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Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)
16-18 November, 2016

Multi-Mode Filter Composed of Single-mode SAW/BAW Resonators
単一モード SAW/BAW 共振子で構成される多モードフィルタ

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1. Introduction

Because of superior out-of-band rejection, acoustically-coupled multi-mode filters are widely used in the Rx section of RF duplexers. They are realized by the acoustically-coupled SAW technology because location of multiple resonances can be adjusted properly by the electrode pattern[1,2)].

Use of the BAW technology is attractive because of its better power durability and lower loss. A few attempts with excellent device performances were reported[3-5)]. However, they were not mass produced, because tricky mechanism(s) are necessary for the coupling adjustment and their process control is extremely difficult.

This paper discusses possibility of electrically-coupled multi-mode filters. Fig. 1 shows the equivalent circuit of multi-mode filter[1)]. Our attempt is to construct this circuit using multiple single-mode resonators. It is shown that high filter performances are achievable provided that a high performance balun is available. A circuit is proposed to cancel the balun imperfection, and its effectiveness is discussed.

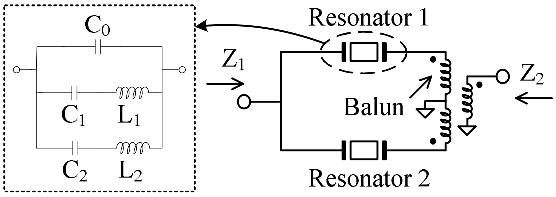

Fig.1 Equivalent circuit of multi-mode filter

2. Design of electrically coupled multi-mode filter

Hereafter, we discuss the case where each resonator in Fig.1 supports two resonances for simplicity. Let us denote the resonance frequencies of the resonator 1 as f_1 and f_3 and those of the resonator 2 as f_2 and f_4. The basic design rules of multi-mode filters are (a) the resonator 1 causes the anti-resonances at f_2 and f_4, and the resonator 2 causes the anti-resonance at f_3 and f_5, and (b) the shunt capacitance C_0 of these resonators is $1/4\pi f_c R_0$, where R_0 is the peripheral circuit impedance. Under the proper design, admittance of these resonators are expressed as follows:

$$Y_1 = j\omega c^2 C_0 \frac{(1-f^2/f_2^2)(1-f^2/f_4^2)}{(1-f^2/f_1^2)(1-f^2/f_3^2)} \qquad (1)$$

$$Y_2 = j\omega c^2 C_0 \frac{(1-f^2/f_3^2)(1-f^2/f_5^2)}{(1-f^2/f_2^2)(1-f^2/f_4^2)} \qquad (2)$$

where $c=(1+\gamma^{-1})^{0.5}$ and γ is the capacitance ratio of the equivalent resonators. Note that the following condition is added for obtaining good out-of-band rejection above the passband:

$$\frac{f_1^2 f_3^2}{f_2^2 f_4^2} = \frac{f_2^2 f_4^2}{f_3^2 f_5^2} = c^{-2} \qquad (3)$$

Here we set

$$f_{n+1} = c^{0.5} f_n \quad (n=1\sim4) \qquad (4)$$

to satisfy Eq. (3). Then Eqs. (1) and (2) can be modified as:

$$Y_1 = j\omega C_1\left[1+\frac{\gamma^{-1}}{1-f^2/f_1^2}\right] + j\omega C_3\left[1+\frac{\gamma^{-1}}{1-f^2/f_3^2}\right] \qquad (5)$$

$$Y_2 = j\omega C_2\left[1+\frac{\gamma^{-1}}{1-f^2/f_2^2}\right] + j\omega C_4\left[1+\frac{\gamma^{-1}}{1-f^2/f_4^2}\right] \qquad (6)$$

where

$$C_1 = C_2 = \frac{(c^2+c+1)}{(c+1)^2}C_0 \quad \text{and} \quad C_3 = C_4 = \frac{c}{(c+1)^2}C_0 .$$

Eqs. (5) and (6) indicate that the filter circuit given in Fig. 1 can be realized by the use of four single mode resonators with the resonance frequency f_n and shunt capacitance of C_n (n=1~4) with identical γ instead of two dual-mode resonators.

Fig.2 shows the frequency response of a tri-mode filter deigned by the above-mentioned procedure with γ=15. The resonator Q factor was set at 1,000. Typical frequency response of multi-mode filters can be seen. In the figure, Y_1 and Y_2 of designed resonators are also shown. It is understood that a flat and wide passband is synthesized owing to coincidence of three resonance frequencies with three anti-resonance frequencies. On the other hand, out-of-band rejection is owed to common-mode rejection of the balun because input signals can transmit through the

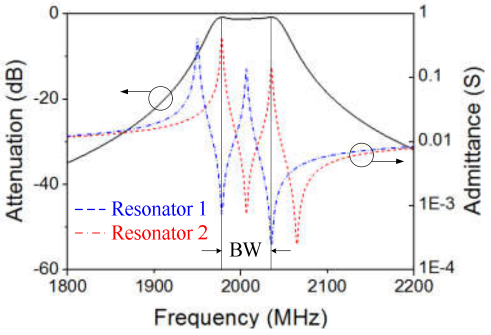

Fig.2 Frequency dependence of designed tri-mode filter and resonator admittance

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resonators.

In the present case, combination of resonances is limited to three for simplicity. It is known that use of more resonances results in enhancement of the out-of-band rejection[2]. In such cases, we can apply the above-mentioned design procedure after extension.

Cascade-connection of this configuration is also effective to enhance the out-of-band rejection.

3. Circuits for Common-mode suppression

In the calculation shown in Fig. 1, the balun is assumed to offer complete common-mode rejection. However, it is finite in practice, and gives significant impact to the out-of-band rejection of the total filter performance.

Here we propose to the circuit shown in Fig. 3 for the common-mode suppression. For differential signals, no voltage drop occurs to two grounded inductors. Thus the circuit is equivalent to phase shifters and 100% power transfer is possible when proper design is applied. On the other hand, as for common-mode signals, they can generate a resonance with shunt capacitors, which causes a transmission zero only to common-mode signals.

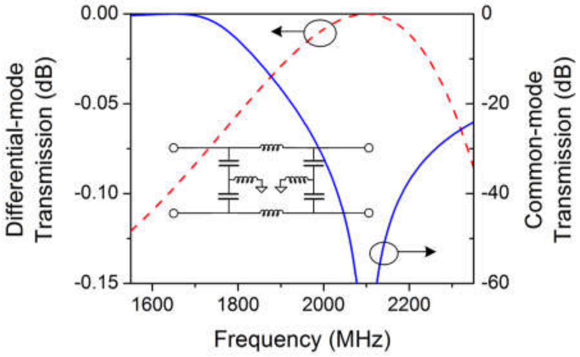

Fig.3 A circuit for the common-mode suppression and its frequency response

Fig.3 also shows the typical frequency response of this circuit. It is seen that the common-mode transmission is well suppressed while the differential mode can transmit the circuit for a certain range of frequencies.

The circuit shown in Fig. 3 is low-pass intrinsically, and thus better common-mode suppression is achievable at frequencies higher than the passband. When we replace capacitances in Fig. 3 with inductances and vice versa, we can construct another circuit for the common-mode suppression. The circuit is high-pass intrinsically, and better common-mode suppression is achievable at frequencies lower than the passband.

4. Filter design in combination with commercial balun

A Tx filter for Band 1 is designed using an LC-type balun[6] produced by MURATA CO., LTD. Fig. 4 shows the filter responses for three cases. When the real balun is employed (b), the response is significantly deteriorated not only in the rejection band but also the passband from the case where the ideal balun is employed (a). This deterioration is caused by leakage of common-mode signals. On the other hand, when the real balun is applied with the circuit shown in Fig. 3 (c), the passband characteristics are almost identical with those of the ideal one (a), and the out-of band characteristics are also almost identical except at frequencies much lower than the passband. This deterioration is caused by the low-pass characteristic of the circuit shown in Fig. 3.

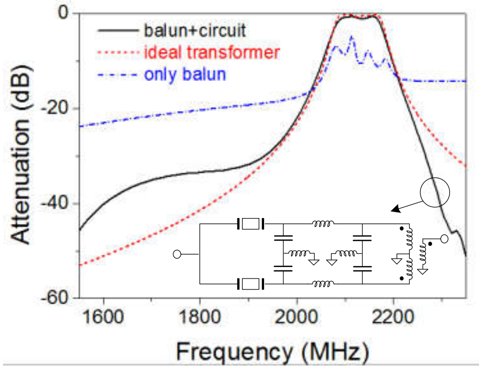

Fig.4 Filter performances with three different configurations: (a) with ideal balun, (b) with real balun, and (c) with real balun and circuit shown in Fig. 3.

5. Conclusion

This paper discussed an electrically-coupled multi-mode. First, the basic design principles were discussed, and it was shown that high filter performances are achievable provided that a high performance balun is available. Then a circuit for the common-mode rejection was proposed. A Tx Band 1 filter was designed, and effectiveness of the proposed circuit and applicability of the present filter were examined.

The circuit shown in Fig. 3 is almost identical with matching circuits in RF circuits. Thus the filter configuration discussed here seems to be most appropriate to use in RF modules including low noise and/or power amplifiers where use of matching circuits is mandatory.

Acknowledgement

This work was supported by the National Natural Science Foundation of China and the China Academy of Engineering Physics (U1430102). GT acknowledges the support of the Japanese Government (MEXT) for the scholarship through the Super Global University Project.

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