NOVEL LINEAR TRANSFORMATION SWITCHED-CAPACITOR FILTER DESIGN

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Abstract This paper presents a novel method that is applied to realize the Linear Transformation (LT) Switched-Capacitor Filter (SCF). It adopts the Voltage Control Voltage Source (VCVS) equalized transformation to revise the original LC ladder filter and induce it into 16 basic sections and then extend the principle of the LT in order to fit active and 3 port networks and give out switched-capacitor circuits corresponding to the 16 basic sections, which can realize all four kinds of filters —— LP, HP, BP, BS filters. Designed examples are given here. An Nth order filter only requires N amplifiers and the circuit is insensitive to parasitic capacitances. The experimental results of a 3rd order elliptic LP and a 6th order elliptic BP are given and agree with the theory.

Key words Switched-capacitor filter; Linear transformation; Voltage control voltage source

I. Introduction

Poschenrieder[1] in 1966 first put forward the concept of using a switched-capacitor instead of resistance. By the end of 1970s, with the development of the technology of MOS LSI, the switched-capacitor network brought to people's attention more and more. Its small volume, high precision, low consuming power and the excellent advantage of temperature character clear up a new way for the design of filter and the development of no filter application.

At present, the mature SCF design methods are the Block Building Cascade[2,3], SGF[4,5], Simulated Inductance[6], VIS[7,8] and WSCF[9]. Besides these, the paper[10] also discussed another novel design method, i. e. the method of Linear Transformation (LT) which simulates the doubly terminated LC ladder filters. It was first put forward by A. G. Constantinides and A. G. Dimopoulos[11] and was used for the design of the active filter. Its general principle is by using LT to change port variables from the V-I domain to a new one that is easy for the active network to realize. By selecting different transformation matrices different structures can be obtained. It is not only convenient, but also flexible for the design of active filters with this method. The paper[10] applied the method of port variable transformation to the SCF design, but the filter that has limited poles needs a larger number of amplifiers. In this paper, the VCVS equalized transformation is adopted, and then the SCF is designed according to the method of extending LT in order to reduce the number of amplifiers. An Nth order filter only requires N amplifiers. The paper describes the designed examples of LP, HP, BP and BS filters and the experimental results of a 3rd order LP and a 6th order BP filter.

II. The General Principle of LT

The general principle of port transformation has been discussed [11]. we give the following simple explanation in order to popularize it and fit the cases of the active and 3 port network.

1. Linear transformation [1)]

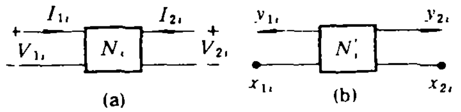


Fig. 1 (a) passive two port network
(b) The structure of LT

Fig.1(a) is a passive two port network and its port variables are $[V_{1i} I_{1i}]^T$ and $[V_{2i} I_{2i}]^T$. The original port variables can be changed into $[x_{1i}\ y_{1i}]^T$ and $[x_{2i}\ y_{2i}]^T$ by transformation matrices S_{1i} and S_{2i} in Eqs.(1) and (2).

$$\begin{bmatrix} x_{1i} \\ y_{1i} \end{bmatrix} = S_{1i} \begin{bmatrix} V_{1i} \\ I_{1i} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} x_{2i} \\ y_{2i} \end{bmatrix} = S_{2i} \begin{bmatrix} V_{2i} \\ I_{2i} \end{bmatrix} \tag{2}$$

Fig. 1 (b) shows the structure of LT corresponding to the original network Fig. 1 (a).

Let T_i be the transfer function of the two port network in Fig. 1 (a), i.e.

$$\begin{bmatrix} V_{1i} \\ I_{1i} \end{bmatrix} = T_i \begin{bmatrix} V_{2i} \\ I_{2i} \end{bmatrix} \tag{3}$$

The corresponding structure of LT can be obtained from Eqs. (1), (2) and (3), and the transfer function in Fig. 1 (b) is

$$\begin{bmatrix} x_{1i} \\ y_{1i} \end{bmatrix} = S_{1i} T_i S_{2i}^{-1} \begin{bmatrix} x_{2i} \\ y_{2i} \end{bmatrix} \tag{4}$$

Our actual need is also to use the active and 3 port network linear transformation. So the original equation should be revised. For the active network in Fig. 2 (a), Eqs. (3) and (4) should be revised as

$$\begin{bmatrix} V_{1i} \\ I_{1i} \end{bmatrix} = T_i \begin{bmatrix} V_{2i} \\ I_{2i} \end{bmatrix} + M_i [v_1 \cdots v_m i_1 \cdots i_n]^T \tag{3a}$$

$$\begin{bmatrix} x_{1i} \\ y_{1i} \end{bmatrix} = S_{1i} T_i S_{2i}^{-1} \begin{bmatrix} x_{2i} \\ y_{2i} \end{bmatrix} + S_{1i} M_i [v_1 \cdots v_m i_1 \cdots i_n]^T \tag{4a}$$

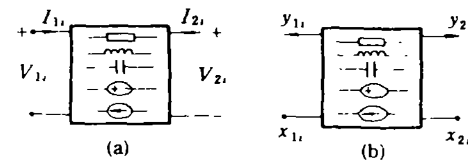


Fig.2 (a) Active two port network
(b) The structure of LT

1) The second subscript of the variables is the basic mark and the first one is the mark of the port of this section.

If $v_1 \cdots v_m$, $i_1 \cdots i_n$ are port variables, then Eqs. (3a), (4a) are derived in the following:

$$\begin{bmatrix} V_{1i} \\ I_{1i} \end{bmatrix} = T_i \begin{bmatrix} V_{2i} \\ I_{2i} \end{bmatrix} + \sum_{\substack{j=1 \\ j \neq i}}^{q} \sum_{p=1}^{2} T_{pj} \begin{bmatrix} V_{pj} \\ I_{pj} \end{bmatrix} \tag{3b}$$

$$\begin{bmatrix} x_{1i} \\ y_{1i} \end{bmatrix} = S_{1i} T_i S_{2i}^{-1} \begin{bmatrix} x_{2i} \\ y_{2i} \end{bmatrix} + S_{1i} \sum_{\substack{j=1 \\ j \neq i}}^{q} \sum_{p=1}^{2} T_{pj} S_{pj}^{-1} \begin{bmatrix} x_{pj} \\ y_{pj} \end{bmatrix} \tag{4b}$$

where q means the number of subnetworks.

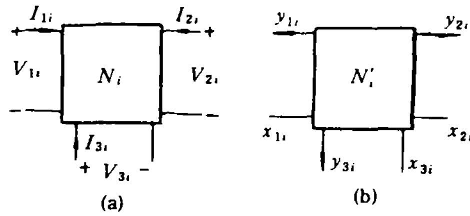


Fig.3 (a) Passive 3 port network
(b) The structure of LT

The transfer functions of 3 port networks in Fig. 3 in the V-I domain and x-y domain are as follows:

$$\begin{bmatrix} V_{1i} \\ I_{1i} \end{bmatrix} = T_i \begin{bmatrix} V_{2i} \\ I_{2i} \end{bmatrix} + T_i' \begin{bmatrix} V_{3i} \\ I_{3i} \end{bmatrix} \tag{3c}$$

$$\begin{bmatrix} x_{1i} \\ y_{1i} \end{bmatrix} = S_{1i} T_i S_{2i}^{-1} \begin{bmatrix} x_{2i} \\ y_{2i} \end{bmatrix} + S_{1i} T_i' S_{3i}^{-1} \begin{bmatrix} x_{3i} \\ y_{3i} \end{bmatrix} \tag{4c}$$

The input terminal in Fig.4 (a) can be described by the following equations:

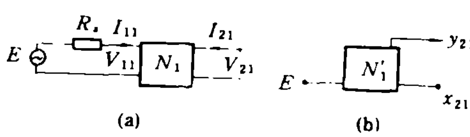


Fig.4 (a) Input terminal of the doubly terminated LC filter
(b) The structure of LT

$$[1 \ R_s] \begin{bmatrix} V_{11} \\ I_{11} \end{bmatrix} = E \tag{5}$$

$$\begin{bmatrix} V_{11} \\ I_{11} \end{bmatrix} = T_1 \begin{bmatrix} V_{21} \\ I_{21} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} x_{21} \\ y_{21} \end{bmatrix} = S_{21} \begin{bmatrix} V_{21} \\ I_{21} \end{bmatrix} \tag{7}$$

From Eqs. (5), (6) and (7) is yielded the design equation:

$$[1\ R_s]T_1S_{21}^{-1}\begin{bmatrix}x_{21}\\ y_{21}\end{bmatrix}=E \tag{8}$$

The corresponding LT structure is the same as Fig. 4 (b). Therefore, for the output terminal of Fig. 5 (a), the following can be obtained:

$$[1\ R_L]T_n^{-1}S_{1n}^{-1}\begin{bmatrix}x_{1n}\\ y_{1n}\end{bmatrix}=0 \tag{9}$$

Its LT structure is shown in Fig. 5 (b).

2. Connecting condition

Fig. 6 (a) shows the connection of two networks in the V-I domain. The connecting condition is

$$\begin{bmatrix}V_{12}\\ I_{12}\end{bmatrix}=\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}V_{21}\\ I_{21}\end{bmatrix} \tag{10}$$

Fig. 6 (b) is the corresponding LT structure, where N_c is a connecting network. The connecting condition of LT structures of networks N_1' and N_2' is obtained from Eqs. (1), (2) and (10).

$$\begin{bmatrix}x_{12}\\ y_{12}\end{bmatrix}=S_{12}\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}S_{11}^{-1}\begin{bmatrix}x_{21}\\ y_{21}\end{bmatrix} \tag{11}$$

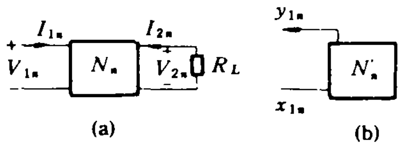


Fig. 5 (a) Output terminal of the doubly terminated LC filter
(b) The structure of LT

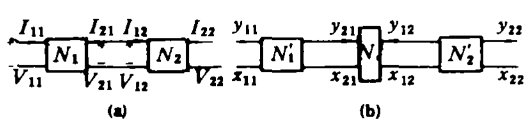


Fig. 6 (a) Cascade of 2 networks in the V-I domain
(b) Cascade of the corresponding LT structure

III. VCVS Equalized Transformation and 16 Basic Sections

Among the doubly terminated LC ladder filters, the series arms of the parallels of inductor and capacitor in Fig. 7 (a) have three following VCVS equalized transformations: the transformation pulling the capacitor down in Fig. 7 (b); the transformation pulling the inductor down in Fig. 7 (c); the transformation pulling the capacitor and inductor down in Fig. 7 (d). For the series arm of the series of inductor and capacitor in Fig. 8 (a), there exists the transformation pulling down the series of capacitor and inductor. These transformations mentioned above can be easily proved by the nodel voltage equation. The process of proof is omitted here.

It can be seen that in the processes of LP, HP, BP and BS filter design, by adopting the VCVS equalized transformation disscussed above, some elements of series arm can be merged into adjoining shunt arms in order to reduce the number of amplifiers. Apart from that, the four kinds of filters after the VCVS equalized transformation

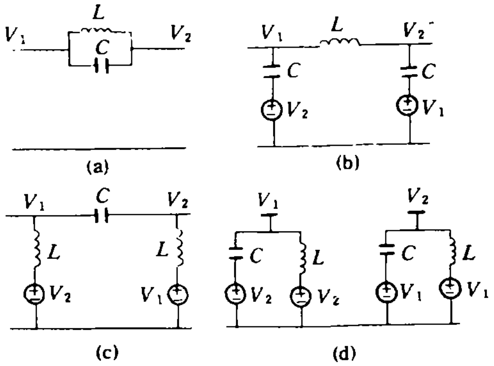


Fig.7 VCVS equalized transformation (I)

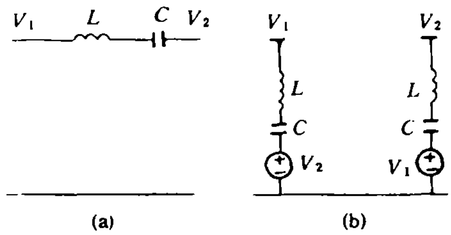
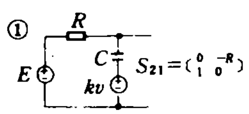
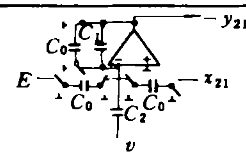
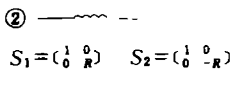
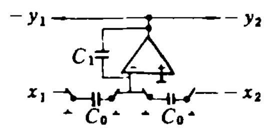
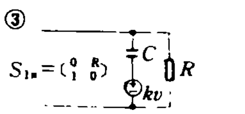
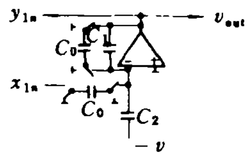
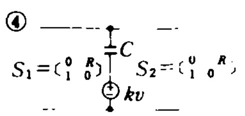
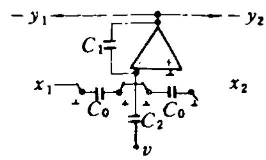
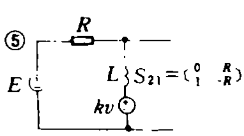
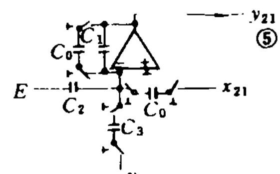
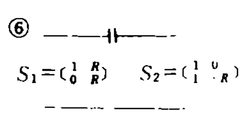
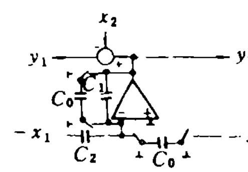


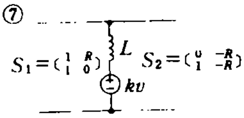
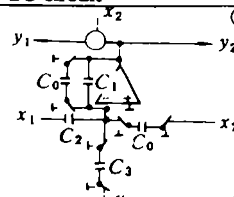
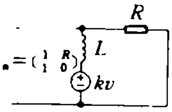
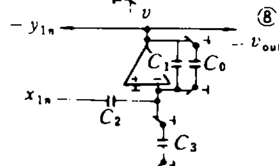
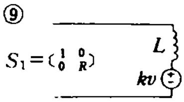
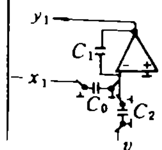
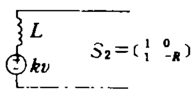
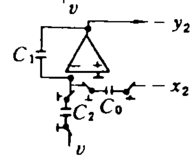
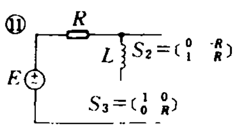
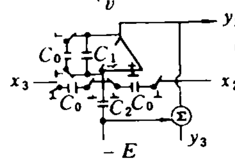
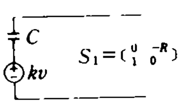
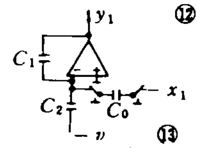
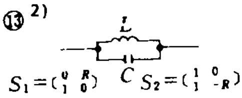
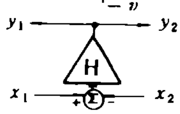
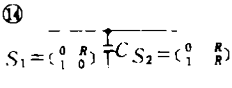
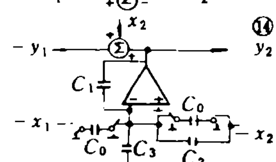
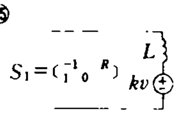
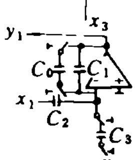
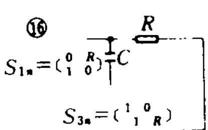
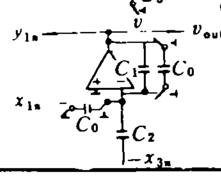
Fig.8 VCVS equalized transformation (II)

can be induced into 16 basic sections. The port transformation matrices of these basic sections, the transfer functions in the x-y domain and the SC circuits realizing the LDI $s \to z$ transformation are given in Tab. 1. The transfer functions in Tab. 1 can be induced from Eqs. (4), (4b), (4c), (8) and (9), and the proof processes are omitted here.

Tab. 1. 16 Basic sections

Basic section	Equation in the x-y domain	SC circuit
① 	$y_{21}=\dfrac{E-x_{21}+SkRCv}{1+SRC}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{kRC}{T}$	 ①
② 	$y_1=y_2=\dfrac{R}{SL}(x_1-x_2)$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT}$	 ②
③ 	$y_{1n}=\dfrac{x_{1n}+SkRCv}{1+SRC}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{kRC}{T}$	 ③
④ 	$y_1=y_2=\dfrac{x_1-x_2+SkRCv}{SRC}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{kRC}{T}$	 ④
⑤ 	$y_{21}=\dfrac{x_{21}+E\dfrac{SL}{R}+kv}{1+\dfrac{SL}{R}}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=\dfrac{L}{RT},\ \dfrac{C_3}{C_0}=k$	 ⑤
⑥ 	$\begin{cases} y_2=\dfrac{x_1SRC+x_2}{1+SRC} \\ y_1=-x_2+y_2 \end{cases}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{RC}{T}$	 ⑥

Tab.1 (continued)

Basic section	Equation in the x- y domain	SC circuit
⑦  $S_1=\begin{pmatrix}1&R\\1&0\end{pmatrix}$ $S_2=\begin{pmatrix}0&-R\\1&-R\end{pmatrix}$	$\begin{cases} y_2=\dfrac{x_1\dfrac{SL}{R}+x_2+kv}{1+\dfrac{SL}{R}} \\ y_1=-x_2+y_2 \end{cases}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=\dfrac{L}{RT},\ \dfrac{C_3}{C_0}=k$	 ⑦
⑧  $S_{1n}=\begin{pmatrix}1&R\\1&0\end{pmatrix}$	$y_{1n}=\dfrac{x_{1n}\dfrac{SL}{R}+kv}{1+S\dfrac{2L}{R}}$ $\dfrac{C_1}{C_0}=\dfrac{2L}{RT},\ \dfrac{C_2}{C_0}=\dfrac{L}{RT},\ \dfrac{C_3}{C_0}=k$	 ⑧
⑨  $S_1=\begin{pmatrix}1&0\\0&R\end{pmatrix}$	$y_1=\dfrac{x_1-kv}{\dfrac{SL}{R}}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=k$	 ⑨
⑩  $S_2=\begin{pmatrix}1&0\\1&-R\end{pmatrix}$	$y_2=\dfrac{-x_2+kv}{\dfrac{SL}{R}}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=k$	 ⑩
⑪  $S_2=\begin{pmatrix}0&-R\\1&R\end{pmatrix}$ $S_3=\begin{pmatrix}1&0\\0&R\end{pmatrix}$	$\begin{cases} y_2=\dfrac{x_3+x_2+E\dfrac{SL}{R}}{1+\dfrac{SL}{R}} \\ y_3=y_2-E \end{cases}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=\dfrac{L}{RT}$	 ⑪
⑫  $S_1=\begin{pmatrix}0&-R\\1&0\end{pmatrix}$	$y_1=\dfrac{-x_1+SkRCv}{SRC}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{kRC}{T}$	 ⑫
⑬ 2)  $S_1=\begin{pmatrix}0&R\\1&0\end{pmatrix}$ $S_2=\begin{pmatrix}1&0\\1&-R\end{pmatrix}$	$y_1=y_2=\dfrac{\dfrac{1}{2}S^2+\dfrac{1}{2LC}}{S^2+S\dfrac{1}{2RC}+\dfrac{1}{LC}}(x_1-x_2)$	 ⑬
⑭  $S_1=\begin{pmatrix}0&R\\1&0\end{pmatrix}$ $S_2=\begin{pmatrix}0&R\\1&R\end{pmatrix}$ $S_3=\begin{pmatrix}1&0\\-1&R\end{pmatrix}$	$\begin{cases} y_2=\dfrac{x_1-x_2+SRCx_2+SRCx_3}{SRC} \\ y_1=y_2-x_2 \end{cases}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{RC}{T},\ \dfrac{C_3}{C_0}=\dfrac{RC}{T}$	 ⑭
⑮  $S_1=\begin{pmatrix}-1&R\\1&0\end{pmatrix}$	$y_1=\dfrac{-x_1\dfrac{SL}{R}+kv}{1+\dfrac{SL}{R}}$ $\dfrac{C_1}{C_0}=\dfrac{L}{RT},\ \dfrac{C_2}{C_0}=\dfrac{L}{RT},\ \dfrac{C_3}{C_0}=k$	 ⑮
⑯  $S_{1n}=\begin{pmatrix}0&R\\1&0\end{pmatrix}$ $S_{3n}=\begin{pmatrix}1&0\\1&R\end{pmatrix}$	$y_{1n}=\dfrac{x_{1n}+x_{3n}SRC}{1+SRC}$ $\dfrac{C_1}{C_0}=\dfrac{RC}{T},\ \dfrac{C_2}{C_0}=\dfrac{RC}{T}$	 ⑯

2) The building block adopts the circuit in [3], and Fig.15 gives out the circuit and values of the element.

IV. Designed Examples

This section gives the designed examples of LP, HP, BP and BS filters according to the basic principles discussed in the above section. The design processes are: (1) the VCVS equalized transformation of the original LC filter; (2) choosing the proper transformation matrices; (3) realizing the basic sections by using Tab.1; (4) connecting each section with connecting networks.

1. LP filter design

Fig.9 (a) illustrates an original 5th order elliptic LP filter and Fig.9(b) shows the equivalent circuit of pulling down the capacitor VCVS equalized transformation.

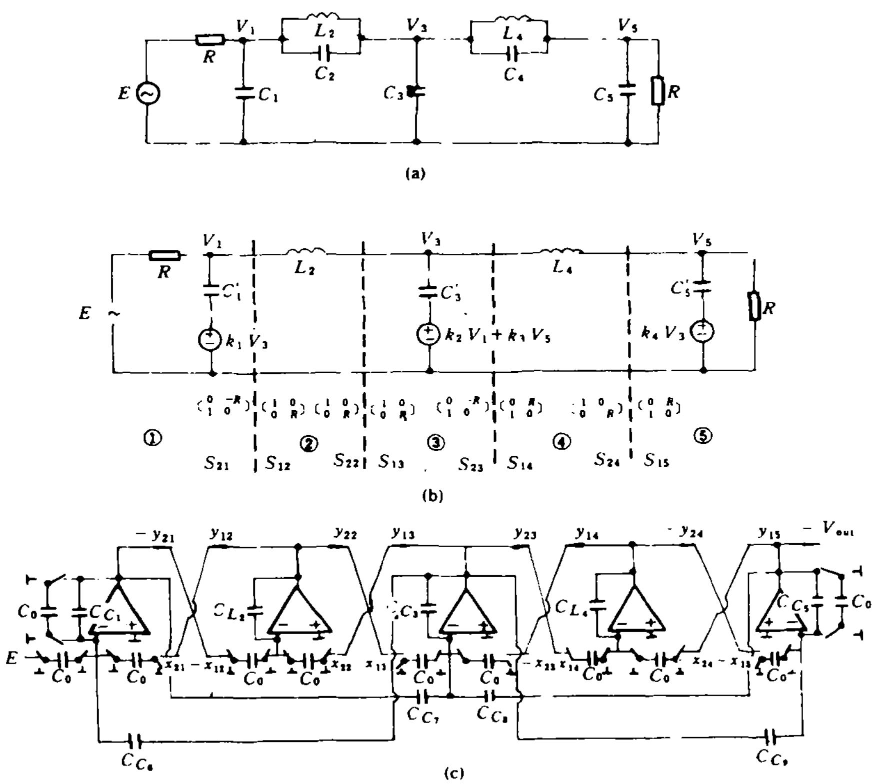


Fig.9 (a) The original 5th order elliptic LP filter
(b) VCVS equivalent circuit and the matrices corresponding to each port
(c) 5th order LP SCF

where

$$\begin{cases} C_1' = C_1 + C_2 \\ C_3' = C_2 + C_3 + C_4 \\ C_5' = C_4 + C_5 \end{cases} \tag{12}$$

$$\begin{cases} k_1 = C_2 / (C_1 + C_2) \\ k_2 = C_2 / (C_2 + C_3 + C_4) \\ k_3 = C_4 / (C_2 + C_3 + C_4) \\ k_4 = C_4 / (C_4 + C_5) \end{cases} \tag{13}$$

The dotted line in Fig. 9 (b) divides it into each basic section and Fig. 9 (b) illustrates the port transformation matrices of each basic section. Sections ① to ⑤ correspond to ①, ②, ④, ②, ③ in Tab. 1 respectively. Bring the port transformation matrices of the adjoining ports into Eq. (11), it shows that the connecting network between the basic sections is the crossing connecting networks in Fig. 10. Finally the LP SCF in Fig. 9 (c) can be obtained.

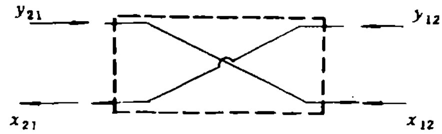


Fig. 10 Connecting network N_c

2. HP filter design

Fig. 11 (a) is an original 5th order elliptic HP filter and Fig. 11 (b) is the equivalent circuit after the transformation of pulling down the inductor of Fig. 11 (a),

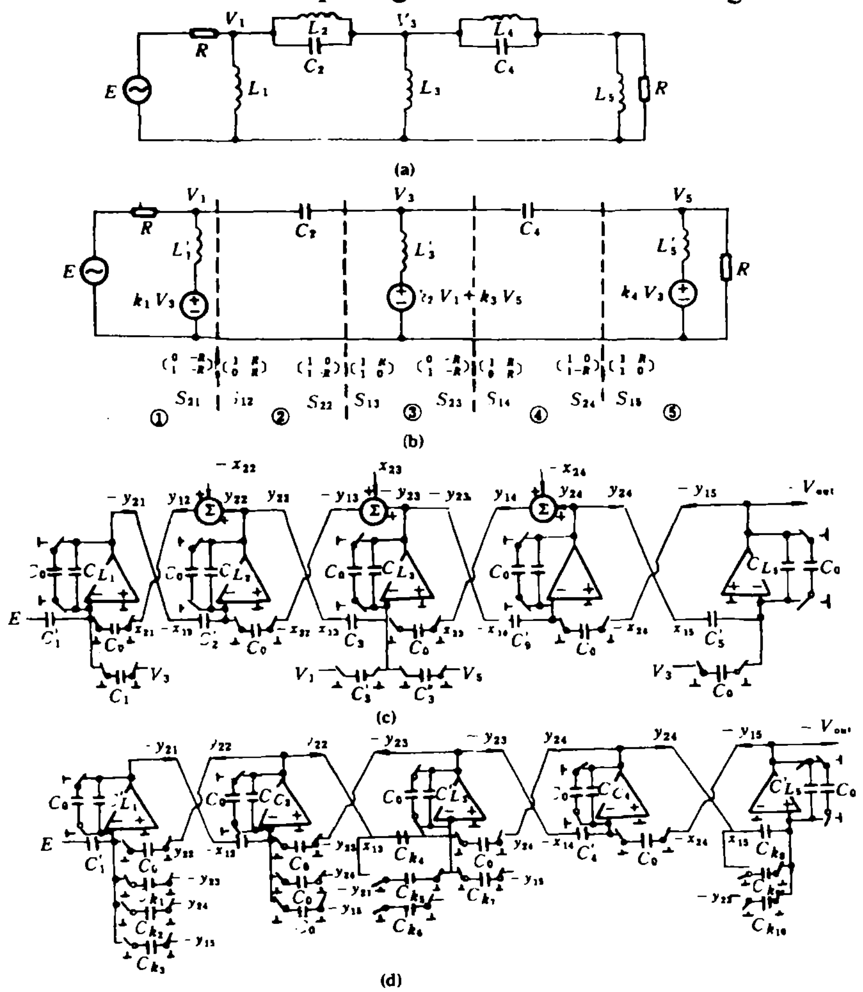


Fig. 11 (a) The original 5th order elliptic HP filter
(b) VCVS equivalent circuit and the matrices corresponding to each port
(c) 5th order HP SCF (not arranged)
(d) 5th order HP SCF

where

$$\left.\begin{aligned} L_1' &= L_1L_2/(L_1+L_2) \\ L_3' &= L_2L_3L_4/(L_2L_3+L_3L_4+L_2L_4) \\ L_5' &= L_4L_5/(L_4+L_5) \end{aligned}\right\} \tag{14}$$

$$\left.\begin{aligned} k_1 &= L_1/(L_1+L_2) \\ k_2 &= L_3L_4/(L_2L_3+L_3L_4+L_2L_4) \\ k_3 &= L_2L_3/(L_2L_3+L_3L_4+L_2L_4) \\ k_4 &= L_5/(K_4+L_5) \end{aligned}\right\} \tag{15}$$

The dotted line in Fig. 11 (b) divied it into each basic section and Fig. 11 (b) illustrates the port transformation matrices of each basic section. Sections ① to ⑤ correspond to ⑤, ⑥, ⑦, ⑥, ⑧ in Tab. 1 respectively. Substitute the port transformation matrices of the adjoining ports into Eq. 11, so that the connecting network can be obtained such as in Fig. 10. Fi g. 11 (c) shows the SC circuit. The adders in Fig. 11 (c) are easily replaced by SC circuits. Finally the HP SCF in Fig. 11 (d) can be obtained.

3. BP fi'ter design

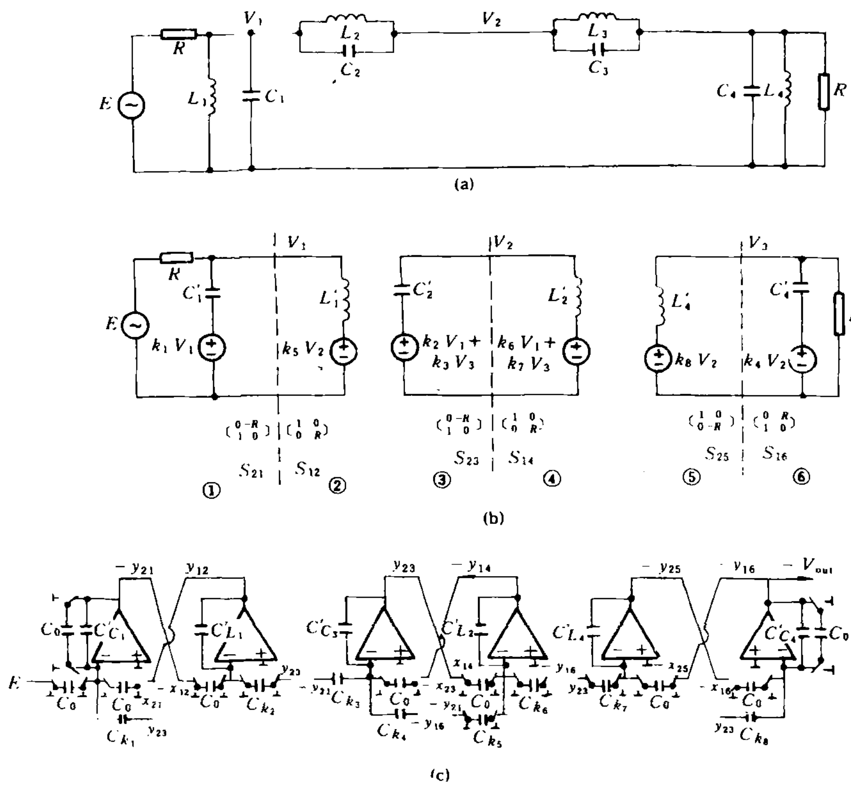


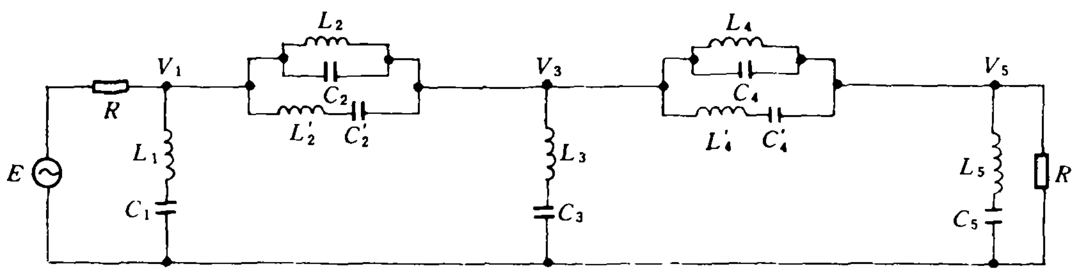
Fig. 12 (a) The original 6th order BP filter
(b) VCVS equivalent circuit and the matrices corresponding to each port
(c) 6th order BP SCF

Fig. 12 (a) is an original 6th order elliptic BP LC filter. The equivalent circuit in Fig. 12 (b) can be obtained through the transformation of pulling down the inductor and pulling down the capacitor. Fig. 12 (b) illustrates each basic section and shows the port transformation matrices of each section,
where

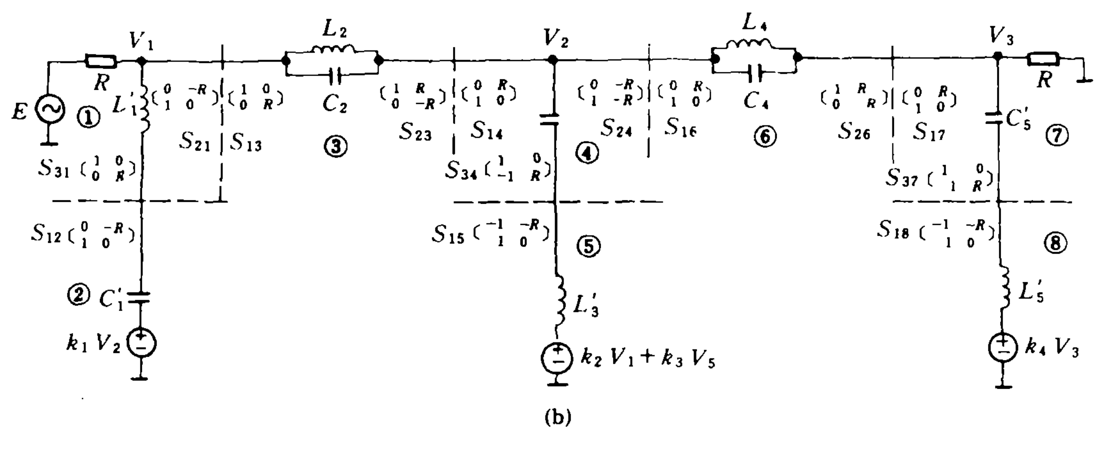
$$\left.\begin{aligned} C_1' &= C_1 + C_2 \\ C_2' &= C_2 + C_3 \\ C_4' &= C_3 + C_4 \end{aligned}\right\} \tag{16}$$

$$\left.\begin{aligned} L_1' &= L_1L_2/(L_1 + L_2) \\ L_2' &= L_2L_3/(L_2 + L_3) \\ L_4' &= L_3L_4/(L_3 + L_4) \end{aligned}\right\} \tag{17}$$

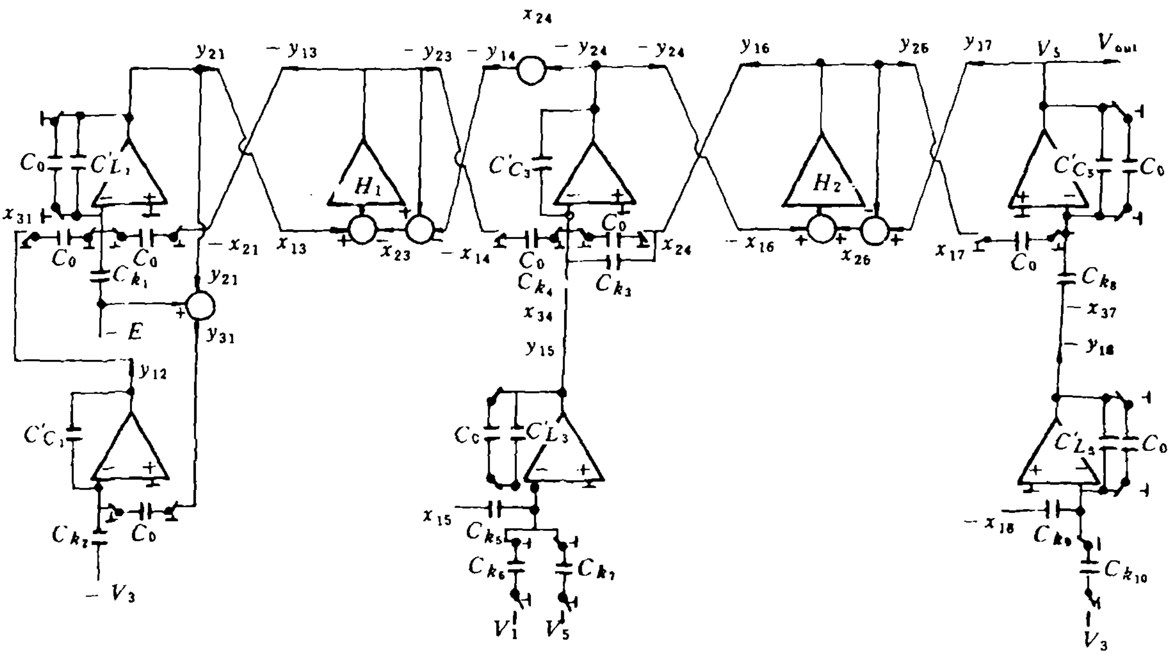
$$\left.\begin{aligned} k_1 &= C_2/(C_1 + C_2) \\ k_2 &= C_2/(C_2 + C_3) \\ k_3 &= C_3/(C_2 + C_3) \\ k_4 &= C_3/(C_3 + C_4) \\ k_5 &= L_1/(L_1 + L_2) \\ k_6 &= L_3/(L_2 + L_3) \\ k_7 &= L_2/(L_2 + L_3) \\ k_8 &= L_4/(L_3 + L_4) \end{aligned}\right\} \tag{18}$$



(a)



(b)



(c)

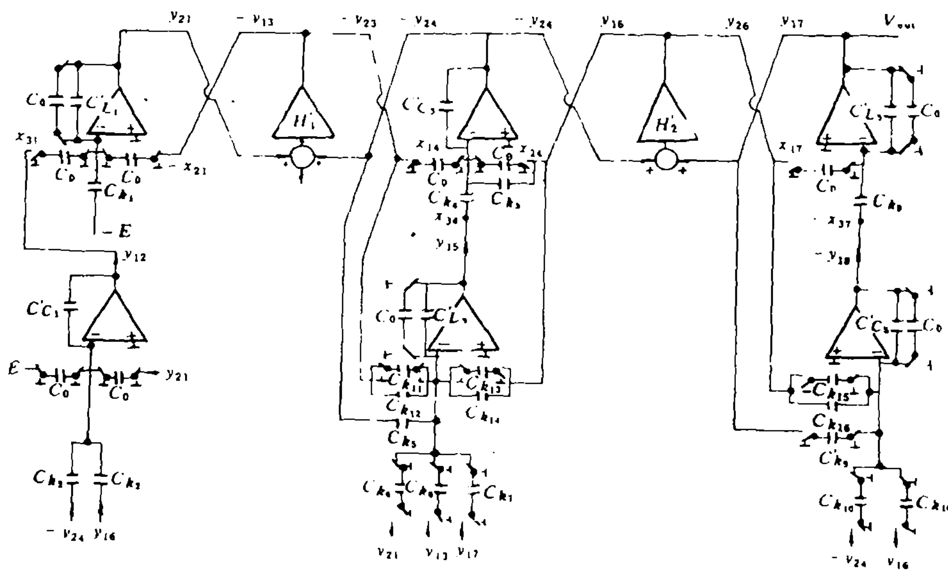

(d)

Fig.13 (a) The original 10th order elliptic BS LC filter
(b) VCVS equivalent circuit and the matrices corresponding to each port
(c) 10th order BS SCF (not arranged)
(d) 10th order BS SCF

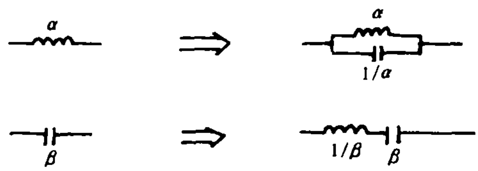


Fig.14 The relation between LP and BS filters

Sections ① to ⑥ in Fig.12(b) correspond respectively to ①, ⑨, ⑫, ⑨, ⑩, ③ in Tab.1 and from the transformation matrices the connecting network can be obtained such as in Fig.10. In the end, the BP SCF is given out in Fig.12(c).

4. BS filter design

Fig.13(a) is a 10th order BS LC filter. It is obtained from the 5th order elliptic LP filter according to the relation between LP and BS filters in Fig.14.

Through the transformation pulling down the series of inductor and capacitor in Fig.13(a), then using the existing relation in Fig.14:

$$L_1C_1 = L_2'C_2' = L_3C_3 = L_4'C_4' = L_5C_5 \tag{19}$$

the VCVS equivalent circuit can be obtained, shown in Fig.13(b), where

$$\left.\begin{aligned} L_1' &= L_1C_1/(C_1+C_2') \\ L_3' &= L_3C_3/(C_2'+C_3+C_4') \\ L_5' &= L_5C_5/(C_4'+C_5) \end{aligned}\right\} \tag{20}$$

$$\left.\begin{aligned} C_1' &= C_1+C_2' \\ C_3' &= C_2'+C_3+C_4' \\ C_5' &= C_4'+C_5 \end{aligned}\right\} \tag{21}$$

$$\left.\begin{aligned} k_1 &= C_2'/(C_1+C_2) \\ k_2 &= C_2'/(C_2'+C_3+C_4') \\ k_3 &= C_4'/(C_2'+C_3+C_4') \\ k_4 &= C_4'/(C_4'+C_5) \end{aligned}\right\} \tag{22}$$

Fig.13(b) is divided into each basic section and shows the port transformation matrix of each basic section. Sections ① to ⑧ correspond separately to ⑪, ⑫, ⑬, ⑭, ⑮, ⑬, ⑯, ⑮ in Tab.1. From the port transformation matrices and Eq.(11), it is shown that the connecting networks of sections ①②; ①③; ④⑤; ④⑥; ⑦⑧ are such as in Fig.10. The connection networks between sections ③④ and between sections ⑥⑦ should meet separately the relations:

$$\left.\begin{aligned} x_{14} &= y_{23} \\ x_{23} &= y_{14} - y_{23} \end{aligned}\right\} \tag{23}$$

and

$$\left.\begin{aligned} x_{17} &= y_{26} \\ x_{26} &= y_{17} - y_{26} \end{aligned}\right\} \tag{24}$$

So SC circuit can be obtained in Fig.13(c). By the arrangement for Fig.13(c), BS SCF can be obtained finally in Fig.13(d), where the building blocks are characterized by the relations:

$$-y_{13}=-y_{23}=-\frac{S^2+\frac{1}{L_2C_2}}{S^2+S\frac{1}{RC_2}+\frac{1}{L_2C_2}}(y_{21}-y_{14})$$
$$=H_1'(y_{21}-y_{14}) \tag{25}$$

$$y_{16}=y_{26}=-\frac{S^2+\frac{1}{L_4C_4}}{S^2+S\frac{1}{RC_4}+\frac{1}{L_4C_4}}(-y_{24}+y_{17})$$
$$=H_2'(-y_{24}+y_{17}) \tag{26}$$

H_1' and H_2' in Fig. 13 (c) can be realized by using the building block circuit introduced in [3], shown in Fig. 15. Its transfer function is as follows:

$$H(S)=-\frac{k_2S^2+k_0}{S^2+\frac{\omega_0}{Q}S+\omega_0^2} \tag{27}$$

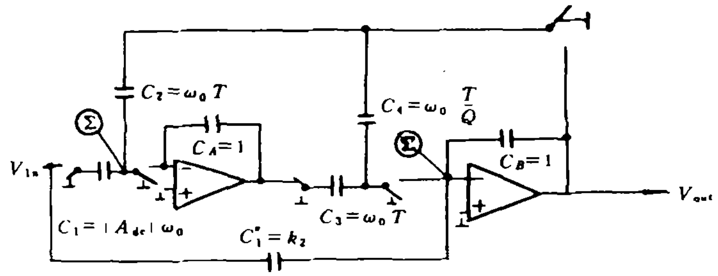


Fig. 15 Building block circuit

The designs of LP, HP, BP, BS SCF have been shown. In the introduction it has been pointed out that the method of this paper can save more amplifiers than the method in [10]. Tab. 2 illustrates the comparison of the number of amplifiers for the four kinds of flters when adopting the different methods.

Tab. 2

Type	Number of order	Number of amplifiers	
		In [10]	In this paper
LP	5	7	5
HP	5	7	5
BP	6	8	6
BS	10	14	10

V. Experimental Results

According to the discussion mentioned above, Fig. 16 gives out a design result of the 3rd order elliptic LP SCF. The original LP LC filter is C03 − 20 − 18, and the circuit parameters are:

Passband: $f \leqslant f_p = 1.236$kHz, Ripple: 0.177dB

Stopband: $f \geqslant f_s = 4$kHz, $A_{min} = 40.23$dB

Sampling period: $T = 10\mu s$

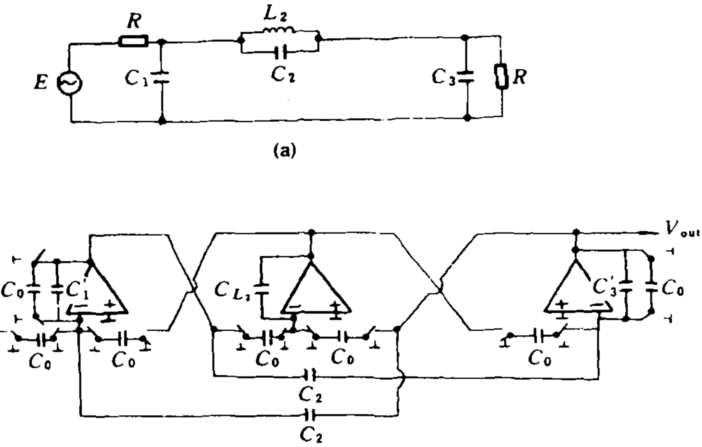


Fig.16 (a) The original 3rd order elliptic LP LC filter
(b) 3rd order LP SCF

Fig. 17 shows the experimental test results, apart from the attenuation in the range near f_p rises a little for nonideal effects, they meet the need of the design. For the element ratios of experimental circuit, see Tab. 3.

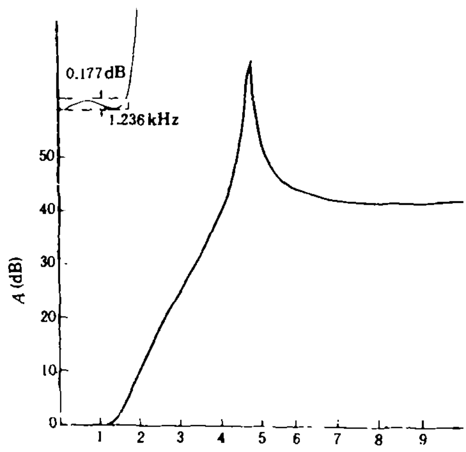


Fig.17 The tested curve of the 3rd order LP SCF

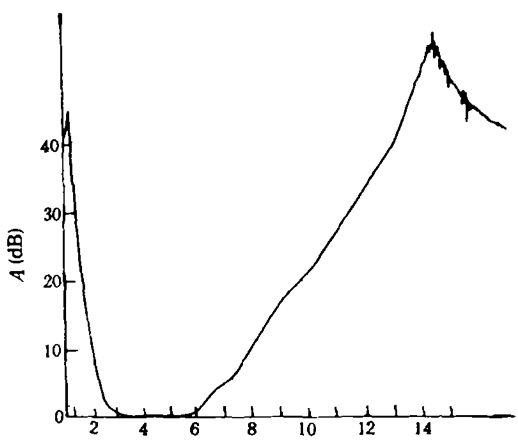


Fig.18 The tested curve of the 6th order BP SCF

Tab.3

The rate of capacitor value for 3rd order LP SCF				
$C_0 = 1.000$	$C_1 = 15.533$	$C_2 = 0.861$	$C_{L2} = 13.962$	$C_3' = 15.533$
The rate of capacitor value for 6th order BP SCF				
$C_0 = 1.000$	$C_{c_1}' = 3.220$	$C_4' = 0.739$	$C_{c_3}' = 1.934$	$C_{L_2}' = 1.819$
$C_{L4} = 1.093$	$C_{c_4}' = 4.758$	$C_{k1} = 0.198$	$C_{k2} = 0.364$	$C_{k3} = 0.198$
$C_{k4} = 1.736$	$C_{k_5} = 0.899$	$C_{k6} = 0.102$	$C_{k7} = 0.061$	$C_{k8} = 1.736$

Fig. 18 shows the tested curve of a 6th order BP SCF, and its experimental circuit is shown in Fig. 12. The circuit parameters are passband: 3 — 6kHz; ripple: less than 0.177dB.The element values of the experiment circuit are given in Tab. 3.Sampling frequency is 50kHz. The results of tested curve in Fig. 18 agree with the theory.

Both experimental circuits mentioned above use LF347 as amplifiers,MC14066 as switches. The characteristic curves are tested by the HP 3570 nêtwork analyser and HP 3330B automatic synthesis meter. It is drawn by the XWX Da Hua recorder.

VI. Conclusion

The paper has shown that SCF can be designed by using VCVS equalized transformation and LT technique. It is simple and flexible. An Nth order filter only needs N amplifiers and is insensitive to parasitic capacitance. The experimental results given as applications confirm the design method.

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