Electronically and Orthogonally Tunable SITO Voltage-Mode Multifunction Biquad Filter Using LT1228s

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Abstract—The commercially available IC LT1228 is an interesting active device due to its advantage features, such as a fast transconductance amplifier, a wide bandwidth over a wide range of voltage gain, low total harmonic distortion (THD), high impedance differential input, etc. The single-input triple-output (SITO) voltage-mode (VM) multifunction biquadratic filters using ICs, LT1228s are introduced in this research. This circuit design provides the three-filtering functions, low-pass (LP), high-pass (HP), and band-pass (BP), without changing the circuit architecture. It comprises three LT1228s, four resistors, and two capacitors connected to the ground. The low impedance voltage output nodes are HP and BP responses. The quality factor (Q) and the pole frequency (ω0) can be electronically and orthogonally tuned by altering the third LT1228’s bias current (Ib). The PSPICE simulation and the experiment are verified to describe the circuit operation.

Index Terms—LT1228; Voltage-mode; SITO; Biquadratic filter; Active building block.

I. INTRODUCTION

The realization of a continuous-time filter utilizing the electronically adjustable active building block (ABB) has been mainly focused on the research topic due to its advantages, e.g., it gives better adjustment than varying the value of the passive device. It is a significant building block of analog signal processing, automatic control, and instrumentation systems, such as touch-tone telephone systems, three-way crossover networks, digital television (DTV), and phased locked loop circuits. A circuit simultaneously provides LP, HP, and BP filters are always used in the electrical and electronics engineering field, such as the three-way crossover network [1]–[3].

The current feedback amplifier (CFA) has drawn in extensive regard for design superior performance electronic circuits. CFA is essentially a current mode device and is utilized in high-frequency operations. Moreover, it gives faster slew rates, lower distortion, very high full-power bandwidth, and provides a large output current drive capability. Numerous commercial CFA ICs are accessible, e.g., AD844 CFA using the macro model available from Analog Devices, AD8011 from Analog Devices [4], [5].

The LT1228 integrated circuit by Linear Technology is one of the intriguing elements [6]. It comprises two independent sub-elements: the operational transconductance amplifier (OTA), whose transconductance (g_m) can be electronically controlled by bias current and the CFA which can be used as a voltage buffer or amplifier.

The voltage-mode multifunction biquadratic filters using ABB implemented from the commercially available ICs have been recently published in [7]–[19]. The biquad multifunction filters utilizing LT1228 as an active element were proposed in [12], [13], [15], [16]. The ABB employed [8]–[10] is constructed from the different commercially available ICs. Some filters proposed in [10], [14], [18] don’t use the grounded capacitors. The biquad filter in [18] is not provided the low output impedance. As a result, it requires the buffer to connect the other circuits. Both ω_0 and Q of the proposed filters in [7], [9], [11], [14], [18] cannot be offered electronically controllable, while the circuits proposed in [8], [10], [12], [14], [17], [18] cannot be independently tuned. An electronically and orthogonally controllable SITO VM multifunction biquadricating filtering circuit using LT1228 as an active building block is proposed in this paper. This circuit can orthogonally and electronically control the filtering parameters, the ω_0 and Q. It gives low output impedances at HP and BP responses, so it can be directly cascaded to other circuits. This filter uses the grounded capacitors being attractive for the cancellation of non-ideal effects of LT1228. To affirm the circuit performance of the presented filter, the PSPICE simulation utilizing the LT1228 and theoretical results are described.

II. PRINCIPLE OF OPERATION

The schematic symbol, equivalent circuit, and block diagram of LT1228 are illustrated in Fig. 1(a), Fig. 1(b), and Fig. 1(c). The LT1228 OTA has a current source with high output impedance Pin 1) and a differential voltage with high input impedance (Pin 2 and Pin 3). Pins 4 and 7 are the positive and negative supply voltages. The transconductance, g_m, is controlled by the current that flows into Pin 5, I_b. The CFA’s non-inverting input is designed to drive the voltage terminals with low output impedance (Pin

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The ideal property of LT1228 is expressed in (1):

\[
\begin{bmatrix}
I_{V_+} \\
I_{V_-} \\
I_y \\
I_w
\end{bmatrix} =
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
g_m & g_m & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
V_+ \\
V_- \\
V_+ - V_- \\
I_x
\end{bmatrix},
\]

(1)

where \( R_T \) is the trans-resistance gain. In an ideal case, \( R_T \) approaches infinity. The transconductance \( g_m \) of LT1228 can be described as follows

\[
g_m = I_b / 3.87V_T,
\]

where \( I_b \) is the DC bias current and \( V_T \) is the thermal voltage. It reveals from (2) that the \( g_m \) is electronically controlled by bias current \( I_b \), which is required for the modern circuit. However, the \( g_m \) is inversely proportional to temperature.

III. SYNTHESIS OF MULTIFUNCTION FILTER

The proposed filter is synthesized from the block diagram in Fig. 2. It consists of five basic blocks: the voltage summing circuit, two lossless integrators, and two voltage amplifiers. The inputs of the voltage summing circuit are \( V_{lp}, V_{hp}, \) and \( V_m \), while the output voltage node of the summing circuit is \( V_{hp} \). The voltage node, \( V_{hp} \), is the output of the first lossless integrator multiplied by the voltage gain amplifier, \( K \). The \( V_{lp} \) is the output of the second lossless integrator. The time constant of the first and the second integrators are defined as \( a \) and \( b \), respectively.

The three voltage transfer functions for \( V_{hp}, V_{hp}, \) and \( V_{lp} \) of the block diagram shown in Fig. 2 are respectively obtained as:

\[
\frac{V_{lp}}{V_m} = \frac{1}{ab},
\]

\[
\frac{V_{hp}}{V_m} = \frac{-s^2 - sK + \frac{3}{a} + \frac{3}{ab}}{s^2 + sK + \frac{3}{a} + \frac{3}{ab}},
\]

(3)

Equations (4)–(6) indicate that the unity passband voltage gain is obtained for the BP and HP functions and one-third passband voltage-gain is obtained for the LP function. The \( \omega_0 \) and \( Q \) are respectively obtained as

\[
\omega_0 = \frac{3}{ab},
\]

(6)

\[
Q = \frac{1}{K} \frac{3a}{b}.
\]

(7)

Equations (6) and (7) shows that the \( Q \) can be adjusted without disturbing the \( \omega_0 \) by varying the voltage gain, \( K \). Simultaneously adjusting the time constants \( a \) and \( b \) of the integrator circuits can control the \( \omega_0 \) without affecting the \( Q \). Then \( \omega_0 \) and \( Q \) are independently controlled, where the \( Q \) can be adjusted by the voltage gain, \( K \), and the \( \omega_0 \) can be linearly adjusted by the time constants of both integrators.

IV. PROPOSED MULTIFUNCTION FILTER

The proposed multifunction filter is shown in Fig. 3. It consists of three LT1228s, four resistors, and two grounded capacitors. The filter in Fig. 3 is synthesized from the block diagram in Fig. 2.
LT1228. Finally, the amplifier consists of the resistor \( R_x \) and the third LT1228. The single input voltage, \( V_{in} \), is applied to the voltage summing circuit, while the first integrator produces the low-pass filtering output voltage node, \( V_{LP} \). The voltage summing produces the high-pass filtering output voltage node, \( V_{HP} \), and the voltage amplifier produces the band-pass filtering output voltage node, \( V_{BP} \). With this design, three voltage mode second-order filtering functions are simultaneously given without changing the filtering architecture. Moreover, the proposed filter provides the low output impedance at output voltage nodes \( V_{HP} \) and \( V_{BP} \). These voltage transfer functions of the proposed circuit are given by:

\[
V_{LP} = \frac{g_{m1}g_{m2}}{s^2 + g_{m1}R_xg_{m2} + 3g_{m1}g_{m2}} C_1 C_2
\]

\[
V_{BP} = \frac{-g_{m1}R_xg_{m2}}{s^2 + g_{m1}R_xg_{m2} + 3g_{m1}g_{m2}} C_1 C_2
\]

\[
V_{HP} = \frac{1}{s^2 + g_{m1}R_xg_{m2} + 3g_{m1}g_{m2}} C_1 C_2
\]

From (8)–(10), the high-pass and band-pass functions are obtained unity passband voltage gain, while the low-pass function is also obtained one-third passband voltage gain. In addition, from them, the inverting for the high-pass and band-pass functions is achieved and the non-inverting for the low-pass response is achieved. The \( \omega_0 \) and \( Q \) are described as follows:

\[
\omega_0 = \frac{3g_{m1}g_{m2}}{C_1 C_2},
\]

\[
Q = \frac{1}{g_{m1}R_x} \frac{3g_{m1}g_{m2}}{g_{m2}C_1}.
\]

Substituting the \( I_{Bi1}, I_{Bi2} \), and \( I_{Bi3} \) from (2) into transconductances \( g_{m1}, g_{m2} \), and \( g_{m3} \) to (11) and (12), the \( \omega_0 \) and \( Q \) of the proposed filter are as follows:

\[
\omega_0 = \frac{3.87V_s}{C_1 C_2},
\]

\[
Q = \frac{1}{I_{Bi3}R_x} \frac{3.87V_s}{I_{Bi3}C_1}.
\]

From (13) and (14), it can be seen that \( \omega_0 \) can be electronically tuned by \( I_{Bi1} \) and \( I_{Bi2} \). Moreover, the \( Q \) can be altered without disturbing \( \omega_0 \) by changing the value of \( I_{Bi3} \). If the bias currents \( I_{Bi1} = I_{Bi2} = I_B \) (this property is easily implemented by using a microcontroller or microcomputer) are simultaneously adjusted and choosing \( C_1 = C_2 = C \), the filtering parameters in (11) become

\[
\omega_0 = \frac{I_B}{3.87V_s\sqrt{3}},
\]

\[
Q = \frac{\sqrt{3}}{I_B R_x}.
\]

It can be remarked from (15) and (16) that \( \omega_0 \) and \( Q \) are independently, electronically controlled. Moreover, the \( \omega_0 \) and \( Q \) can be linearly and electronically adjusted.

V. PARASITIC EFFECT ON LT1228

In real response, the parasitic elements of LT1228 affect the performance of the circuit, so they are described in detail in this section. These parasitic elements are grounded passive elements (resistors and capacitors) at high impedance \( V_s, V_{..}, \) and \( y \) terminal. They can be characterized as \( R_x, C_s, R_x, C_s, R_y, \) and \( C_s \), respectively. The impedance terminals \( x \) and \( w \) show up in the arrangement resistors \( R_x, \) and \( R_y \) individually since these terminals have low impedance. The trans-resistance gain \( R_T \) is paralleled by \( C_T \). According to the data sheet of LT1228 [6], to reduce the effect of \( C_T \) and \( R_T \) and to get higher operating frequency, the feedback resistor \( (R_f) \) in this filter) connecting from \( w \) to \( x \) terminal in the summing circuit should be low. In addition, if the bandwidth of the presented filter is expected to be lower than 10 MHz, the greatest effect stems from \( R_x, C_s, R_y, \) and \( C_s \). So, the effect of \( R_x, R_y, R_T, \) and \( C_T \) is ignored. Moreover, if the operational frequency of the presented filter is expected to be lower than \( G_{s3} / C_s \), the effect of \( C_{s3} \) is also ignored. Considering these parasitic elements, the voltage transfer functions of the proposed filter are as follow:

\[
V_{LP} = \frac{\frac{g_{m1}g_{m2}}{C_1 C_2}}{D(s)},
\]

\[
V_{HP} = \frac{-K^* g_{m1}G_{s1} + K^* g_{m2}g_{s2}}{C_1 C_2 C_2} D(s),
\]

\[
V_{BP} = \frac{-s^2 - \left( \frac{G_{j1} C_1 + G_{j2} C_2}{C_1 C_2} \right) s - \frac{G_{j1} G_{j2}}{C_1 C_2}}{D(s)},
\]

where

\[
D(s) = \left[ s^3 + \left( \frac{G_{j1} C_2 + G_{j2} C_1}{C_1 C_2} \right) s + \frac{G_{j1} G_{j2} + 3g_{m1}g_{m2} + K^* g_{m2}g_{s1}}{C_1 C_2} \right]
\]

and

\[
K^* = \frac{g_{m3}}{G_{s3}}, \quad C^*_1 = C_1 + C_{s1}, \quad C^*_2 = C_2 + C_{s2} + C_{s3} + C_3, \quad G_{s1} = \frac{1}{R_{s1}}, \quad G_{s2} = \frac{1}{R_{s2}} + \frac{1}{R_{s3}}, \quad G_{s3} = \frac{1}{R_{s3}} + \frac{1}{R_4}.
\]
From (20), the non-ideal factors of the natural frequency and quality are given by:

\[
\omega_0 = \sqrt{\frac{G_{11}G_{22} + K_n s C_1}{C_1}} \quad \text{(21)}
\]

\[
Q = \frac{1}{\frac{G_{11}}{C_1} + \frac{K_n s C_1}{C_1^2}} \quad \text{(22)}
\]

It is seen from (17) to (22) that the parasitic elements in LT1228 affect the filtering performances which are the operational frequency, passband voltage gain, natural frequency, and quality factor.

VI. SIMULATION RESULTS

The functionality of the presented filter has been matched with the LT1228 PSPICE macro model simulation. In this simulation, the symmetrical supply voltages are ±5 VDC, the components are chosen as follows: \( I_{B1} = I_{B2} = I_{B3} = 100 \mu A, R_1 = R_2 = R_3 = R_4 = 1 \mathrm{k\Omega}, \) and \( C_1 = C_2 = 2.7 \mathrm{nF}. \) The \( f_0 \) and \( Q \) from (15), (16) are obtained as 102.097 kHz and 1.732, respectively. The magnitude of LP, HP, and BP versus frequency of the proposed voltage-mode multifunction biquadratic filter is shown in Fig. 4. The simulated \( f_0 \) is 100.46 kHz and \( Q \) is 1.71. The percent deviations of the expected and simulated values of \( Q \) and \( f_0 \) are 1.27 % and 1.6 %, respectively. Figure 5 shows the HP frequency response with different values of \( R (R_1 = R_2 = R_3 = R) \), where the values of \( R \) in the summing circuit are set to 0.2 k\Omega, 0.6 k\Omega, and 5 k\Omega. It is verified that the bandwidth at the low value of the feedback resistor (\( R_4 \)) in the proposed filter is higher than the bandwidth at the high value of \( R_4 \) as described in the parasitic section. Thus, these resistors are chosen as 1 k\Omega to achieve higher operational frequency. Figure 6 indicates the test of the transient response of the presented voltage-mode band-pass filter where the sinusoidal input voltage is applied to 50 mV\(_{p}\) and \( f_0 = 100 \mathrm{kHz}. \)

The \( Q \) value is controlled without disturbing the \( f_0 \) as shown in Fig. 7. It is verified that \( Q \) can be orthogonally controlled by simultaneously adjusting the DC bias current, \( I_{B1}, \) to 123.5 \mu A, 185.5 \mu A, and 371 \mu A. Figure 8 confirms that \( Q \) can be controlled by varying the value of resistance \( R_4 \) without affecting \( f_0 \) as expected in (15), (16), where \( R_4 \) is assigned to 1 k\Omega, 2 k\Omega, and 3 k\Omega. The control of the pole frequency can be electronically tuned by simultaneously varying the values of \( I_{B1} \) and \( I_{B2} \) as described in (15), (16). This adjustment of \( I_{B1} \) and \( I_{B2} \) is easily implemented by using a microcontroller or microcomputer. This is verified by the simulated results in Fig. 9. The BP responses are simulated for three different values, where \( f_0 \) is set to 123.311 kHz, 185.353 kHz, and 373.25 kHz at the same value of \( Q = 1.6. \) The simulation results of the total harmonic distortion (THD) versus the magnitude of the input voltage are illustrated in Fig. 10. The input linear range of the proposed filter is around 50 mV\(_{p}\) because the internal construction of LT1228 is BJT OTA.

The 10 mV\(_{p}\) of the sinusoidal input voltage signal is applied with three frequencies, such as 10 kHz, 100 kHz, and 1 MHz. The input and the output voltage signals for the BP frequency spectrum result are demonstrated in Fig. 11. It

### Fig. 4. Magnitude responses of BP, LP, and HP.

### Fig. 5. Simulated HP frequency responses for different values of \( R (R_1 = R_2 = R_3 = R). \)

### Fig. 6. Time-domain responses of the presented BP function.

### Fig. 7. Simulated BP frequency responses for different values of \( I_{B3}. \)

### Fig. 8. Simulated BP frequency responses for different values of \( R_4. \)

### Fig. 9. Simulated BP responses for different values of \( I_{B4} (I_{B1} = I_{B2} = I_{B3}). \)
is found that the attenuation between the pole frequency (100 kHz) and $f = 10$ kHz is -25.52 dB, while the attenuation between the pole frequency (100 kHz) and $f = 1$ MHz is -5.82 dB.

The simulation results in Figs. 6–11 indicate that the proposed filter operates well as expected. The operational frequency is around 10 MHz. The total harmonic distortion is lower than 1% when the applied amplitude of the input signal is lower than 50 mVp.

![Fig. 3](image)

**Fig. 3.** THD test of the BP versus input voltage amplitude.

![Fig. 10](image)

**Fig. 10.** THD test of the BP versus input voltage amplitude.

![Fig. 11](image)

**Fig. 11.** The desirable test signal of the BP.

## VII. EXPERIMENTAL RESULTS

To verify the performance of the proposed biquadratic multifunction filtering design in Fig. 3, the tests are made by using three LT1228s. The power supply voltage is ±5 V using GW Instek GPS-3303 power supply. In the experiment, the components are selected: $C_1 = C_2 = 2.7$ nF, $R_1 = R_2 = R_3 = R_4 = 1$ kΩ, and $I_{B1} = I_{B2} = I_{B3} = 100$ μA. The calculated pole frequency and the quality factor are $f_0 = 102.097$ kHz and $Q = 1.732$, respectively. The sinusoidal input signal and the output waveforms are measured by the Keysight DSOX1102G oscilloscope. Figure 12 illustrates the experimental and theoretical results of the filter with the input voltage amplitude being 50 mVp–p to keep LT1228 operating in linear range. The experimental pole frequency is $f_0 = 100$ kHz. Due to the parasitic elements of LT1228, the experimental results slightly deviate from the ideal results at low-frequency, and tolerances of the parasitic capacitance effect at high frequency (higher 10 MHz). Next, the transient response of the BP filtering function is also investigated by applying a 50 mVp–p sinusoidal input voltage for the three frequencies (50 kHz, 100 kHz, and 500 kHz) shown in Fig. 13. It is found that at low (50 kHz) and high frequency (500 kHz), the output voltages are attended, while at natural frequency (100 kHz), the input and the output voltages are the same magnitude. Figure 14 shows the magnitude response of the band-pass filter at different $I_{B1}$ values (123.5 μA, 185.5 μA, and 371 μA). It is verified that the pole frequency is linearly and electronically tuned by $I_{B1}$ without affecting the $Q$ as expected in (15), (16). To keep the $f_0$ value constant at 100 kHz by varying the resistor $R_q$, the adjustment of the $Q$ value is verified in Fig. 15. The band-pass responses for the three different values of $f_0$ at $Q = 1.6$ can be obtained by simultaneously varying the values of the bias currents, $I_{B1}$ and $I_{B2}$ (where the three different values of these bias currents are 123.5 μA, 185.5 μA, and 371 μA). In practical, this adjustment of $I_{B1}$ and $I_{B2}$ is easily implemented by using a microcontroller. This result is demonstrated in Fig. 16.

The experimental results in Figs. 12–16 indicate that the proposed filter operates well as expected. However, at high frequency, the parasitic capacitances in LT1228 will affect the performance of the proposed filter as results in Fig. 12, Figs. 14–16.
Fig. 13. The transient response of the proposed SITO BP function (orange line is the input and green line is the output): (a) \( f = 50 \) kHz, (b) \( f = 100 \) kHz, (c) \( f = 500 \) kHz.

Fig. 14. The experimental response of BP for different values of \( I_{B3}. \)

VIII. COMPARISON AND DISCUSSION

Table I compares the proposed multifunction biquad filter with recent biquad filters using ABBs implemented from the commercially available ICs [7]–[18]. The proposed filter and the circuits in [9], [12] are single input multiple output.

The biquad filters in [7], [9], [11], [13], [15]–[17] are multiple input multiple output, and the filters in [8], [10], [14], [18] are multiple input single output configuration. The biquad multifunction filters in [8]–[10] are constructed from the different commercially available ICs. The filters in [15], [16] consist of five LT1228s.

| Ref. | ABB | No. of commercial ICs | All grounded C | Providing several functions at the same time | Filtering functions | No. of low Z nodes | Electronic tuning both \( f_c \) and \( Q \) | Independent tuning of \( f_c \) and \( Q \) | Voltage supplies |
|------|-----|----------------------|----------------|------------------------------------------|-------------------|-------------------|----------------------------------|-------------------|---------------|
| [7]  | AD844 | 3 | Yes | No | LP, HP, BP | 3 | No | Yes | ±6 V |
| [8]  | VDDDA | 4 | Yes | No | LP, HP, BP, BR, AP | 1 | Yes | No | ±5 V |
| [9]  | VD-DIBA | 4 | Yes | Yes | LP, HP, BP, BR, AP | 2 | No | Yes | ±5 V |
| [10] | VDBA | 4 | No | No | LP, HP, BP, BR, AP | 1 | Yes | No | ±5 V |
| [11] | AD844 | 3 | Yes | Yes | LP, BP, BR | 3 | No | Yes | ±6 V |
| [12] | LT1228 | 2 | Yes | Yes | LP, BP, HP | 2 | Yes | No | ±5 V |
| [13] | LT1228 | 4 | Yes | Yes | LP, BP, BR | 3 | Yes | No | ±15 V |
| [14] | AD844 | 3 | No | No | LP, HP, BR, AP | 1 | No | No | ±6 V |
| [15] | LT1228 | 5 | Yes | Yes | LP, BP, HP, BR, AP | 3 | Yes | Yes | ±15 V |
| [16] | LT1228 | 5 | Yes | Yes | LP, BP, HP, BR, AP | 3 | Yes | Yes | ±15 V |
| [17] | AD844 | 3 | Yes | Yes | LP, BP, HP, BR | 3 | No | No | ±6 V |
| [18] | FTFN | 2 | No | No | LP, BP, HP, BR, AP | 0 | No | No | ±10 V |
| This work | LT1228 | 3 | Yes | Yes | LP, BP, HP | 2 | Yes | Yes | ±5 V |

Notes: VDDDA and VD-DIBA are constructed from two commercially available ICs, LM13700 and AD830; VDBA is constructed from two commercially available ICs, CA3080 and LF356; FTFN is constructed from two commercially available ICs, AD844.
In [10], [14], [18], these filters employ the floating capacitor, while the proposed filter uses grounded capacitors which ensure the compensation of the parasitic effects in ABB. The filters in [7], [8], [10], [14], [18] cannot simultaneously provide several filter responses. Although the proposed filter provides only LP, HP, and BP responses, but it is sufficient to be applied in some applications, such as the three-way crossover network. The biquad filter in [18] does not provide the low output impedance. As a result, it requires the buffer to connect the other circuits. Both $\omega_0$ and $Q$ of the proposed filter in [7], [9], [11], [14], [18] cannot be offered electronic controllability which is not suitable for modern circuits which are controlled by microcontroller or microprocessor. The $\omega_0$ and $Q$ of the filters proposed in [8], [10], [12], [14], [17], [18] cannot be independently tuned.

IX. CONCLUSIONS

In this work, an electronically and independently controllable SITO voltage-mode multifunction biquadratic filtering circuit is proposed. The proposed filter consists of triple LT1228s, two grounded capacitors, and four resistors. This proposed filter capable of producing three transfer functions, such as LP, HP, and BP, is suitable to be used in the three-way crossover network. HP and BP responses give low output impedance is the advantage of this filter because it can be directly cascaded to other circuits without using the additional buffer. Moreover, the quality factor and the pole frequency can be independently and electronically controlled. The quality factor can be controlled by altering the third LT1228’s external DC bias current value without affecting the $\omega_0$. The simulation and experimental results are achieved to verify the theoretical analysis. The operational frequency range is lower than 10 MHz. The total harmonic distortion is lower than 1 % when the applied amplitude of the input signal is lower than 50 mVp.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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