Novel Electronically Tunable Biquadratic Mixed-Mode Universal Filter Capable of Operating in MISO and SIMO Configurations

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Abstract: In this paper, a novel electronically tunable biquadratic universal mixed-mode filter is presented. The filter is based on extra X current conveyor transconductance amplifier (EXCCTA), recently introduced by authors. The proposed filter employs two EXCCTAs, two capacitors, a switch, and four resistors. The filter can work in both multi-input-single-output (MISO) and single-input-multi-output (SIMO) configurations without change in its structure. The filter provides all five responses in voltage-mode (VM), current-mode (CM), transimpedance-mode (TIM), and transadmittance-mode (TAM). The attractive features of the filter include (i) ability to operate in both MISO and SIMO configurations in all four modes, (ii) no requirement of capacitive matching, (iii) tunability of quality factor (Q) independent of natural frequency (ω₀) in MISO & SIMO configurations and (iv) no requirement for double/negative input signals (voltage/current) in MISO configuration. The non-ideal gain and sensitivity analysis is also carried out to study the effects of process variations and passive components spread on filter performance. The filter is designed in Cadence Virtuoso using Silterra Malaysia 0.18µm PDK. The complete layout of the EXCCTA is designed and the parasitic extraction is done. The filter is tested at a supply voltage of ±1.25 V and the obtained results validate the theoretical findings.

Keywords: analog signal processing, voltage-mode, current-mode, transimpedance-mode, transadmittance-mode, extra X current conveyor transconductance amplifier, EXCCTA, universal filter

Nov elektronsko nastavljiv bikvadratičen univerzalen filter v mešanem načinu delovanja sposoben delovanja v MISO in SIMO konfiguraciji

Izvleček: Članek predstavlja nov elektronsko nastavljiv bikvadratičen filter v mešanem načinu delovanja. Filter sloni na dodatnem X tokovnem transkonduktančnem ojačevalniku (EXCCTA). Filter je sestavljen iz dveh EXCCTA-jev, dveh kondenzatorjev, stikala in Strih tranzistorjev. Filter lahko deluje v eno-vhodni multi izhodni (MISO) ali multi-vhodno eno-izhodni (SIMO) konfiguraciji brez spremembe v strukturi. Ponuja vse pet odzovov v napetostnem (VM), tokovnem (CM), transimpedančnem (TIM) in transadmitančnem načinu (TAM). Prednostne lastnosti filtra so (i) delovanje v MISO ali SIMO načini, (ii) ni potrebe po kapacitivnem ujemanju, (iii) nastavljivost faktorja kvalitete (Q) brez odvisnosti od osnovne frekvence v MISO in SIMO načinu in (iv) brez potrebe po dvojnem negativnem vhodu signal v MISO načinu. Opravljena je tudi analiza občutljivosti in ojačanja filtra zaradi varijacij procesa in toleranc pasivnih komponent. Filter je narejen v Cadence Virtuoso z uporabo Silterra Malaysia 0.18µm PDK. Načrtano je celotna shema EXCCTA in opravljen test pri napajalni napetosti ±1.25 V.

Ključne besede: analogno procesiranje signalov, EXCCTA, univerzalen filter, transkonduktančni tokovni ojačevalnik

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1 Introduction

The design and development of frequency filters is an important field of communication engineering and research. The filters are an integral part of almost every electronic system [1–3]. The universal filter structure is the most versatile and sought-after filter configuration as it provides all five generic filter responses namely, low-pass (LP), high-pass (HP), band-pass (BP), band-reject (BR), and all-pass (AP) from same configuration. It serves as a stand-alone solution for all filtering requirements. They are employed in data acquisition systems as analog front-end, in communication systems, biomedical signal processing, instrumentation, and oscillator design, etc. [3–15]. Owing to their wide bandwidth, high slew-rate, simple circuit, good linearity, and better performance under low-voltage low-power (LVLP) environment current-mode (CM) active building blocks (ABBs) are preferred for designing analog filters [2,5,6]. The most popular CM ABBs are the second-generation current conveyor (CCII) [1–6], current feedback operational amplifier (CFOA) [16], fully differential current conveyor (FDCCII) [18], differential voltage current conveyor (DVCC) [20], current controlled current conveyor transconductance amplifier (CCCTA) [21], differential difference current conveyor (DDCC) [23], etc. In present day complex signal processing systems the need for interaction between current-mode and voltage-mode (VM) circuits arises often. This requirement can be met by employing transadmittance-mode (TAM) and transimpedance-mode (TIM) circuits to facilitate distortion free interfacing between CM and VM units [7–11, 23]. Although several TAM and TIM filter structures have been proposed, but a single topology providing the CM, VM, TAM, and TIM responses will be an added advantage in terms of area and power requirements. Numerous mixed-mode universal filters can be found in the open literature [7–34] that were designed to cater to the above-mentioned requirements. The filter structures can be classified in three basic groups such as single-input-multi-output (SIMO), multi-input-multi-output (MIMO), and multi-input-single-output (MISO). The comparison between the filter structures can be done based on following important criteria:

<table>
<thead>
<tr>
<th>References/ Year</th>
<th>Mode of Operation</th>
<th>Mode of Operation</th>
<th>(i)</th>
<th>(ii)</th>
<th>(iii)</th>
<th>(iv)</th>
<th>(v)</th>
<th>(vi)</th>
<th>(vii)</th>
<th>(viii)</th>
<th>(ix)</th>
<th>(x)</th>
<th>(xi)</th>
<th>(xii)</th>
<th>(xiii)</th>
<th>(xiv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[16]/2005 SIMO</td>
<td>3-CFOA</td>
<td>9C+2R</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
<td>112.5 KHz</td>
<td>No</td>
<td></td>
<td></td>
</tr>
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<td>[17]/2006 SIMO</td>
<td>2-FTFN</td>
<td>2C+3R</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
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<td>[18]/2008 SIMO</td>
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<td>2C+3R</td>
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<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<td>No</td>
<td>Yes</td>
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<td>Yes</td>
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<td>N.A.</td>
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<td>Yes</td>
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<td>No</td>
<td>No</td>
<td>No</td>
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<td>N.A.</td>
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<td>Yes</td>
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<td>No</td>
<td>No</td>
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<td>N.A.</td>
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<td>[23]/2011 SIMO</td>
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<td>2C+4R</td>
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<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<td>Yes</td>
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<td>[24]/2017 SIMO</td>
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<td>2C+4R</td>
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<td>Yes</td>
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<td>N.A.</td>
<td>3.183 MHz</td>
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<td>[25]/2017 SIMO</td>
<td>3-VDTA</td>
<td>2C</td>
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<td>Yes</td>
<td>No</td>
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<td>Yes</td>
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<td>3.04 MHz</td>
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<td>[26]/2017 SIMO</td>
<td>6-OTA</td>
<td>2C</td>
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<td>Yes</td>
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<td>No</td>
<td>No</td>
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<td>[27]/2017 SIMO</td>
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<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<tr>
<td>[36]/2016 SIMO</td>
<td>2-FDCCII</td>
<td>2C+5R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
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<td>[37]/2018 SIMO</td>
<td>2-FDCCII</td>
<td>2C+4R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
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<td>7-CCII</td>
<td>2C+8R</td>
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<td>Yes</td>
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<td>N.A.</td>
<td>N.A.</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>No</td>
<td></td>
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<tr>
<td>[29]/2006 MISO</td>
<td>3-CCII</td>
<td>3C+4R+2-switch</td>
<td>No</td>
<td>No</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>-</td>
<td>No</td>
<td></td>
<td></td>
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<tr>
<td>[30]/2009 MISO</td>
<td>4-OTA</td>
<td>2C</td>
<td>Yes</td>
<td>Yes</td>
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<td>N.A.</td>
<td>N.A.</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>1.59 MHz</td>
<td>Yes</td>
<td></td>
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<tr>
<td>[31]/2010 MISO</td>
<td>2-MOCCII</td>
<td>2C+2R</td>
<td>Yes</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>1.27 MHz</td>
<td>Yes</td>
<td></td>
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<td>[32]/2013 MISO</td>
<td>4-MOCCII</td>
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<td>Yes</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>-</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[33]/2016 SIMO/ MISO</td>
<td>1-FDCCII+1-DDCC</td>
<td>2C+6R</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>1.59 MHz</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[34]/2018 MISO</td>
<td>5-DVCC</td>
<td>2C+5R</td>
<td>Yes</td>
<td>Yes</td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>1 MHz</td>
<td>No</td>
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<td></td>
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<tr>
<td><strong>Proposed</strong> MISO/SIMO</td>
<td>2-EXCCCTA</td>
<td>2C+4R+switch</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>8 MHz</td>
<td>Yes</td>
<td></td>
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</tbody>
</table>

*N.A. (not applicable) [points (v)-(vii) are not applicable in case of MISO filters, points (x)-(xii) are not applicable in case of SIMO filters, point (iv) is not applicable in case of resistor less filters]
(i) number of ABBs employed,
(ii) number of passive components needed,
(iii) no need for capacitive matching,
(iv) no requirement for resistive matching except for AP response,
(v) use of grounded capacitors in SIMO configuration,
(vi) availability of explicit current output from high impedance node in SIMO configuration,
(vii) low input impedance for CM and TIM in SIMO configuration,
(viii) provision to control quality factor independent of the natural frequency,
(ix) ability to provide all five filter responses in all four modes of operation,
(x) low output impedance for MISO (VM and TIM),
(xi) availability of explicit current output for MISO (CM and TAM),
(xii) no requirement for double/negative input signals (voltage/current) in MISO configuration,
(xiii) test natural frequency,
(xiv) inbuilt tunability.

A detailed comparison of the state-of-the-art mixed-mode filters with the proposed design is presented in Table 1.

It can be inferred from the table that the filter structures [16, 19-26, 28-30, 32, 34] employ three or more ABBs for the design. The designs in [16, 28, 29, 33, 34] utilize seven or more passive components. The design in [29] requires capacitive matching, which is undesirable in today’s submicron technologies. In filters [16-17, 21, 22, 26, 28-30, 32] the quality factor cannot be controlled independent of the natural frequency. The filter structures [17-22, 25, 27, 34] are not truly universal mixed-modes since they cannot realize all five filter responses in VM, CM, TAM and TIM operation. None of the above mixed-mode filters except [20] is designed at natural frequency higher than 4 MHz. The filter structures [16-18, 20, 23-29, 33, 34] lack inbuilt tunability. None of the existing filters (with the exception of [33]) can work in both MISO and SIMO configurations and provide all five filter responses in all Four modes of operation. In addition, some other drawbacks of the design [33] are: (i) the design is not modular as it uses two different ABBs, namely FDC-CII and DDCC, also it requires five input voltages and six input currents in MISO configuration, (ii) both capacitors are connected to X terminals which is undesired as it effects the high frequency performance as shown in [35], (iii) use negative and double inputs in MISO configuration, and (iv) lack of built-in tunability. The literature survey points out that although many exemplary mixed-mode filter designs exist, the research in the mix-mode filter design is still limited and newer designs need to be developed to cater to increasing demand of mixed-signal processing systems. In context, this paper aims to introduce a novel mixed-mode filter structure composed of two extra X current conveyor transconductance amplifier (EXCCTA), one switch, two capacitors, and four resistors, which employs only three input current/voltage signals in MISO operation and is free from the above drawbacks of [33]. The striking features of the proposed filter are: (i) provides all five filter responses in all four modes of operation, (ii) it can work in both MISO and SIMO configuration without change in topology, (iii) it has inbuilt tunability, and (iv) the filter exhibits low active and passive sensitivities to passive elements. Beside these the filter enjoys all the properties mentioned in Table 1. The precise design, layout and simulation of the EXCCTA, is done in Cadence Virtuoso using Silittera Malaysia 0.18µm PDK. The layout verification and parasitic extraction is carried out using Mentor Graphics Calibre. The post layout results bear close resemblance with the theoretical predictions.

2 Extra X current conveyor transconductance amplifier (EXCCTA)

The EXCCTA is a versatile electronically tunable ABB carrying features of extra X current conveyor (EXCCII) [13] and operational transconductance amplifier (OTA) [14] in one compact integrated circuit implementation. The EXCCTA provides two independent low impedance current input terminals $X_n$, together with a high impedance voltage input terminal $Y$. It also has OTA at the output stage imparting tunability to the structure. The block diagram and voltage–current relations of the EXCCTA are given in Figure 1 and Equation (1), respectively. The complete CMOS implementation [15] is presented in Figure 2. The class AB output stage is utilized in the first stage to minimize supply voltage and power dissipation.

![Figure 1: Block diagram of EXCCTA](image)

$$
\begin{bmatrix}
I_T \\
V_{XP} \\
V_{XN} \\
I_{ZP+} \\
I_{ZP-} \\
I_{ZN+} \\
I_{ZN-} \\
I_{Ox}
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & -1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & \pm g_m & 0 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
V_T \\
I_{XP} \\
I_{XN} \\
V_{ZP+} \\
V_{ZP-} \\
V_{ZN+} \\
V_{ZN-} \\
V_{Ox}
\end{bmatrix}
$$
The proposed electronically tunable mixed-mode universal filter is presented in Figure 3. The filter employs four resistors, two capacitors, and two EXCCTAs. The filter can work in both SIMO and MISO configurations by adding a single pole double throw (SPDT) switch. The operation and features of the filter in each configuration are discussed below.

3.1 SIMO configuration

In SIMO configuration, the currents $I_1$ to $I_3$ and input voltages $V_{in1}$ to $V_{in3}$ are set to zero. This grounds all the passive components except $R_3$ as can be inferred from Figure 3(b).

In addition, in SIMO configuration no switch is needed for generating filter responses in all four modes. In SIMO configuration the filter has following attributes: (i) inbuilt tunability, (ii) use of grounded capacitors and no capacitive matching requirement, (iii) high input impedance in CM and TIM, (iv) CM and TAM output available from explicit high impedance nodes, (v) tunability of $Q$ independent of $\omega_0$, (vi) AP gain tunability in VM and TIM, and (vii) availability of all filter function in all four mode.

3.1.1 SIMO voltage-mode and transadmittance-mode operation

To obtain VM and TAM responses, the input current $I_0$ is set to zero and the input voltage $V_{in}$ is applied as shown in Figure 3(b). The routine analysis of the circuit leads to the transfer functions as given in Equations (2-6). The VM responses are obtained from terminals $V_{out1(SIMO)}$ to $V_{out4(SIMO)}$ as follows:

$$T_{VM} \left( s \right) = \frac{V_{out1(SIMO)} \left( s \right)}{V_{in} \left( s \right)} = \frac{1}{s^2 C_1 R_1 R_2 + s C_1 g_m R_1 R_3 + g_{m2} R_3 \left( 2 \right)}$$
\[ T_{VM_{AP}}(s) = \frac{V_{out[1(SIMO)}(s)}{V_{in}(s)} = \frac{s^2C_1C_2R_3R_2}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (3)

\[ T_{VM_{AP}}(s) = \frac{V_{out[2(SIMO)}(s)}{V_{in}(s)} = \frac{sC_2R_2}{s^2C_1C_2R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (4)

To obtain unity gain AP response a simple resistive matching of \( R_1 = R_3 \) is required and the response is obtained across resistor \( R_4 \).

\[ T_{VM_{AP}}(s) = \frac{V_{out[4(SIMO)}(s)}{V_{in}(s)} = \frac{R_3(s^2C_1C_2R_2 - sC_2g_{m1}R_2 + g_{m2})}{s^2C_1C_2R_1R_3 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (5)

If the O2- terminal is disconnected from the resistor \( R_4 \), Equation (5) turns to:

\[ T_{VM_{AP}}(s) = \frac{V_{out[4(SIMO)}(s)}{V_{in}(s)} = \frac{s^2C_1C_2R_2 + g_{m2}}{s^2C_1C_2R_1R_3 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (6)

and a BR response is obtained.

The TAM responses are obtained from high impedance terminals \( I_{out[1(SIMO)} \) to \( I_{out[3(SIMO)} \) terminals. The transfer functions are given in Equations (7-11).

\[ T_{TAM_{AP}}(s) = \frac{I_{out[2(SIMO)}(s)}{I_{in}(s)} = \frac{sC_1R_2g_{m1}}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (9)

\[ T_{TAM_{AP}}(s) = \frac{I_{out[1(SIMO)}(s) + I_{out[3(SIMO)}(s)}{I_{in}(s)} = \frac{s^2C_1C_2R_2 + g_{m2}}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (10)

\[ T_{TAM_{m}}(s) = \frac{I_{out[4(SIMO)}(s)}{I_{in}(s)} = \frac{s^2C_1C_2R_2 - sC_2g_{m1}R_2 + g_{m2}}{s^2C_1C_2R_1R_3 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (11)

In TAM, the BR and AP responses can be obtained by appropriately connecting the HP, LP and BP currents. It must be pointed out that, if the filter is designed to work in SIMO configuration then there is no need for the SPDT switch.

### 3.1.2 SIMO current-mode and transimpedance-mode operation

To obtain CM and TIM response, input voltage \( V_{in} \) is set to zero and the input current \( I_{in} \) is applied to the filter. In CM operation all passive elements are grounded. The CM responses are available from high impedance terminals \( I_{out[1(SIMO)} \) to \( I_{out[3(SIMO)} \) and TIM responses are obtained from terminals \( V_{out[1(SIMO)} \) to \( V_{out[4(SIMO)} \). The CM filter transfer functions are given in Equations (12-16). In CM, the BR and AP responses can be obtained by appropriately summing the output currents \( I_{HP, LP, BP} \).

\[ T_{CM_{AP}}(s) = \frac{I_{out[1(SIMO)}(s)}{I_{in}(s)} = \frac{s^2C_1C_2R_2R_3}{s^2C_1C_2R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (12)

\[ T_{CM_{m}}(s) = \frac{I_{out[2(SIMO)}(s)}{I_{in}(s)} = \frac{-sC_1g_{m1}R_2R_3}{s^2C_1C_2R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3} \] (13)
The TIM filter transfer functions are given in Equations (17-21) as follows:

\[ T_{CM_{LP}}(s) = \frac{I_{out[3SIMO]}(s)}{I_{in}(s)} = \frac{g_{m2}R_1}{s^2C_2R_2R_1 + sC_2g_{m1}R_2 + g_{m2}R_3} \]  

(14)

\[ T_{CM_{HP}}(s) = \frac{I_{out[1SIMO]}(s) + I_{out[3SIMO]}(s)}{I_{in}(s)} = \frac{R_3(s^2C_2R_2 + g_{m2})}{s^2C_2R_2 + sC_2g_{m1}R_2 + g_{m2}R_3} \]  

(15)

\[ T_{CM_{BP}}(s) = \frac{I_{out[2SIMO]}(s) + I_{out[3SIMO]}(s)}{I_{in}(s)} = \frac{R_1(s^2C_2R_2 - sC_2g_{m1}R_2 + g_{m2})}{s^2C_2R_2 + sC_2g_{m1}R_2 + g_{m2}R_3} \]  

(16)

Note that to obtain unity gain AP response a simple resistive matching of \( R_1 = R_3 \) is required and the response is obtained across resistor \( R_4 \):

\[ T_{CM_{AP}}(s) = \frac{I_{out[4SIMO]}(s)}{I_{in}(s)} = \frac{R_4(s^2C_2R_2 - sC_2g_{m1}R_2 + g_{m2})}{s^2C_2R_2 + sC_2g_{m1}R_2 + g_{m2}R_3} \]  

(20)

while BR response is obtained, if the O2- terminal is disconnected from resistor \( R_4 \):

\[ T_{CM_{BR}}(s) = \frac{I_{out[4SIMO]}(s)}{I_{in}(s)} = \frac{-R_4R_5 (g_{m2} + s^2C_2R_2)}{s^2C_2R_2 + sC_2g_{m1}R_2 + g_{m2}R_3} \]  

(21)

Subsequently, the expression for natural frequency and \( Q \) of the SIMO mixed-mode filter are:

\[ f_0 = \frac{1}{2\pi} \sqrt{\frac{g_{m2}R_3}{C_2R_2R_3}} \]  

(22)

\[ Q = \frac{1}{g_{m1}} \sqrt{\frac{C_1g_{m2}R_1}{C_2R_2R_3}} \]  

(23)

3.2 MISO configuration

In MISO configuration, the input current \( I_{in} \) and input voltage \( V_{in} \) are set to zero. The input currents \( I_1 \) to \( I_3 \) and input voltages \( V_1 \) to \( V_3 \) are applied to obtain the required filter responses. In this configuration only three resistors are employed, resistor \( R_4 \) is not required and can be eliminated as shown in Figure 3(c). The attractive features of the filter include: (i) low output impedance for VM and TIM, (ii) high output impedance explicit current output for CM and TAM, (iii) no requirement for double/negative input signals (voltage/current), (iv) tunability, (v) simultaneous availability of VM and TIM/CM and TAM responses from same input sequence, and (vi) filter is cascadable in all four modes. The operation of the filter is described below.

3.2.1 MISO voltage-mode and transadmittance-mode operation

To obtain VM and TAM responses, the input voltage \( V_1 \) to \( V_3 \) are applied according to the Table 2 and the SPDT switch is connected to point B.

Table 2: Input voltage excitation sequence

<table>
<thead>
<tr>
<th>Response</th>
<th>Inputs</th>
<th>Passive Matching Condition</th>
<th>Active Matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>0 0 1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>HP</td>
<td>1 0 0</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BP</td>
<td>0 1 0</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BR</td>
<td>1 0 1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>AP</td>
<td>1 1 1</td>
<td>g_{m1}=g_{m2}</td>
<td></td>
</tr>
</tbody>
</table>
The output responses are obtained from low impedance terminal $V_{\text{out(MISO)(VM-Mode)}}$ and high impedance terminal $I_{\text{out(MISO)(TAM-Mode)}}$. The transfer functions for VM and TAM modes are given as:

$$V_{\text{out(MISO)(VM-Mode)}} = \frac{s^2C_1C_2R_1R_3V_1 - sC_2g_{m2}R_2R_3V_3 + g_{m2}R_2V_3}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3}$$

$$I_{\text{out(MISO)(TAM-Mode)}} = g_{m1}\left[\frac{s^2C_1C_2R_1R_1V_1 - sC_2g_{m2}R_2R_3V_3 + g_{m2}R_2V_3}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3}\right]$$

while $f_0$ and $Q$ correspond to Equations (22) and (23), respectively.

### 3.2.2 MISO current-mode and transimpedance-mode operation

To obtain CM and TIM responses, the input voltages $V_1$ to $V_3$ are set to zero, the SPDT switch is connected to point A, and input current signals $I_1$ to $I_3$ are applied according to Table 3.

**Table 3:** Input current excitation sequence

<table>
<thead>
<tr>
<th>Response</th>
<th>Inputs</th>
<th>Passive Matching Condition</th>
<th>Active Matching</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP</td>
<td>0 0 1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>HP</td>
<td>0 1 1</td>
<td>No</td>
<td>$g_{m1}R_2 = 1$</td>
</tr>
<tr>
<td>BP</td>
<td>1 0 0</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>BR</td>
<td>0 1 1</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>AP</td>
<td>1 1 0</td>
<td>$R_2 = R_1$</td>
<td>No</td>
</tr>
</tbody>
</table>

The CM responses are obtained from high impedance terminal $I_{\text{out(MISO)(CM-Mode)}}$ and TIM responses from low impedance terminal $V_{\text{out(MISO)(TIM-Mode)}}$. The transfer functions for quality factor and pole frequency are given as:

$$I_{\text{out(MISO)(CM-Mode)}} = g_{m1}\left[\frac{s^2C_1C_2R_1R_1V_1 - sC_2g_{m2}R_2R_3V_3 + g_{m2}R_2V_3}{s^2C_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3}\right]$$

$$V_{\text{out(MISO)(TAM-Mode)}} = R_3R_1\left[\frac{sC_2g_{m1}R_2R_1 + (sC_2g_{m1} + g_{m2})R_1}{sC_1C_2R_1R_2 + sC_2g_{m1}R_2R_3 + g_{m2}R_3}\right]$$

Note that except for AP there is no requirement for matching passive components. In case of HP response, the value of transconductance $g_{m1}$ should be adjusted to achieve $g_{m1}R_2 = 1$, which can be easily accomplished by adjusting the bias current $I_{\text{bias}}$ of the first EXCCTA.

As a brief conclusion it must be emphasised that the proposed filter can realize SIMO (all modes) and MISO (VM and TAM) responses without requiring any switch. The switch is only required to obtain MISO (CM and TIM) responses.

### 4 Non-Ideal and sensitivity analysis

The non-ideal model of the EXCCTA is presented in Figure 4. As can be deduced, the various parasitic resistances and capacitances appear in parallel with the input and output nodes of the device. The low impedance X node has a parasitic resistance and inductance in series with it. The other non-ideal effects that influence the response of the EXCCTA are the frequency dependent non-ideal current ($\alpha_P$, $\alpha_N$), voltage ($\beta_P$, $\beta_N$), and OTA transconductance transfer ($\gamma$, $\gamma'$) gains. These gains cause a change in the current and voltage signals during transfer leading to undesired response.

**Figure 4:** Non-ideal model of EXCCTA with parasitics

Taking into account the non-ideal gains the V-I characteristics of the EXCCTA in (1) will be modified as follows:

$$I_x = 0, V_{XP} = \beta_P V_Y, V_{XN} = \beta_N V_Y, I_{XP} = p I_{XP},$$

where $p$ is the non-ideal gain.
As a result of component tolerance and non-idealities in EXCCTA the response of the practical filter deviates from the ideal one. To get a measure of the deviation, the relative sensitivity is applied. Mathematically, relative sensitivity is defined as

\[
\lim_{\Delta \to 0} \frac{\partial y}{\partial x} = \frac{\Delta y}{\Delta x},
\]

where \( x \) is the component that is varied and \( y \) is the \( \omega_0 \) and \( Q \) in our case.

The sensitivities of \( \omega_0 \) and \( Q \) with respect to the non-ideal gains and passive components are given below.

The non-ideal analysis considering the effect of non-ideal current, voltage, and transconductance transfer gains is carried out for SIMO (VM and CM) and MISO (VM and CM) configurations to see its effect on the transfer function, \( f_0 \) and \( Q \) of the proposed filters. The modified expressions of filter transfer functions, \( f_0 \) and \( Q \) for the SIMO, and MISO configurations are presented in Equations (32-44).

\[
T_{\text{FM},0} (s) = \frac{\alpha_p \beta_p \alpha_p \beta_p}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{FM},2} (s) = \frac{s^2 C_1 C_2 R_L}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{FM},1} (s) = \frac{s C_2 R_L \alpha_p \beta_p}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{FM},2} (s) = \frac{R_f (s^2 C_1 C_2 R_L \alpha_p \beta_p - s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p)}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{CM},0} (s) = \frac{g_m R_L \gamma f \alpha_p \beta_p}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{CM},1} (s) = \frac{s C_2 R_L \alpha_p \beta_p}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
T_{\text{CM},2} (s) = \frac{-s C_2 R_L \alpha_p \beta_p \alpha_p \beta_p}{s^4 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \alpha_p \beta_p}
\]

\[
f_{\text{FM,[SIMO & MISO (CM & TIM)]}} = \frac{1}{2 \pi} \sqrt{\frac{\gamma f \alpha_p \beta_p \beta_p}{C_1 C_2 R_L}} (39)
\]

\[
Q_{\text{FM,[SIMO & MISO (CM & TIM)]}} = \frac{1}{\gamma f \alpha_p \beta_p} \sqrt{\frac{\gamma f \beta_p}{C_1 g_m R_L}} (40)
\]

\[
f_{\text{CM,[SIMO & MISO (CM & TIM)]}} = \frac{1}{2 \pi} \sqrt{\frac{\gamma f \alpha_p \beta_p \beta_p}{C_1 C_2 R_L}} \gamma f \alpha_p \beta_p \beta_p \beta_p (39)
\]

\[
Q_{\text{CM,[SIMO & MISO (CM & TIM)]}} = \frac{1}{\gamma f \alpha_p \beta_p} \sqrt{\frac{\gamma f \beta_p}{C_1 g_m R_L}} \gamma f \alpha_p \beta_p \beta_p \beta_p (40)
\]

\[
V_{\text{out [MISO]}(VM-Mode)} = \frac{\gamma f \alpha_p \beta_p \beta_p \beta_p}{s^2 C_1 C_2 R_L + s C_2 g_m R_L \gamma f \alpha_p \beta_p + g_m R_L \gamma f \alpha_p \beta_p \beta_p \beta_p} (39)
\]

\[
V_{\text{out [MISO]}(CM-Mode)} = \frac{\gamma f \alpha_p \beta_p \beta_p \beta_p}{s^2 C_1 C_2 R_L + s C_2 g_m R_L \alpha_p \beta_p \beta_p \beta_p} (39)
\]

\[
f_{\text{out [MISO]}(VM-Mode)} = \frac{1}{2 \pi} \sqrt{\frac{\gamma f \alpha_p \beta_p \beta_p \beta_p}{C_1 C_2 R_L}} \gamma f \alpha_p \beta_p \beta_p \beta_p (39)
\]

\[
Q_{\text{out [MISO]}(CM-Mode)} = \frac{1}{\gamma f \alpha_p \beta_p} \sqrt{\frac{\gamma f \beta_p}{C_1 g_m R_L}} \gamma f \alpha_p \beta_p \beta_p \beta_p (40)
\]
The sensitivities are low and have absolute values not higher than unity.

5 Simulation results

To validate the proposed mixed-mode filter, the EXCCTA is designed in Cadence Virtuoso software using 0.18µm PDK provided by Silterra Malaysia. The widths and lengths of the MOS transistors are given in Table 4. The supply voltage is set to ±1.25 V and the bias current of th OTAs is set to 120µA resulting in transconductance of $g_{m1} = g_{m2} = 1.0321 \text{ mS}$. The complete layout of the EXCCTA is designed as presented in Figure 5. The layout verification and parasitic extraction are done using Mentor Graphics Calibre verification tool. The high-performance nhp and php MOSFETs from the PDK library are employed in the design. The EXCCTA occupied a total chip area of (52.78×22.085)µm$^2$.

### Table 4: Width and length of the MOS transistors

<table>
<thead>
<tr>
<th>Transistor</th>
<th>Width (µm)</th>
<th>Length (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1-M4</td>
<td>3.06</td>
<td>0.36</td>
</tr>
<tr>
<td>M5-M8</td>
<td>4</td>
<td>0.36</td>
</tr>
<tr>
<td>M9-M11, M19-M21</td>
<td>2.16</td>
<td>0.36</td>
</tr>
<tr>
<td>M12, M13, M22, M23</td>
<td>1.08</td>
<td>0.72</td>
</tr>
<tr>
<td>M14-M18, M24-M28</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>M29-M32</td>
<td>1.8</td>
<td>0.36</td>
</tr>
<tr>
<td>M33-M36</td>
<td>5.4</td>
<td>0.36</td>
</tr>
<tr>
<td>M37-M40</td>
<td>1.8</td>
<td>0.72</td>
</tr>
</tbody>
</table>

5.1 SIMO configuration operation

First of all, the SIMO configuration of the proposed filter is validated. The filter is designed for centre frequency of 7.622 MHz by setting passive components and OTA bias current values as follows: $R_1 = 1 \text{ kΩ}$, $R_2 = 2 \text{ kΩ}$, $R_3 = 1 \text{ kΩ}$, $R_4 = 1 \text{ kΩ}$, $C_1 = 15 \text{ pF}$, $C_2 = 15 \text{ pF}$, and $g_{m1} = g_{m2} = 1.0321 \text{ mS}$. For the sake of comparison, the EXCCTA based filter responses are plotted along with the ideal filter results obtained using the Matlab software. The VM responses are shown in Figure 6. The AP response is obtained across resistance $R_4$. In addition, the gain of the AP response can be tuned through $R_4$ without affecting other filter parameters as is evident from Figure 7.
To analyse the quality factor tuning, the BP response is plotted for different values of $I_{\text{Bias1}}$, current of OTA$_1$. It can be deduced from Figure 8 that the quality factor can be tuned independent of the centre frequency. The signal processing capability of the VM filter is verified by examining the transient response of the filter. A sinusoidal voltage input signal at 7.622 MHz is applied and the observed LP, BP, HP responses are plotted as given in Figure 9. The total harmonic distortion (THD) of the filter for LP, BP, HP and AP responses is plotted for different input signal amplitudes. The THD remains within acceptable limits for large input range as presented in Figure 10.

To study the effect of process variation on the proposed filter Monte Carlo analysis is carried out for 10% variation in both capacitor $C_1$ and $C_2$ values for BP response. The analysis is done for 200 runs and the results are presented in Figure 11.

The results for CM SIMO filter are presented in Figures 12 and 13. The BR and AP responses are obtained by summing $I_{\text{HP}}$, $I_{\text{LP}}$ and $I_{\text{BP}}$ currents appropriately as discussed in section 3. The quality factor variation with OTA1 bias current $I_{\text{Bias1}}$ is depicted in Figure 14.
The Monte Carlo analysis is carried out for 10% variation in both capacitor $C_1$ and $C_2$ values for LP response in CM operation. The analysis is done for 200 runs and the results are given in Figures 15. To further see the effect of process variability another Monte Carlo analysis is done using the Monte Carlo parameters given in the product design kit (PDK) for the MOS transistors. The results are presented in Figure 16. As can be deduced the mean value of frequency showed a deviation of approximately 6.1% for designed frequency. The THD for LP, HP, and BP responses are presented in Figure 17.

The TAM filter responses are given in Figures 18 and 19, which prove that the filter can generate all five responses in this mode. The BR and AP responses can be obtained by summing the $I_{BP}$, $I_{HP}$, and $I_{LP}$ currents.
The LP, BP, and HP responses in TIM configuration are shown in Figure 20. The AP response is given in Figure 21. To verify the frequency tunability the LP response is plotted for different values of resistance \( R_2 \). Figure 22 shows that the frequency tuning also effects the \( Q \) of the filter, however, it can be adjusted independent of frequency by varying \( I_{Bias1} \) of OTA1.

### 5.2 MISO VM and TAM configuration operation

The filter is designed for \( f_0 = 7.9577 \) MHz by setting passive component and OTA bias current values as follows: \( R_1 = 1 \) k\( \Omega \), \( R_2 = 1 \) k\( \Omega \), \( R_3 = 969 \) \( \Omega \), \( C_1 = 20 \) p\( \text{F} \), \( C_2 = 20 \) p\( \text{F} \), and \( g_{m1} = g_{m2} = 1.0321 \) mS. It must be noted that in MISO configuration resistor \( R_4 \) is not required and will be removed. The inputs are applied according to conditions outlined in Table 2. The filter provides VM and TAM responses simultaneously from the same input sequence. The VM filter responses are presented Figure 23. The VM AP response is given in Figure 24. The independent tunability of the \( Q \) is depicted in Figure 25 for different bias currents \( I_{Bias1} \) of OTA1. To check the phase and signal processing accuracy of the filter, transient analysis is done at 7.9577 MHz with sinusoidal voltage input of 200mV (p-p) for BP configuration. Figure 26 validates the correct functioning of the filter.
Figure 26: VM MISO configuration: Transient analysis of BP filter

The TAM responses of the MISO filter are presented in Figure 27. The AP response is given in Figure 28. The VM outputs are obtained from low impedance node and TAM outputs are obtained from explicit high impedance node which make this filter cascadable.

Figure 27: TAM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

Figure 28: TAM MISO configuration: Gain and phase responses of the AP filter

5.3 MISO CM and TIM configuration operation

The CM and TAM filter is designed for $f_0 = 8.16$ MHz by setting passive component and OTA transconductance values as follows: $R_1 = 1 \, k\Omega$, $R_2 = 1 \, k\Omega$, $R_3 = 969 \, \Omega$, $C_1 = 20$ pF, $C_2 = 20$ pF, and $g_{m1} = g_{m2} = 1.0321 \, mS$. In MISO filter there is again no need for $R_4$. The inputs currents are applied according to sequence given in Table 3. The filter provides CM and TIM responses simultaneously from the same input sequence. The CM outputs are available from explicit high impedance node and the TIM outputs are available from low impedance node making the filter cascadable. The CM responses are given in Figures 29, 30 and the TIM responses are presented in Figures 31, 32.

Figure 29: CM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

Figure 30: CM MISO configuration: Gain and phase responses of the AP filter

Figure 31: TIM MISO configuration: Frequency responses of the LP, BP, HP, and BR filter

Figure 32: TIM MISO configuration: Gain and phase responses of the AP filter
The proposed filter is validated in both MISO and SIMO configurations. The filter responses are found close to the theoretical ones. In CM and TAM operation, the filter response degrades beyond 350 MHz as seen from the graphs. This problem can be mitigated by increasing the output impedance of $Z_P$ and $Z_N$ terminals by employing cascode transistors in the output stage. Moreover, careful layout can further increase the accuracy of the filter.

6 Conclusion

In this study, a new EXCCTA based electronically tunable mixed-mode filter structure is proposed. The filter employs two EXCCTAs, four resistors, two capacitors, and a single switch. This is the first presented filter to date that has inbuilt tunability and can realize all five filter responses in all four modes of operation (VM, CM, TAM, and TIM) in both MISO and SIMO configurations. The detailed theoretical analysis, non-ideal gain analysis, and sensitivity study are given. The layout of the EXCCTA is designed in Cadence software and extensive simulations are carried out to examine and validate the proposed filter in all four modes of operation. The proposed filter has the following advantages: (i) ability to operate in both MISO and SIMO configurations in all four modes, (ii) no requirement of capacitive matching, (iii) low input impedance in SIMO (CM and TIM) configuration, (iv) high output impedance explicit current output for SIMO (CM and TAM), (v) tunability of $Q$ independent of frequency in MISO and SIMO configurations, (vi) use of grounded capacitors in SIMO configuration, (vii) low output impedance for MISO (VM and TIM), (viii) high output impedance explicit current output for MISO (CM and TAM), (ix) no requirement for double/negative input signals (voltage/current) in MISO configuration, and (x) low active and passive sensitivities. The simulation results are consistent with the theoretical predictions.

7 Acknowledgement

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8 References


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