A Current-mode Electronically Controllable Multifunction Biquadratic Filter Using CCCIIs

S. Srisakultiew[1], S. Lawanwisut[2] and M. Siripruchyanun[3]

***Abstract*— This article presents a current-mode multifunction biquadratic filter performing completely standard functions low-pass, high-pass, band-pass, band-reject and all-pass functions. The circuit principle is based on second-generation current-controlled current conveyor (CCCII) with three input terminals and one output terminal. The features of the circuit are that, the pole frequency can be tuned via the bias currents. The circuit topology is very simple, consisting of merely 2 CCCIIs and 2 grounded capacitors. Without any external resistor and using only grounded elements, the proposed circuit is very comfortable to further develop into an integrated circuit architecture. The PSpice simulation results are shown. The given results agree well with the theoretical anticipation. The total power consumption is approximately 1.87mW at ±1.5V power supply voltages.**

***Keywords*— Current-mode, Biquadratic filter, CCCII.**

I. INTRODUCTION

An analog filter is an important building block, widely used for continuous-time signal processing. It can be found in many fields: including, communications, measurement, and instrumentation, and control systems [1-2]. One of most popular analog filters are multi-purpose and universal filters that can be classified either as multi-input and single-output (MISO) filter [3] or single-input and multi-output (SIMO) filter [4]. The MISO current-mode filters have rather simple structures [5]. Recently, a multifunction filter working in current-mode has being been more popular than the voltage-mode type. Since the last two decades, there has been much effort to reduce the supply voltage of analog systems. This is due to the demand for portable and battery-powered equipment. Since a low-voltage operating circuit becomes necessary, the current–mode technique is ideally suited for this purpose. Actually, a circuit using the current-mode technique has many other advantages, such as, larger dynamic range, higher bandwidth, greater linearity, simpler circuitry and lower power consumption [6-7].

A second generation current conveyor (CCII) is a reported active component, especially suitable for a class of analog signal processing [8]. The fact that the device can operate in both current and voltage-modes provides flexibility and enables a variety of circuit designs. In addition, it can offer advantageous features such as high slew-rate, high-speed, wide bandwidth and simple implementation [8-9]. However, the parasitic resistance at *X* (R_x) port cannot be controlled so when it is used in some circuits, it unavoidably requires some external passive components, especially the resistors. This makes it not appropriate for IC implementation due to occupying more chip area, consuming high power and without electronic controllability. On the other hand, the introduced second-generation current-controlled conveyor (CCCII) [10] has the advantage of electronic adjustability over the CCII. Also, the use of multiple-output current conveyors is found to be useful in the derivation of current-mode single-input three-output filters using a reduced number of active components [11-12].

From our survey, it is found that several implementations of current-mode multifunction biquadratic filters have been reported [13-33]. Unfortunately, these reported circuits suffer from one or more of following weaknesses:

- Excessive use of the passive elements, especially the external resistors [15-17, 19, 23-26, 28-33].
- Lack of electronic adjustability [15-17, 19, 23-26, 28-32].
- Require changing circuit topologies to achieve several functions [14-16, 20-21, 24-26].
- Some outputs of the filter responses are not in high output impedance [13-14, 15, 17-18].
- Cannot provide completely standard function [19-20, 22, 24-25, 28-29, 31]

The aim of this paper is to propose a current-mode multifunction biquadratic filter, emphasizing on use of the CCCIIs and grounded capacitors. The features of the proposed circuit are that, the proposed multifunction bi-quadratic filter can completely provide 5 functions which are low-pass high-pass band-pass band-reject and all-pass, without changing circuit topology, the circuit description is very simple, employing only grounded capacitors as passive components, thus it is suitable for fabricating in monolithic chip. The quality factor and pole frequency can be electronically adjusted. The PSpice simulation results are also shown, which are in correspondence with the theoretical analysis.

II. PRINCIPLE OF OPERATION

A. *Multiple-output Current Controlled Current Conveyor (MO-CCCII)*

Since the proposed circuit is based on MO-CCCII, it will be introduced in this section. Typically, the MO-CCCII is a

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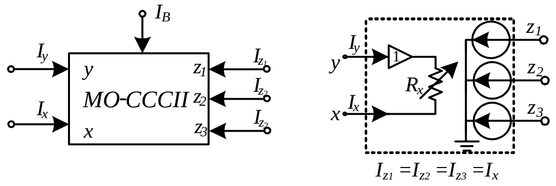
versatile analog building block which including 3-ports, x, y and z. The matrix-relationship between voltage and current are variables among port *x*, *y* and *z* of ideal following matrix equation in Eq. (1). Where the positive and negative signs of the current i_z denote the positive (CCCII+) and negative (CCCII-), respectively, and R_x is an intrinsic resistance of CCCII. The x-terminal resistance is calculated by Eq. (2) and V_T is the thermal voltage. Fig.1 (a) and (b) illustrates the symbol and equivalent circuit, respectively.

$$\begin{bmatrix} i_y \\ v_x \\ i_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & R_x & 0 \\ 0 & \pm 1 & 0 \end{bmatrix} \begin{bmatrix} v_y \\ i_x \\ v_z \end{bmatrix}, \tag{1}$$

where

$$R_x = \frac{V_T}{2I_B}, \tag{2}$$



(a) (b)

Fig. 1. MO-CCCII (a) Symbol, (b) Equivalent circuit.

B. Implementation of the filter

The proposed filter is designed by cascading summing currents and the current-mode lossless integrator as systematically shown in Fig. 2. From block diagram in Fig. 2, its transfer function can be found to be [34-36]

$$I_{out} = \frac{\left(s^2 + sb + ab\right) I_{in3} + sbI_{in2} + abI_{in1}}{s^2 + sb + ab}. \tag{3}$$

From Eq. (3), the pole frequency (ω_0) and quality factor (Q_0) of each filter response can be expressed as

$$\omega_o = \sqrt{ab}, \tag{4}$$

and

$$Q_o = \sqrt{\frac{a}{b}}. \tag{5}$$

It is found that the pole frequency and the quality factor can be adjusted by either *a* or *b*.

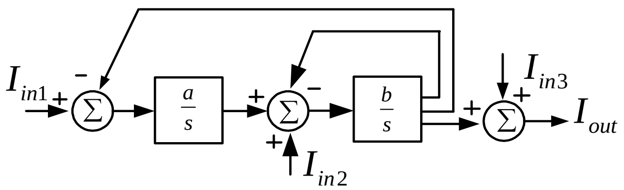


Fig 2. Block diagram for filter implementation [34].

C. Proposed current-mode multifunction biquadratic filter

The filter is designed by cascading the lossless integrators as systematically shown in Fig. 3. From circuit in Fig. 3, the current transfer function can be expressed as

$$\frac{I_{out}}{I_{in}} = \frac{1}{s\tau}, \tag{6}$$

where $\tau = \dfrac{2I_B}{CV_T}$

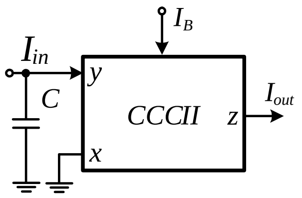


Fig. 3. Lossless integrator using CCCII.

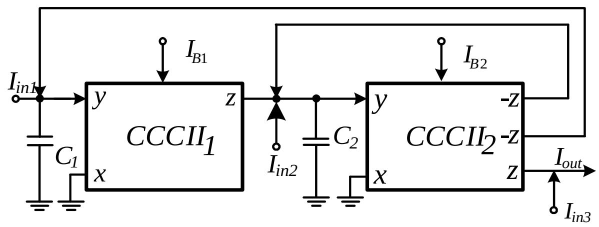


Fig. 4. Proposed current-mode multifunction biquadratic filter.

The complete current-mode multifunction biquadratic filter is shown in Fig. 4. From Eq. (7), the output current of the circuit in Fig. 4 can be obtained as

$$I_{out} = \frac{\left(s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1}R_{x2}C_1C_2}\right) I_{in3} + \frac{s}{C_2 R_{x2}} I_{in2} + \frac{1}{R_{x1}R_{x2}C_1C_2} I_{in1}}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1}R_{x2}C_1C_2}}. \tag{7}$$

From Eq. (7), the all standard transfer functions can be obtained by selecting appropriate inputs by following conditions

1) If $I_{in} = I_{in1}$, and $I_{in2} = I_{in3} = 0$, a low-pass function is achieved at the output. The transfer function can be written to be

$$\frac{I_{out}}{I_{in}} = \frac{\frac{1}{R_{x1}R_{x2}C_1C_2}}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1}R_{x2}C_1C_2}}. \tag{8}$$

2) If $I_{in} = -I_{in1} = -I_{in2} = I_{in3}$, a high-pass function can be obtained. The transfer function can be written to be

$$\frac{I_{out}}{I_{in}} = \frac{s^2}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1}R_{x2}C_1C_2}}. \tag{9}$$

3) If $I_{in} = I_{in2}$, and $I_{in1} = I_{in3} = 0$, the obtained output function is a band-pass. The transfer function can be given by

$$\frac{I_{out}}{I_{in}} = \frac{\frac{s}{C_2 R_{x2}}}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1} R_{x2} C_1 C_2}}. \tag{10}$$

4) If $I_{in} = I_{in3} = -I_{in2}$, and $I_{in1} = 0$, a band-reject function is provided. The transfer function can be written to be

$$\frac{I_{out}}{I_{in}} = \frac{s^2 + \frac{1}{R_{x1} R_{x2} C_1 C_2}}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1} R_{x2} C_1 C_2}}. \tag{11}$$

5) If $I_{in} = I_{in3} = -2I_{in2}$, and $I_{in1} = 0$, an all-pass filter is obtained. The transfer functions can be written to be

$$\frac{I_{out}}{I_{in}} = \frac{s^2 - \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1} R_{x2} C_1 C_2}}{s^2 + \frac{s}{C_2 R_{x2}} + \frac{1}{R_{x1} R_{x2} C_1 C_2}}. \tag{12}$$

The selection to obtain each function can be achieved by digital method, the digital selection circuit can be found in [37].

The pole frequency (ω_0) and quality factor (Q_0) can be expressed to be

$$\omega_0 = \frac{1}{\sqrt{C_1 C_2 R_{x2} R_{x3}}}, \tag{13}$$

and

$$Q_0 = \sqrt{\frac{C_1 R_{x2}}{C_2 R_{x3}}}, \tag{14}$$

where $R_{x1} = \frac{V_T}{2I_{B1}}$, $R_{x2} = \frac{V_T}{2I_{B2}}$. Thus, we get

$$\omega_0 = \frac{2}{V_T} \sqrt{\frac{I_{B1} I_{B2}}{C_1 C_2}}, \tag{15}$$

and

$$Q_0 = \sqrt{\frac{C_1 I_{B2}}{C_2 I_{B1}}}. \tag{16}$$

From Eqs. (15) and (16), the pole frequency can be electronically controlled, which is independent from the quality factor by varying I_{B1} and I_{B2} (keeping their ratio constant). Furthermore, bandwidth of the system can be expressed by

$$BW = \frac{\omega_0}{Q_0} = \frac{2I_{B1}}{V_T C_1}. \tag{17}$$

We found that the bandwidth can be linearly controlled by I_{B1}.

D. Sensitivity analysis

The sensitivities of the proposed filter can be found to be:

$$S^{\omega_0}_{C_1,C_2} = -\frac{1}{2}, \quad S^{\omega_0}_{I_{B1},I_{B2}} = \frac{1}{2}, \tag{18}$$

$$S^{Q_0}_{I_{B2},C_1} = \frac{1}{2}, \quad S^{Q_0}_{I_{B1},C_1} = -\frac{1}{2}. \tag{19}$$

and

$$S^{BW}_{V_T,C_2} = -1, \quad S^{BW}_{I_{B1}} = 1. \tag{20}$$

Therefore, all active and passive sensitivities are equal or less than unity in magnitude.

E. Non-ideal Case

For non-ideal case, the voltage and current tracking errors of the MO-CCCII effect on the performance of the proposed filter. By routine analysis, the MO-CCCII with non-ideal case can be respectively characterized with the following equations

$$I_y = 0, V_x = \beta V_y + R_x I_x, I_z = \alpha I_x, \tag{21}$$

$\beta = 1 - \varepsilon_V$ ($\varepsilon_V << 1$) is the voltage gain, where ε_V is the voltage tracking error from V_y to V_x of MO-CCCII. α is the current gain equal to $1 - \varepsilon_i$ ($\varepsilon_i << 1$), where ε_i is the output current tracking error of MO-CCCII. In the case of non-ideal and reanalysis of proposed filter circuit in Fig. 4, it yields the output current as

$$I_{out} = \frac{\left(s^2 + \frac{s\alpha_2\beta_2}{C_2 R_{x2}} + \frac{\alpha_1\alpha_2\beta_1\beta_2}{R_{x1} R_{x2} C_1 C_2}\right) I_{in3} + \frac{s\alpha_2\beta_1}{C_2 R_{x2}} I_{in2} + \frac{\alpha_1\alpha_2\beta_1\beta_2}{R_{x1} R_{x2} C_1 C_2} I_{in1}}{s^2 + \frac{s\alpha_2\beta_2}{C_2 R_{x2}} + \frac{\alpha_1\alpha_2\beta_1\beta_2}{R_{x1} R_{x2} C_1 C_2}}, \tag{22}$$

In this case, the ω_0 and Q_0 are changed to

$$\omega_0 = \sqrt{\frac{\alpha_1\alpha_2\beta_1\beta_2}{C_1 C_2 R_{x1} R_{x2}}} \tag{23}$$

and

$$Q_0 = \sqrt{\frac{\alpha_2\beta_2 C_1 R_{x1}}{\alpha_1\beta_1 C_2 R_{x2}}}, \tag{24}$$

while BW is still equal to Eq. (17). These errors affect the sensitivity to temperature and high frequency response of the proposed circuit, then the MO-CCCII should be designed to achieve these errors as low as possible, for example, using a high performance current mirror. Consequently, these deviations are very small and can be ignored.

III. Simulation Results

To prove and investigate the performances of the proposed circuit, the PSpice simulation program was used for the examination. The PNP and NPN transistors employed in the CCCIIs were simulated by respectively using the parameters of the PR200N and NR200N bipolar transistors of ALA 400 transistor array from AT&T [38]. Fig. 5 depicts schematic description of the CCCII used in the simulations. The circuit was biased with ±1.5V power supplies voltage, $C_1=C_2=1nF$, $I_{B1}=I_{B2}=50\mu A$. The results shown in Fig. 6 are the gain responses of the proposed multifunction biquadratic filter. It is clearly seen that it can provide low-pass high-pass band-pass band-reject and all-pass functions dependent on selection as depicted in Eqs. (8)-(12). Fig. 7 shows gain responses of band-pass function, where I_{B1} and I_{B2} are equally set to keep the ratio to be constant and changed for several values. It is found that pole frequency can be adjusted without affecting the quality factor as analyzed in Eqs. (15)-(16). Fig. 8 shows gain responses of band-pass function where I_{B1} is set for several values. It is found that pole frequency can be adjusted electronically. Fig. 9 shows evaluated pole frequency compared with simulation result. The transient and spectrum responses of the proposed filter from band-pass function for center frequency of 547.293kHz can be seen in Fig. 10 and 11, respectively, where THD is 0.227%. Total power consumption obtained from PSpice is about 1.87mW.

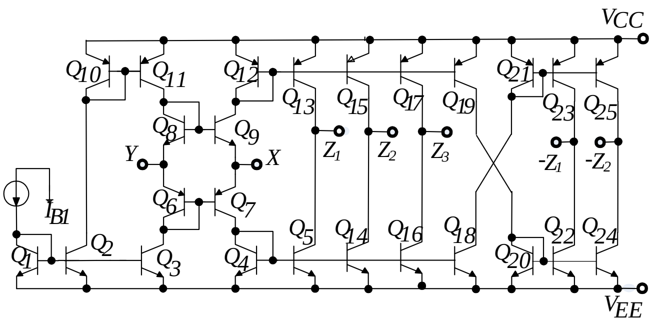


Fig. 5. Internal construction of MO-CCCII.

IV. Conclusion

The current-mode multifunction biquadratic filter with three input terminals and one output terminal based on CCCII has been presented. The advantages of the proposed circuit are that, it performs completely standard functions, which are low-pass high-pass band-pass band-reject and all-pass functions from the same circuit configuration, without component matching conditions and changing circuit topology. The pole frequency can be electronically adjusted without affecting the quality factor. The circuit description comprises only 2 MO-CCCIIs and 2 grounded capacitors. With mentioned features, it is very suitable to realize the proposed circuit in monolithic chip to use in battery-powered, portable electronic equipment such as wireless communication system.

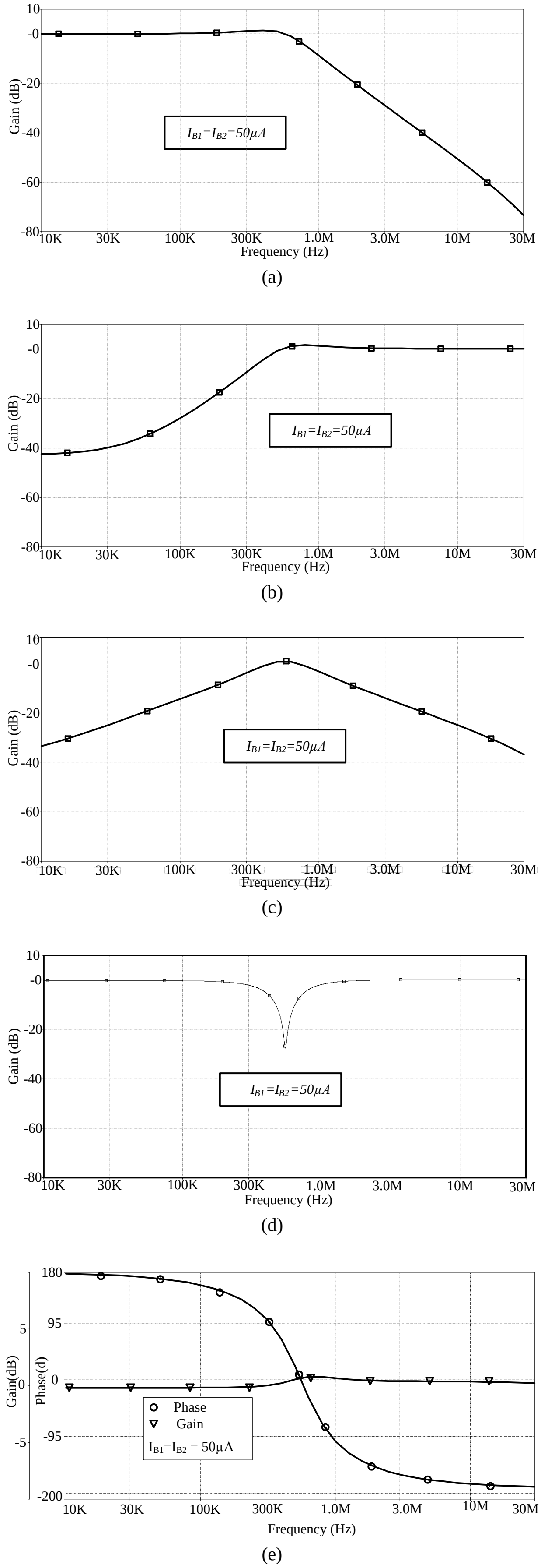


Fig. 6. Gain responses of the biquadratic filter (a) LP (b) HP (c) BP (d) BR (e) AP.

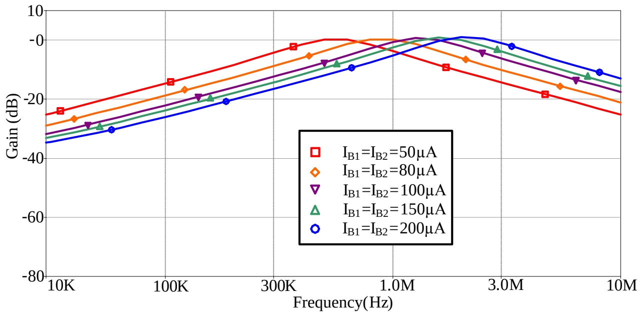


Fig 7. Band-pass responses for different values of I_{B1} and I_{B2} with keeping their ratios constant.

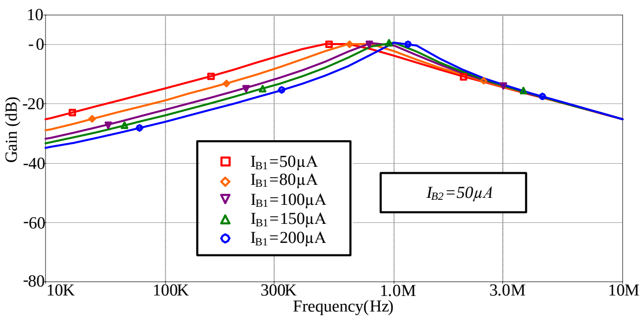


Fig 8. Current-mode bandpass responses for different values of I_{B1}

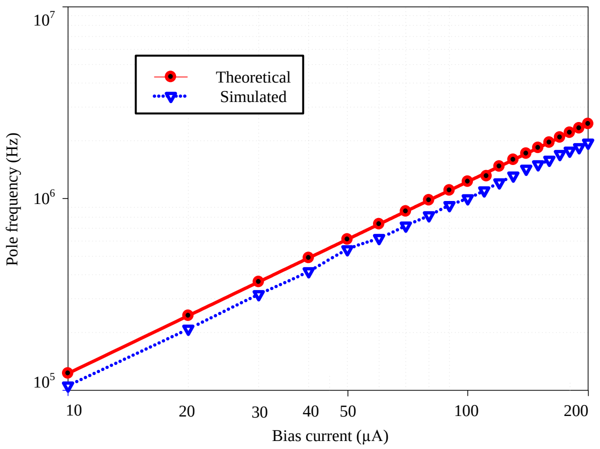


Fig 9. Deviation of the calculated pole frequency compared with the simulated value.

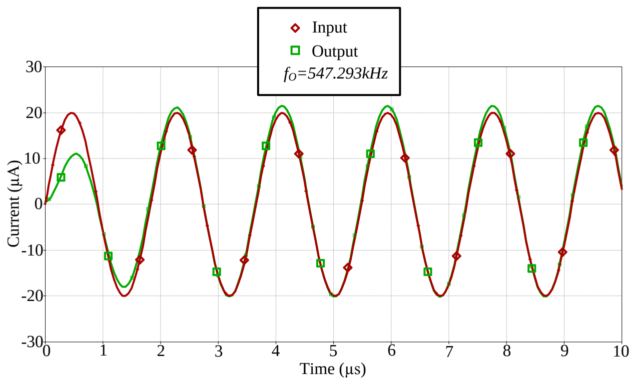


Fig 10. Transient responses at center frequency of 547.293kHz obtained from the proposed filter for BP function.

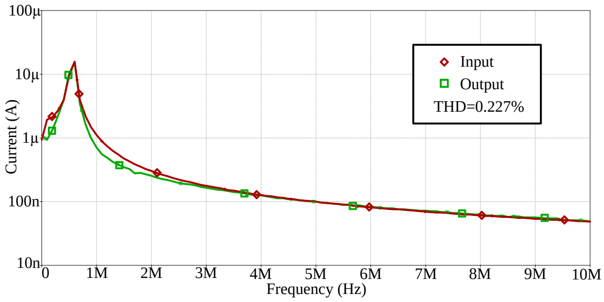


Fig. 11. Frequency spectrum of obtained signal in Fig. 10.

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