). All subdivided blocks are cascade-connected acoustically and parallel-connected electrically. The specifications are the same with those used in II.

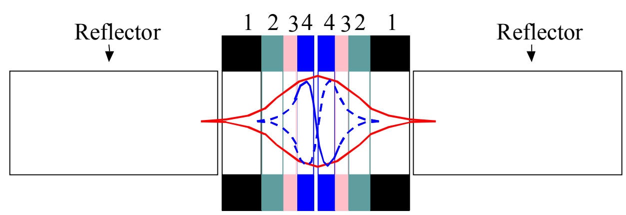


Fig. 7 Pitch Modulated DMS filter.

Fig. 8 shows the admittance of the designed DMS filter. It is seen that the lossless condition is almost fulfilled at three frequencies (F=-0.03, F=-0.01 and F=0.02). Compared with Fig. 5, it is seen that the frequency separation between the adjacent resonances is narrow, which is due to the increased IDT length.

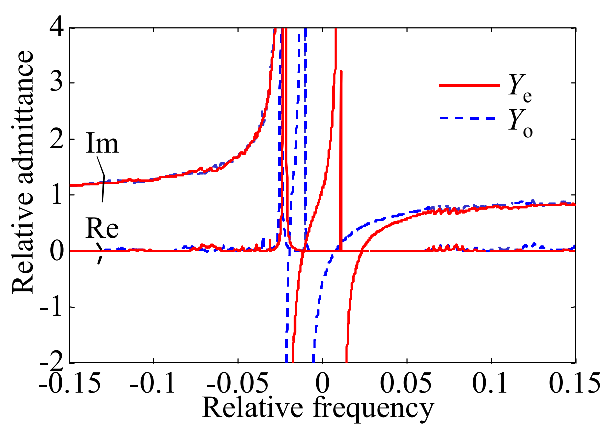


Fig. 8 Input admittance of pitch-modulated DMS filter.

Fig. 9 shows the transmission characteristics when two stages are cascade-connected. In the figure, the broken line shows the response of the conventional DMS filter in Fig. 6. It is seen that the passband width becomes wide and a steep skirt response is achieved. In addition, the transversal response in the upper rejection band is suppressed by more than 15 dB. This is due to the fact that the IDT is 1.7 times as long as the IDT used in the conventional design.

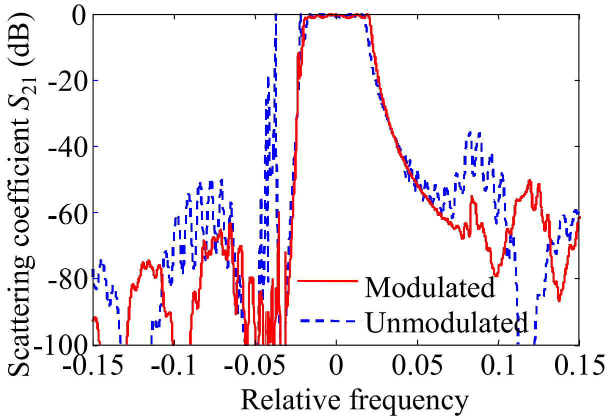


Fig. 9 Transmission Characteristics of designed DMS filter (two-stage cascaded). Solid-line: modulated, and broken-line: unmodulated

Table 2 shows the designed parameters, where L_I and p_I are the IDT length and the periodicity for each subsection. It is seen that p_I increases gradually from the inner portion to the outer portion, and the reflectors have the largest periodicity. This suggests that the lower-order resonances should occur between two reflectors, and that the outer portion of the IDTs should be mainly responsible for SAW excitation. On the other hand, at the higher-order resonances, the outer portion acts as a reflector, while the inner portion is responsible for SAW excitation (see Fig. 7).

Table 2 Designed results of pitch-modulated DMS filter.

	L_I/p_I	p_c/p_I	$\kappa_{12}p_I$
Reflector	55	1.012	0.087π
IDT1	11.5	1.030	0.087π
IDT2	7	1.029	0.087π
IDT3	4.5	1.074	0.087π
IDT4	0.5	1.050	0.087π

Fig. 10 shows the transmission characteristics when the reflectors are removed from the designed DMS filter. Although the insertion loss becomes large at the lower side of the passband, it scaracely changes at the upper side. This means that the reflection by the outer portion of the IDTs is responsible for the upper side of the passband.

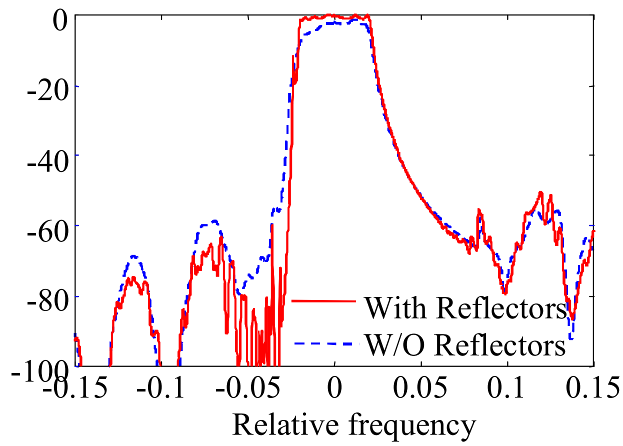


Fig. 10 Transmission Characteristics of two-stage cascaded modulated DMS filter. Solid-line: with reflectors, and broken-line: without reflectors

Fig. 11 shows the radiation conductance G_I of the pitch-modulated IDT. It is seen that G_I is relatively large at the lower side of the passband, while it becomes small at the upper side, which is due to the influence of the internal reflection.

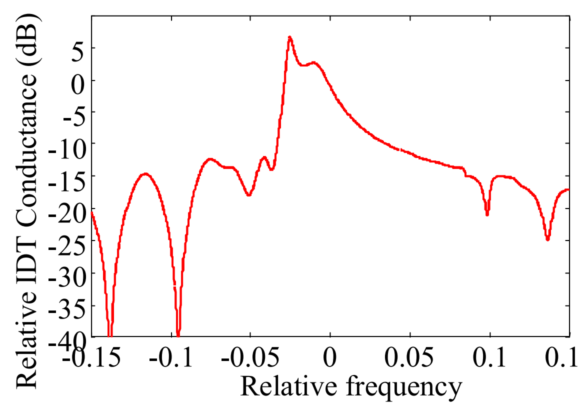


Fig. 11 Radiation conductance of pitch-modulated IDT.

IV. Modulation of κ_{12}

From the operation mechanism described above and the result shown in Fig. 11, it is expected that inner portion of the IDTs should possess small SAW reflection coefficient κ_{12} for efficient SAW excitation; the electrode width should be modulated as well as the IDT pitch so that the inner portion of IDTs possess smaller κ_{12} than the outer portion.

To verify this, the DMS filter was designed again by adding κ_{12} of subdivided blocks as variables.

Fig. 12 shows the designed result. In the figure, the broken line is the response of the DMS filter with modulated p_I shown in Fig. 9. It is seen that the passband width is increased and the skirt response becomes steeper by the increased number of the resonances employed.

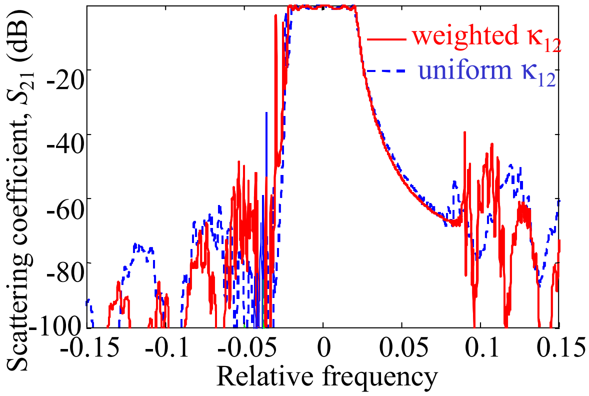


Fig. 12 Transmission Characteristics of two-stage cascaded modulated DMS filter. Solid-line: κ_{12} modulated, and broken-line: κ_{12} unmodulated

Table 3 shows the designed parameters. As is expected, it is seen that κ_{12} increases gradually from the inner to outer portion, and the reflectors has the larges value of κ_{12}. Here, the total IDT length is increased upto $34p_I$ to modulate κ_{12}.

Table 3 Designed results of pitch and κ_{12}-modulated DMS filter.

	L_I/p_I	p_c/p_I	$\kappa_{12}p_I$
Reflector	50	1.021	0.119π
IDT1	12	1.034	0.113π
IDT2	12	1.035	0.119π
IDT3	7	1.044	0.076π
IDT4	3	1.065	0.0748π

It is also expected that the device performance could be further improved by modulating the excitation efficiency ζp_I, though ζp_I and $\kappa_{12}p_I$ are not independently adjustable.

V. Conclusions

This paper discussed how the location of multiple resonance frequencies is adjusted in the DMS filter employing the pitch-modulated IDTs and reflectors.

The IDTs are pitch-modulated so that the outer portion has slightly larger pitch than the inner portion, and the pitch of the outermost reflectors is made largest. This makes it possible to vary an effective reflective position with frequency, and, therefore, to adjust the location of multiple resonance frequencies simultaneously.

Although not discussed, the pitch-modulation is also effectively applied to the reflectors. This allows to increase the variable range in the effective reflective position to improve the device performance further.

Acknowledgements

The authors thank to Dr. Satoh and Mr. Ueda of Fujitsu Laboratories and Mr. Ikata, Mr. Kawachi and Mr. Tajima of Fujitsu Media Devices for their fruitful discussions. This work was partially supported by the Grant-in-Aids for Fundamental Scientific Research from the Ministry of Education, Sports, Science and Culture.

References

[1] T.Morita, Y.Watanabe, M.Tanaka and Y.Nawazawa: Wideband Low Loss Double Mode SAW Filters, Proc. IEEE Ultrasonics Symp. (1992) pp. 95-104

[2] O.Ikata, T.Miyashita, T.Matsuda, T.Nishikawa and Y.Satoh: Development of Low-Loss Band–Pass Filters Using SAW Resonators for Portable Telephone, Proc. IEEE Ultrasonics Symp. (1992) pp. 112-115.

[3] K.Hashimoto and M.Yamaguchi: Design Considera-tions on Wideband Longitudinally-Coupled Double-Mode SAW Filters, Proc. IEEE Ultrason. Symp. (2002) pp. 153-157.

[4] O.Kawachi, S.Mitobe, M.Tajima, T.Yamaji, S.Inoue and K.Hashimoto: A Low-Loss and Wide-Band DMS Filter Using Pitch-Modulated IDT and Reflector Structures, Proc. IEEE UFFC 50th Anniversary Conf. (2004) pp. 298-301.

[5] S.Inoue, J.Tsutsumi, Y.Iwamoto, T.Matsuda, M.Miura, Y.Satoh, M.Ueda and O.Ikata, 1.9 GHz Range Ultra-Low-Loss and Steep Cut-Off Double Mode SAW Filter for the Rx Band in the PCS Antenna Duplexer, Proc. IEEE Ultrason. Symp. (2003) pp. 389-392.

[6] K.Hashimoto: Surface Acoustic Wave Devices in Telecommunications -Modelling and Simulation-, 5.3.3. Multi-Mode Resonator Filters, Springer Verlag, Heidelberg (2000) pp. 145-148.

[7] K.Hashimoto: Surface Acoustic Wave Devices in Telecommunications -Modelling and Simulation-, Chap. 7 Coupling-of-Modes Theory, Springer Verlag, Heidelberg (2000) pp. 191-235.

[8] P.S.Cross: Surface Acoustic Wave Resonator-Filters Using Tapered Gratings, Proc. IEEE Ultrason. Symp. (1977) pp. 894-899.