Analysis of Nonlinear Behavior in Tunable Filters using SAW/BAW Resonators and Variable Capacitors

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1. Introduction

Recently, tunable filters employing SAW/BAW resonators and variable capacitors (VCs) are paid much attention\(^1,2\). They would make it possible to reduce head account of discrete components such as switches and filters in the radio-frequency (RF) frontend of mobile phones\(^3\). Although diode-type VCs offer wide tunability, they are expected to exhibit relatively strong non-linearity. On the other hand, micro-electro-mechanical-systems (MEMS) type ones are believed to possess relatively weak non-linearity, however they are physically large.

This paper discusses how non-linearity of diode-type VCs influences the non-linear characteristic of tunable filters.

2. Tunable filter configurations

Fig. 1 shows two configurations of the tunable filter used for the discussion. They employ VCs and SAW/BAW resonators employing Cu-grating/15°YX-LiNbO\(_3\) substrate structure\(^4\). For the configuration (a), the resonance frequencies \(f_\text{a} \) and \(f_\text{p} \) of resonators in series and parallel arms are set to be 1,000 and 860 MHz, respectively, and the shunt capacitances of these resonators are set to be 1.98 and 6.36 pF. For the configuration (b), \(f_\text{a} \) and \(f_\text{p} \) are set to be 900 and 880 MHz, respectively.

We employed Infion BB831 as diode-type VCs, and analyzed the second-order intermodulation distortion (IMD2) of the filters when two signals signals “a” and “b” are applied to the port “1”. For the analysis, (a) the jammer frequency \(f_\text{j} \) is fixed, (b) the signal \(f_\text{s} \) is scanned from 0.7 GHz to 1.2 GHz, and (c) IMD2 output \(I_{\text{IMD2}} \) with \(f=f_\text{a}+f_\text{s} \) is selectively detected at the port “2”.

In the following analysis, input power \(I_\text{a} \) and \(I_\text{b} \) for two signals are fixed at 0 dBm. Note that unless non-linearity is not significant, \(I_{\text{IMD2}} \) for arbitrary input power can be estimated by the formula \(I_{\text{IMD2}}=I_\text{a}+I_\text{b} \) in decibels, where \(I_2 \) is \(I_{\text{IMD2}} \) calculated for \(I_\text{a}=I_\text{b}=0 \) dBm.

3. IMD2 of Tunable Filters

Fig. 2 shows \(f_\text{s} \) dependence of \(|S_{\text{21}}|\) and \(I_{\text{IMD2}} \) of the circuit shown in Fig. 1(a). In the figure, solid lines a and b show the results when \(C_\text{sp}=1.2 \) pF and \(C_\text{ps}=16 \) pF, while broken lines c and d show the results when \(C_\text{sp}=0.75 \) pF and \(C_\text{ps}=6.6 \) pF.

There are two regions where \(I_{\text{IMD2}} \) is large. First one is at \(f_\text{s} \approx 0.8 \) GHz, where the generated IMD2 signal with \(f=f_\text{a}+f_\text{s} \) can pass through the filter structure with small attenuation. Second one is at \(f_\text{s} \approx 1.0 \) GHz, where the input signal with \(f=f_\text{s} \) can pass through the filter structure with small attenuation.

It is seen that \(I_{\text{IMD2}} \) at \(f_\text{s} \approx 1.0 \) GHz becomes large when \(f_\text{s} \) approaches to the upper null close to the passband, which is caused by the parallel resonance of resonators in series arms with \(C_\text{sp} \). This \(I_{\text{IMD2}} \) behavior is due to the fact that the current flows though \(C_\text{sp} \) takes a maximum value when \(f_\text{s} \) is close to the upper null but within the passband. \(I_{\text{IMD2}} \) at

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$f_a\approx 1.0$ GHz also becomes large when $f_a$ approaches to the lower null, which is caused by the series resonance of resonators in parallel arms with $C_{pp}$. This $I_{IMD2}$ behavior is due to the fact that the current flow through $C_{ss}$ takes a maximum value when $f_a$ is close to the lower null but within the passband.

As shown in the figure, with an increase in $C_{sp}$ the upper null and the $I_{IMD2}$ peak position move downward, and then the peak value slightly decreases. On the other hand, with a decrease in $C_{sp}$ the lower null and the $I_{IMD2}$ peak position move upward, and the peak value increases slightly. These behaviors might be mainly due to variation of non-linearity generation in VCs with control voltage.

Frequency dependence of $I_{IMD2}$ at $f_a\approx 0.8$ GHz looks similar to those at $f_a\approx 1.0$ GHz. However, their frequency dependences are occurred by different mechanisms. Namely, non-linear output generated across $C_{sp}$ is almost frequency independent in this region because $f_a$ and $f_b$ are far from the resonance. Nevertheless, $I_{IMD2}$ becomes large when $f_a+f_b$ approaches to the upper nulls. This is because impedance of the resonators in series arms becomes large for $f_a+f_b$ due to the anti-resonance at the upper null, while admittance of the resonators in parallel arms becomes large for $f_a+f_b$ due to the resonance at the lower null. This results in large non-linear voltage generated across $C_{sp}$ and $C_{pp}$.

Fig. 3 shows frequency $f_a$ dependence of $|S_{21}|$ and $I_{IMD2}$ in circuit shown in Fig. 1 (b). The VC setting is given in Table 1. $I_{IMD2}$ is large when either $f_a+f_b$ or $f_a$ locates in the filter pass band. Comparison of Fig. 3 with Fig. 2 indicates that $I_{IMD2}$ is less frequency dependent within the frequency regions and about $10$~$15$ dB larger than that generated in the circuit shown in Fig. 1 (a). This difference is caused by influence of the non-linear signal generated by $C_{ps}$.

<table>
<thead>
<tr>
<th>Setup</th>
<th>$C_{ss}$ (pF)</th>
<th>$C_{sp}$ (pF)</th>
<th>$C_{ps}$ (pF)</th>
<th>$C_{pp}$ (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.3</td>
<td>1.4</td>
<td>37</td>
<td>12</td>
</tr>
<tr>
<td>B</td>
<td>2.6</td>
<td>0.6</td>
<td>17.5</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Fig. 4 shows variation of $I_{IMD2}$ with Q values $Q_s$ and $Q_p$ of resonators in series and parallel arms, respectively in circuit shown in Fig. 1 (b). It is seen that height of the left peak slightly increases with $Q_p$ and that of the right peak does slightly with $Q_s$. This is explained by the fact that $Q_p$ and $Q_s$ predominantly influence insertion losses at lower and upper passband edges, respectively. Although not shown, variation of $I_{IMD2}$ with Q values is similar to that of the filter transmission characteristics.

4. Conclusion

The IMD2 characteristic of two types of tunable filters using SAW/BAW Resonators and VCs were simulated. Firstly, we discuss the IMD2 response when one VC is connected to respective resonator. It was shown that the IMD2 becomes large when the input frequency or generated signal is in the filter pass band. Secondly, we discussed the IMD2 response of when VCs are connected in both parallel and series with all of the resonators. This circuit can supply wider tunable range than 1) but sustains larger non-linearity. Finally, It was pointed out that Q values of resonator has scarcely affect on the IMD2 performance of filters.

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Reference