A New Design Concept for Balanced-Type SAW Filters Using a Common-Mode Signal Suppression Circuit

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SUMMARY A new design concept for a common-mode signal suppression circuit for a balanced-type filter has been investigated. The degradation mechanism of the balance characteristics was studied. The degradation is caused by the common-mode signals combined with the differential-mode signals in the balanced terminals. The concept employed is the reduction of the common-mode signal using a common-mode signal suppression circuit, connected to the balanced terminals. A serial resonance circuit is formed, in which the common-mode signals are shorted to ground. The circuit was applied to the balanced-type Surface Acoustic Wave (SAW) filter. The improvement in balance characteristics, without increasing in the insertion loss, was confirmed by experiments for Global System Mobile (GSM) applications.

key words: SAW filter, balanced-type, common-mode, differential-mode, balance characteristics

1. Introduction

The front-end circuit of the Global System Mobile (GSM) terminals requires an antenna switch module, an RF Integrated-Circuit (RFIC) and Surface Acoustic Wave (SAW) filters [1]. The SAW filters are placed between the antenna switch module and the RFIC. The SAW filter converts an unbalanced signal into balanced signals. The antenna switch module with an unbalanced output terminal is connected to the input of the SAW filter. The RFIC with a balanced input terminal is connected to the output of the SAW filter. The longitudinally coupled mode SAW filter has a configuration suitable for the unbalance-balance-conversion scheme [2]–[7].

The SAW filter has three Inter-Digital Transducers (IDTs). The center IDT is connected to the balanced terminal, using both electrode fingers of the IDT. The other IDTs are connected to the unbalanced terminal, using the one-side electrode fingers of each IDT in a parallel connection [4], [6].

The balance characteristics of amplitude and phase of the output signal are very important. The balanced circuit can suppress the common-mode noise from the outside. However, the imbalance degrades the ability of the suppression. In the high frequency band, the degradation of balance characteristics becomes more severe, due to parasitic couplings [4]. The degradation mechanism of the balance characteristics has been analyzed and the equivalent circuits, using capacitances as the parasitic couplings, have already been proposed for the balanced-type SAW filter [6], [7].

Some methods of improving the balance characteristics for balanced-type SAW filter have been reported [4]–[7]. One of these approaches incorporates a new IDT design [5]. Another involves the use of parallel resonance, formed by the parasitic coupling and an external inductor in the pass-band [6]. However, the degradation of the balance characteristics cannot be completely eliminated by these methods because the parasitic coupling is not completely removed.

The concept of mixed-mode Scattering parameters (S-parameters) has been proposed for differential circuits [9], [10]. This theory has been applied to differential circuit measurements using a multi-ports network analyzer. The mixed-mode S-parameter is useful for analyzing the performance of the differential circuit.

In this paper, the authors propose a new design concept for the balanced-type SAW filter with a common-mode signal suppression circuit. Initially, using the mixed-mode S-parameter theory, the relations between a loss, a common-mode leakage and balance characteristics for a filter was established. This leads to the proposal of a new method of improvement. The design concept is that the output impedance for common-mode signal is grounded, reducing the leakage of the common-mode signal through the parasitic capacitances. The validity of the circuit was confirmed, both by simulation and experiments. As the result, the balance characteristics have been improved, with the balanced-type SAW filter exhibiting an excellent performance.

2. The Relations between a Loss, a Common-Mode Leakage and Balance Characteristics

Initially, consider the relations between a loss, a common-mode leakage and balance characteristics for a filter. Figure 1 shows the balanced-type filter, which has balanced-unbalanced terminals. In Fig. 1, $S_{21}$ is the S-parameter from IN to OUT1, and $S_{31}$ is the S-parameter from IN to OUT2. Amplitude difference ($\Delta A$) and phase difference ($\Delta \phi$) are shown below.

$$\Delta A = 20 \log_{10} | -S_{21}/S_{31}| \quad [\text{dB}] \quad (1)$$

$$\Delta \phi = \text{phase}(-S_{21}/S_{31}) \quad [\text{deg.}] \quad (2)$$

Here, the amplitude difference refers to the difference
in amplitude between OUT1 and OUT2, and the phase difference refers to the deviation in the phase difference from 180 degrees between OUT1 and OUT2. For the ideal balance characteristics, $\Delta A$ and $\Delta \phi$ are both zero.

Considering the mixed-mode $S$-parameters, the filter response of the differential-mode ($S_{d21}$) and the common-mode ($S_{c21}$) are defined as shown below.

$$S_{d21} = \frac{1}{\sqrt{2}}(S_{21} - S_{31}) \quad \text{(3)}$$

$$S_{c21} = \frac{1}{\sqrt{2}}(S_{21} + S_{31}) \quad \text{(4)}$$

Here, the losses in the filter, such as the reflection loss and resistive loss, are assumed to be zero. The relationship between $S_{d21}$ and $S_{c21}$ is expressed as shown below.

$$|S_{d21}|^2 + |S_{c21}|^2 = 1 \quad \text{(5)}$$

From equations (3), (4) and (5), the relationship between $S_{d21}$ and $S_{c21}$ is expressed as shown below.

$$|S_{d21}|^2 = |S_{c21}|^2 = 1 \quad \text{(6)}$$

Here, regarding the phase relation between $S_{d21}$ and $S_{c21}$, there is no problem to keep generality, even if it is assumed that the phase $S_{d21}$ is zero and the phase $S_{c21}$ is $\theta$. Then, $S_{d21}$ and $S_{c21}$ are introduced from equations (3), (4) and (6) as shown belows.

$$S_{d21} = \frac{1}{\sqrt{2}} \times [S_{d21} + S_{c21} \times (\cos \theta + j \sin \theta)]$$

$$S_{c21} = -\frac{1}{\sqrt{2}} \times [S_{d21} + \sqrt{1 - |S_{d21}|^2} \times (\cos \theta + j \sin \theta)] \quad \text{(7)}$$

$$S_{31} = -\frac{1}{\sqrt{2}} \times [S_{d21} - S_{c21} \times (\cos \theta + j \sin \theta)]$$

$$S_{31} = -\frac{1}{\sqrt{2}} \times S_{d21} - \sqrt{1 - |S_{d21}|^2} \times (\cos \theta + j \sin \theta) \quad \text{(8)}$$

Amplitude difference ($\Delta A$) and phase difference ($\Delta \phi$) are derived from equations (1), (2), (7) and (8).

$$\Delta A = 20 \log_{10} \left( \frac{S_{d21} + \sqrt{1 - |S_{d21}|^2} \times (\cos \theta + j \sin \theta)}{S_{d21} - \sqrt{1 - |S_{d21}|^2} \times (\cos \theta + j \sin \theta)} \right) \quad \text{[dB]} \quad \text{(9)}$$

$$\Delta \phi = \tan^{-1} \left( \frac{S_{c21} \times \sin \theta}{\sqrt{1 - |S_{c21}|^2} + S_{c21} \times (\cos \theta + j \sin \theta)} \right) \quad \text{[deg.]} \quad \text{(10)}$$

Furthermore, amplitude difference ($\Delta A$) and phase difference ($\Delta \phi$) are expressed by using $S_{c21}$ as shown below.

$$\Delta A = 20 \log_{10} \left( \frac{\sqrt{1 - |S_{c21}|^2} + S_{c21} \times (\cos \theta + j \sin \theta)}{\sqrt{1 - |S_{d21}|^2} - S_{d21} \times (\cos \theta + j \sin \theta)} \right) \quad \text{[dB]} \quad \text{(11)}$$

$$\Delta \phi = \tan^{-1} \left( \frac{S_{c21} \times \sin \theta}{\sqrt{1 - |S_{c21}|^2} + S_{c21} \times (\cos \theta + j \sin \theta)} \right) \quad \text{[deg.]} \quad \text{(12)}$$

Figure 2(a) shows the relations between the amplitude difference, phase difference and the substantial loss of the filter, and (b) shows the relations between the amplitude difference, phase difference and the common-mode leakage of the filter.
difference, the phase difference and the substantial loss of the filter. The loss values of $-0.05$ dB, $-0.10$ dB, $-0.20$ dB and $-0.30$ dB are obtained from $20 \log_{10} |S_{ds21}|$. The loss increases as the amplitude and the phase differences become greater. As shown in Fig. 2(a), the conditions of $\Delta A < 2$ dB and $\Delta \phi < 10$ degrees are essential to maintain the substantial insertion loss lower than $-0.1$ dB. Figure 2(b) shows the relations between the amplitude difference, the phase difference and the common-mode leakage of the filter. The leakage increases as the amplitude and the phase differences become greater.

3. The Design Concept of Common Mode Signal Suppression

3.1 Characteristics of the Balanced-Type SAW Filter

Figure 3 shows a schematic view of the balanced-type SAW filter with a basic configuration. It is a longitudinally coupled mode type, which contains three IDTs. The center IDT is connected to balanced output terminals indicated by OUT1 and OUT2. The other IDTs are connected in parallel to unbalanced input terminal, indicated by IN. The balanced-type SAW filter is able to convert an unbalanced signal to balanced signals.

Figure 4 shows the measured frequency response of the balanced-type SAW filter in the 900 MHz frequency band, referring to the differential-mode output ($S_{ds21}$). The filter was fabricated on a LiTaO$_3$ substrate. Input impedance of unbalanced terminal is $50 \Omega$. Output impedance of balanced terminals is also $50 \Omega$. Thus, the impedances of OUT1 and OUT2 are each $25 \Omega$.

Figures 5(a) and (b) show the balance characteristics in terms of the amplitude difference ($\Delta A$) and the phase difference ($\Delta \phi$), respectively. The frequency range is from 925 MHz to 960 MHz for GSM receiver band. Here, the balance characteristics are obtained by using equations (1) and (2). The ideal values are zero. However, the measured amplitude difference ranges from $-0.90$ to $+0.96$ dB and the phase difference ranges from $-6.3$ to $+8.4$ degrees. The insertion loss is $-1.50$ dB.

3.2 Configuration and Principle of the Common-Mode Suppression Circuit

This section considers the basic principle of the design concept for the common-mode signal suppression circuit. Figure 6 shows a model of the balanced-type SAW filter. Coupling due to the parasitic elements ($C_p1$, $C_p2$) between the input terminal and the output terminals constitute main factors for the balance characteristic degradation, as shown in Fig. 5. This degradation can be explained by considering the signal mode in the balanced terminals. These are the differential-mode signals ($id1$, $id2$) and the common-mode signals ($ic1$, $ic2$). Here, $id1$ and $id2$ are introduced to express $S_{ds21}$, and $ic1$ and $ic2$ are introduced to express $S_{cs21}$.
The $S_{31}$ is the sum of $id1$ and $ic1$, and the $S_{31}$ is the sum of $id2$ and $ic2$. The common-mode signals are in-phase, and the differential-mode signals are anti-phase.

Figure 7 shows a configuration of the proposed common-mode suppression circuit. This consists of an inductor and two capacitors. As shown in Fig. 7, two capacitors, $Cg1$ and $Cg2$, are connected in series between the output terminals OUT1 and OUT2. The inductor, $Lg$, grounds the connection point of the capacitors. When a signal is inputted to the input terminal IN, the common-mode signals $(ic1)$ and $(ic2)$ and the differential-mode signals $(id1)$ and $(id2)$ are outputted.

In explanation of the circuit principle, Fig. 8 shows the equivalent modeling of the circuit. In Fig. 8, (a) is for the common-mode signals, and (b) is for the differential-mode signals. The common-mode signals are grounded via the series resonance circuit formed by the inductor and the capacitors because the common-mode signals are in-phase. Then, the inductor $Lg$ is equivalently divided into two inductors, $Lg1$ and $Lg2$. As shown in Fig. 8(b), for the differential-mode signals, a virtual ground plane is formed at the connection point of $Cg1$ and $Cg2$ because the differential-mode signals are anti-phase if it is assumed that $id1=id2$. Although the output terminals are connected to a ground via the capacitors, the differential-mode signals can be transmitted to the output terminals due to the large impedance of $Cg1$ and $Cg2$ at the design frequency.

### 3.3 Design for the Common-Mode Suppression Circuit

The design procedure for the common-mode suppression circuit is as follows. The serial resonance frequencies of $fs1$ and $fs2$ are designed to be in the pass-band. The resonance frequencies of $fs1$ and $fs2$ are expressed in the following equations if it is assumed that $ic1=ic2$.

\[
fs1 = fs2 = \frac{1}{2\pi} \sqrt{Lg1 \times Cg1} = \frac{1}{2\pi} \sqrt{Lg2 \times Cg2}
\]

(Equation 13)

Equations (14) express the impedances of $Zg1$ and $Zg2$ from the balanced terminal.

\[
Zg1 = Zg2 = \frac{1}{j(2\pi \times fs1 \times Cg1)} = \frac{1}{j(2\pi \times fs2 \times Cg2)}
\]

(Figure 8) The equivalent modeling of the common-mode signal suppression circuit. (a) for the common-mode signals, and (b) for the differential-mode signals.

Furthermore, $Cg1$ and $Cg2$ are designed to have a large impedance to ground plane from equation (14). Thus, common-mode signals are shorted to ground, and differential-mode signals transmit to the output terminals without being shorted.

Figure 9 shows the characteristics of the balanced SAW filter with the common-mode signal suppression circuit of Fig. 7. Here, the measured S-parameters of the SAW filter shown in Figs. 4 and 5 are used. The circuit performance was simulated using the Advanced Design System from Agilent. Figures 9(a) and (b) show the balance characteristics in terms of the amplitude difference and the phase difference. In the circuit design, the element values are set as $Cg1=Cg2=1\,\text{pF}$, $Lg=14\,\text{nH}$, where the $Q$ values of all the elements are 100. Thus, $Lg1$ and $Lg2$ are obtained by $Lg1=Lg2=2 \times Lg=28\,\text{nH}$. The series resonance frequencies $fs1$ and $fs2$ are both 951.1 MHz, which is in the pass-band. The impedances of $Zg1$ and $Zg2$ to ground plane for the differential-mode signals are 167.3 $\Omega$. These values are large enough for transmission of the differential-mode signals.
The balance characteristics have been improved with respect to the characteristics without the circuit shown in Fig. 5. The amplitude difference ranges from $-0.22$ to $+0.20$ dB. The phase difference ranges from $-2.1$ to $+1.0$ degrees. However, the total insertion loss is $1.46$ dB, which is almost the same as that of Fig. 4.

4. Experimental Results

The improvement in the balance characteristics with the common-mode signal suppression circuit was confirmed by the experiment. The balanced SAW filter of Figs. 4 and 5 was used. The inductor is chip-type wired inductor. And the capacitors are chip-type capacitors. Inductance, $L_g$, is $11.8$ nH and capacitances, $C_{g1}$ and $C_{g2}$, are $1.15$ pF, as confirmed by measurement. Then, the series resonance frequency is $966$ MHz. Figures 10 and 11 show the experimental results. Figure 10 shows the frequency response of the filter. Figure 11 shows the balance characteristics. The improvement in balance characteristics was confirmed by the experiment. The measured amplitude difference ranged from $-0.05$ to $+0.35$ dB and the phase difference ranged from $-2.7$ to $+1.0$ degrees. The total insertion loss was $-1.47$ dB. Figure 12 shows the common-mode leakage ($S_{c21}$) of the filter with and without the circuit. The leakage value with the circuit was $-35$ dB over the pass-band, and
the value of around the resonance frequency was less than −45 dB. The drastic improvement was observed. The suppression circuit made an improvement in the balance characteristics, regardless of the fact that the circuit did not degrade the insertion loss.

5. Conclusions

A new design concept for the common-mode signal suppression circuit for a balanced-type filter has been investigated. The degradation of balance characteristics was caused by the common-mode signals. A common-mode suppression circuit was proposed using lumped elements. This utilized series resonance. It was confirmed that the suppression circuit improved the balance characteristics. The design procedure for the circuit was described. The common-mode suppression circuit and the design concept are very attractive for the balanced-type filters for mobile communication applications, such as GSM. Furthermore, this concept for the suppression circuit could be applicable for other balanced-type RF devices.

References