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Comparison of Two 1550 nm Ultra Narrow-Band Optical Infinite Impulse Response Filters for High-Speed Optical Signal Processing

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ABSTRACT

Comparison of the frequency responses of two high-speed optical fiber processing elements is reported. The two filters we considered are a two-loops optical infinite impulse response (IIR) filter and a three-loops optical IIR filter. The theoretical models of these two kinds of optical IIR band pass filters are built up. Some suitable coupling coefficients are searched for simulating the narrow band-pass filters. The frequency responses under different conditions are analyzed. The theoretical models can provide parameter evaluation for experimental design. A higher design flexibility can be given by the three-loops optical IIR filter. These filters can be implemented with PIC (photonic IC) techniques and applied for optical data signal processing.

Keywords：Optical Data Storage, Optical Signal Processing, Optical IIR filter, Optical Fiber Communication

1.INTRODUCTION

In the next generation memory system, high capacity optical data storage will be the future trend. Many methods, such as hologram, CD-R, DVD, are studied for high capacity data storage above Giga-byte [1-3.]. In recent years, some fast data access and optical signal processing methods are extensively reported [4-8.]. Especially reading optically storaged data by fiber, then using time-space-conversion optical signal processing attract a lot of attentions [5.].

Promising progress is shown in high speed optical communication systems developments recently [9-18.]. The fiber optic recirculating delay line is one of the basic optical signal elements generally being studied. We also reported some various designs and applications for high speed signal processing [19-21.]. Ultra fast signal processing over 100 Gbps is difficult to do by traditional electric signal processing circuit. This optical digital signal processor (OPSP) may be applied in high-speed DVD data storage systems as shown in Fig.1. In this paper, we design and analyze two ultra narrow-band optical infinite impulse response IIR filters for high-speed optical signal processing. Those two designed narrow-band optical IIR filters are operating at wavelength of 1550nm. The center of the narrowband filter is located at 100GHz. We use Z-transform to analyze the frequency responses of these two IIR filters：two-loops optical IIR filter and three-loops optical IIR filter. The two theoretical models for comparing their frequency responses are built up. Optimal coupling coefficients are sorted for simulating narrow bandwidth optical band pass filters.

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In *Optical Storage and Optical Information Processing*, Han-Ping D. Shieh, Tom D. Milster, Editors, Proceedings of SPIE Vol. 4081 (2000) • 0277-786X/00/$15.00

2. THEORETICAL MODELS

We use Z-transform techniques to build up the theoretical model of a two-loops optical IIR filter and a three-loops optical IIR filter, respectively in this section. Assume these two kinds filters are linearly time-invariant systems and no temperature fluctuation effect, we derive the transfer functions as following.

2.1 *Two-Loops Optical IIR Filter*

The schematic diagram of two-loops optical IIR filter with two 3×3 optical couplers and four optical delay lines is shown in Fig.2. In Fig.3, we modeled the equivalent theoretical model by signal flow diagram. The signal can be represented as Eq. (1) to Eq. (6)

$$X_1(Z) = K_3[I_1(Z) + r_{X_4} Z^{-X_4} X_4(Z) + r_{X_3} Z^{-X_3} X_3(Z)] \tag{1}$$

$$X_2(Z) = K_2[I_1(Z) + r_{X_4} Z^{-X_4} X_4(Z) + r_{X_3} Z^{-X_3} X_3(Z)] \tag{2}$$

$$X_3(Z) = K_6[I_2(Z) + r_{X_2} Z^{-X_2} X_2(Z) + r_{X_1} Z^{-X_1} X_1(Z)] \tag{3}$$

$$X_4(Z) = K_5[I_2(Z) + r_{X_2} Z^{-X_2} X_2(Z) + r_{X_1} Z^{-X_1} X_1(Z)] \tag{4}$$

$$O_1(Z) = K_1[I_1(Z) + r_{X_4} Z^{-X_4} X_4(Z) + r_{X_3} Z^{-X_3} X_3(Z)] \tag{5}$$

$$O_2(Z) = K_4[I_2(Z) + r_{X_2} Z^{-X_2} X_2(Z) + r_{X_1} Z^{-X_1} X_1(Z)] \tag{6}$$

$I_1(Z)$ and $I_2(Z)$ are the input signals at the input ports. $O_1(Z)$ and $O_2(Z)$ are the output signals at two ports. $X_1(Z)$, $X_2(Z)$, $X_3(Z)$, $X_4(Z)$ represent the input signals of delays Z^{-X_1}, Z^{-X_2}, Z^{-X_3}, Z^{-X_4}, respectively. The coupling coefficients and path transmittive coefficients for each optical output are represented as $K_{j(j=1\sim6)}$ and $r_{Xj(j=1\sim6)}=1$, respectively.

The relationship of the above six equations can be simplified as

$$X_1(Z) = K_3[I_1(Z) + \frac{K_5}{K_6} r_{X_4} Z^{-X_4} X_3(Z) + r_{X3} Z^{-X_3} X_3(Z)] \tag{7}$$

$$X_3(Z) = K_3[I_2(Z) + \frac{K_2}{K_3} r_{X_2} Z^{-X_2} X_1(Z) + r_{X1} Z^{-X_1} X_1(Z)] \tag{8}$$

Substitute Eq. (8) into Eq. (7), we find

$$X_1(Z) = \frac{K_3\left[I_1(Z) + \left(K_5 r_{X_4} Z^{-X_4} + K_6 r_{X_3} Z^{-X_3}\right) I_2(Z)\right]}{\Delta} \tag{9}$$

and

$$\Delta = 1 - K_3K_6 r_{X_1} r_{X3} Z^{-(X_1+X_3)} - K_3K_5 r_{X1} r_{X_4} Z^{-(X_1+X_4)} - K_2K_6 r_{X_2} r_{X_3} Z^{-(X_2+X_3)} - K_2K_5 r_{X_2} r_{X_4} Z^{-(X_2+X_4)} \tag{10}$$

Similarly, we can write $X_3(Z)$ as

$$X_3(Z)=\frac{K_6\left[I_2(Z)+\left(K_3 r_{X_1} Z^{-X_1}+K_2 r_{X_2} Z^{-X_2}\right)I_1(Z)\right]}{\Delta} \tag{11}$$

Then the output signals can be represented as

$$O_1(Z)=\frac{K_1\left[I_1(Z)+\left(K_5 r_{X_4} Z^{-X_4}+K_6 r_{X_3} Z^{-X_3}\right)I_2(Z)\right]}{\Delta} \tag{12}$$

$$O_2(Z)=\frac{K_4\left[I_2(Z)+\left(K_3 r_{X_1} Z^{-X_1}+K_2 r_{X_2} Z^{-X_2}\right)I_1(Z)\right]}{\Delta} \tag{13}$$

In this paper, we assume no input signal launched to port I_2. Therefore, the above two transfer funtions can be simplified as

$$H_{11}(Z)=\frac{O_1(Z)}{I_1(Z)}=\frac{K_1}{\Delta} \tag{14}$$

$$H_{12}(Z)=\frac{O_2(Z)}{I_1(Z)}=\frac{K_4\left(K_3 r_{X_1} Z^{-X_1}+K_2 r_{X_2} Z^{-X_2}\right)}{\Delta} \tag{15}$$

2.2 *Three-Loops Optical IIR Filter*

The schematic diagram of a three-loops optical IIR filter is shown in Fig.4. This filter includes two 4×4 optical couplers and six optical delay lines. The schematic diagram of theoretical model of this filter is illustrated in Fig.5. Similarly, we consider the nodal signals $X_1(Z)$, $X_2(Z)$, $X_3(Z)$, $X_4(Z)$, $X_5(Z)$, and $X_6(Z)$, represent the input signals of the phase delays Z^{-X_1}, Z^{-X_2}, Z^{-X_3}, Z^{-X_4}, Z^{-X_5}, Z^{-X_6}, respectively. The transmittive coefficient of each delay path $r_{Xj(j=1\sim8)}$ is set to be 1. The coupling coefficient of each optical output is represented as $K_{j(j=1\sim8)}$ which is a positive real number. Because of energy conservation, the signal in each coupler should satisfy $K_1+K_2+K_3+K_4+K_5+K_6+K_7+K_8 = (1-L)$, and L means the intrinsic loss of optical couplers. In this paper, we assume the intrinsic loss is small enough that can be neglected. According to Fig.5, the transfer functions can be derived according to the following equations as

$$X_1(Z)=K_4[I_1(Z)+r_{X_4}Z^{-X_4}X_4(Z)+r_{X_5}Z^{-X_5}X_5(Z)+r_{X_6}Z^{-X_6}X_6(Z)] \tag{16}$$

$$X_2(Z)=K_3[I_1(Z)+r_{X_4}Z^{-X_4}X_4(Z)+r_{X_5}Z^{-X_5}X_5(Z)+r_{X_6}Z^{-X_6}X_6(Z)] \tag{17}$$

$$X_3(Z)=K_2[I_1(Z)+r_{X_4}Z^{-X_4}X_4(Z)+r_{X_5}Z^{-X_5}X_5(Z)+r_{X_6}Z^{-X_6}X_6(Z)] \tag{18}$$

$$X_4(Z)=K_8[I_2(Z)+r_{X_1}Z^{-X_1}X_1(Z)+r_{X_2}Z^{-X_2}X_2(Z)+r_{X_3}Z^{-X_3}X_3(Z)] \tag{19}$$

$$X_5(Z)=K_7[I_2(Z)+r_{X_1}Z^{-X_1}X_1(Z)+r_{X_2}Z^{-X_2}X_2(Z)+r_{X_3}Z^{-X_3}X_3(Z)] \tag{20}$$

$$X_6(Z)=K_6[I_2(Z)+r_{X_1}Z^{-X_1}X_1(Z)+r_{X_2}Z^{-X_2}X_2(Z)+r_{X_3}Z^{-X_3}X_3(Z)] \tag{21}$$

$$O_1(Z)=K_1[I_1(Z)+r_{X_4}Z^{-X_4}X_4(Z)+r_{X_5}Z^{-X_5}X_5(Z)+r_{X_6}Z^{-X_6}X_6(Z)] \tag{22}$$

$$O_2(Z) = K_5[I_2(Z) + r_{X_1} Z^{-X_1} X_1(Z) + r_{X_2} Z^{-X_2} X_2(Z) + r_{X_3} Z^{-X_3} X_3(Z)] \tag{23}$$

Similarity, we deduce the above equations and find that

$$X_1(Z) = K_4[I_1(Z) + r_{X4} Z^{-X_4} X_4(Z) + r_{X_5} \frac{K_7}{K_8} Z^{-X_4} X_5(Z) + r_{X6} \frac{K_6}{K_8} Z^{-X_4} X_6(Z)] \tag{24}$$

$$X_4(Z) = K_8[I_2(Z) + r_{X1} Z^{-X_1} X_1(Z) + r_{X_2} \frac{K_3}{K_4} Z^{-X_1} X_2(Z) + r_{X3} \frac{K_2}{K_4} Z^{-X_1} X_3(Z)] \tag{25}$$

From the above two equations, $X_1(Z)$ can be derived as

$$X_1(Z) = \frac{K_4\left[I_1(Z) + \left(K_8 r_{X_4} Z^{-X_4} + K_7 r_{X_5} Z^{-X_5} + K_6 r_{X_6} Z^{-X_6}\right) I_2(Z)\right]}{\Delta'} \tag{26}$$

and

$$\begin{aligned}\Delta' = 1 &- K_4 K_8 r_{X_1} r_{X4} Z^{-(X_1+X_4)} - K_4 K_7 r_{X1} r_{X_5} Z^{-(X_1+X_5)} - K_4 K_6 r_{X_1} r_{X_6} Z^{-(X_1+X_6)} - K_3 K_8 r_{X_2} r_{X_4} Z^{-(X_2+X_4)} \\ &- K_3 K_7 r_{X_2} r_{X5} Z^{-(X_2+X_5)} - K_3 K_6 r_{X_2} r_{X6} Z^{-(X_2+X_6)} - K_2 K_8 r_{X_3} r_{X4} Z^{-(X_3+X_4)} - K_2 K_7 r_{X_3} r_{X5} Z^{-(X_3+X_5)} \\ &- K_2 K_6 r_{X_3} r_{X6} Z^{-(X_3+X_6)}\end{aligned} \tag{27}$$

The $X_4(Z)$ can also be derived as

$$X_4(Z) = \frac{K_8\left[I_2(Z) + \left(K_4 r_{X_1} Z^{-X_1} + K_3 r_{X_2} Z^{-X_2} + K_2 r_{X_3} Z^{-X_3}\right) I_1(Z)\right]}{\Delta'} \tag{28}$$

After a lot of reductions , we can find the transfer functions of the three-loops IIR optical filter as

$$H_{11}(Z) = \frac{O_1(Z)}{I_1(Z)} = \frac{K_1}{\Delta'} \tag{29}$$

$$H_{12}(Z) = \frac{O_2(Z)}{I_1(Z)} = \frac{K_5\left(K_4 r_{X_1} Z^{-X_1} + K_3 r_{X_2} Z^{-X_2} + K_2 r_{X_3} Z^{-X_3}\right)}{\Delta'} \tag{30}$$

3. SIMULATION RESULTS AND COMPARISONS

Here we use the theoretical model derived in the above section, the frequency responses of these two optical IIR filters are simulated. The simulation results can be applied for practical realizing various filters. Taken narrow bandwidth optical band pass filters as example, the optimal parameters searching work is performed.

Table 1 shows three set of searched parameters corresponding to the simulated three examples of frequency responses of the two-loops optical IIR filter. According to the theoretical model we derived in subsection 2.1, three examples of frequency responses of two-loops IIR filters are shown in Fig.6. Example I is the best result we found. If the parameter K_4 increases, the sidelobe will arise as shown in the curveture of example II. The delay coefficients X_1, X_2, X_3, X_4 can be adjusted for designing higher order filters. The simulation result example III shown in Fig.6 give a general scope of view of higher order filter.

The parameters we used for simulating three-loops IIR filters in Fig.7 are listed in Table 2. Similarily, the numerical results are shown as example I, II and III for comparing the results of Fig.6. The optimal result of narrowband filter is shown in example I. When K_4 increases, the sidelobe will grow up as shown in example II like the two loops IIR filters. Increasing the order of this filter, the ripple of this filter will increased as shown in example III. We found the ripple is larger then the two loops IIR filters if the parameter is not well choosen.

Comparison of the optical two numerical results in Fig.6 and Fig.7, we zoom in the two cases of example I and show the spectra details in Fig.8. We can find that the three-loops IIR filter has a narrower optical frequency bandwidth than the two-loops IIR filter. The narrowest bandwidths of the two-loops IIR filter and the three-loops IIR filter we found are 0.00012 Hz and 0.00007 Hz, respectively. The narrow linewidth can provide pure filtering effect for extracting the phase lock loop carrier signal in DVD control systems.

4. CONCLUSIONS

The access data rate of optical storage systems increases rapidly in the last five years. Therefore, the signal processing will follow the trend, increasing the processing speed in the future. Accompany with the age of optical data storage above Tera byte, studying all-optical fiber high speed signal processing elements is important. The research results in this paper are very helpful for practical realizing various optical signal processing filters. The narrow band filter at 100GHz can be applied for clock recovery in high speed data-accessed DVD systems accompany some fiber pick up heads.

ACKNOWLEDGEMENT

This work was partially supported by the National Science Council of R.O.C. under contract NSC89-2215-E-155-003.

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Table 1

	K_1	K_2	K_3	K_4	K_5	K_6	X_1	X_2	X_3	X_4
I	0.0001	0.49995	0.49995	0.001	0.4995	0.4995	1	2	1	2
II	2	4	4	2	4	4	1	2	1	2
III	0.0001	0.49995	0.49995	0.9	0.05	0.05	3	4	5	6

Table 2

	K_1	K_2	K_3	K_4	K_5	K_6	K_7	K_8	X_1	X_2	X_3	X_4	X_5	X_6
I	0.0001	0.3333	0.3333	0.3333	0.001	0.25	0.499	0.25	1	2	3	1	2	3
II	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	1	2	3	1	2	3
III	0.0001	0.3333	0.3333	0.3333	0.91	0.03	0.03	0.03	4	7	1	7	4	1

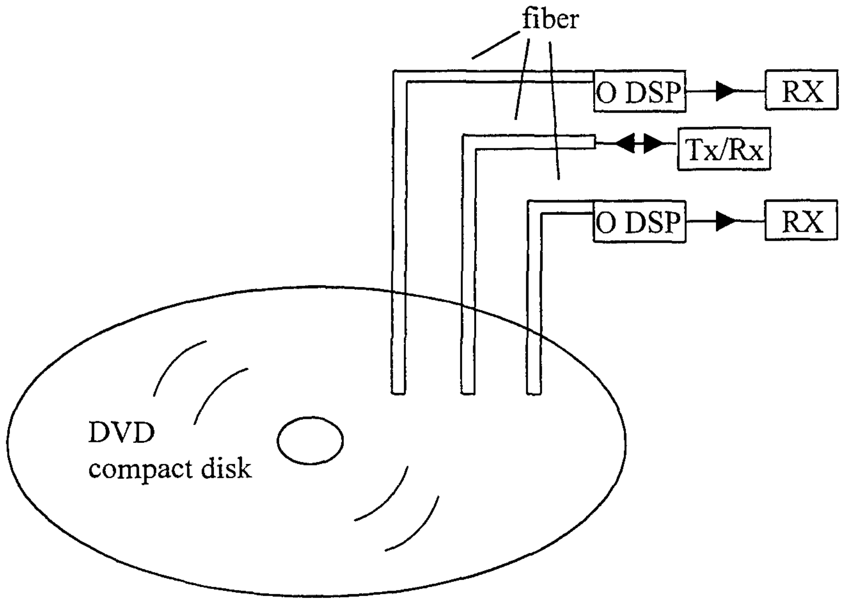

Fig.1 The schematic diagram of application of high speed optical digital signal processing (ODSP) elements

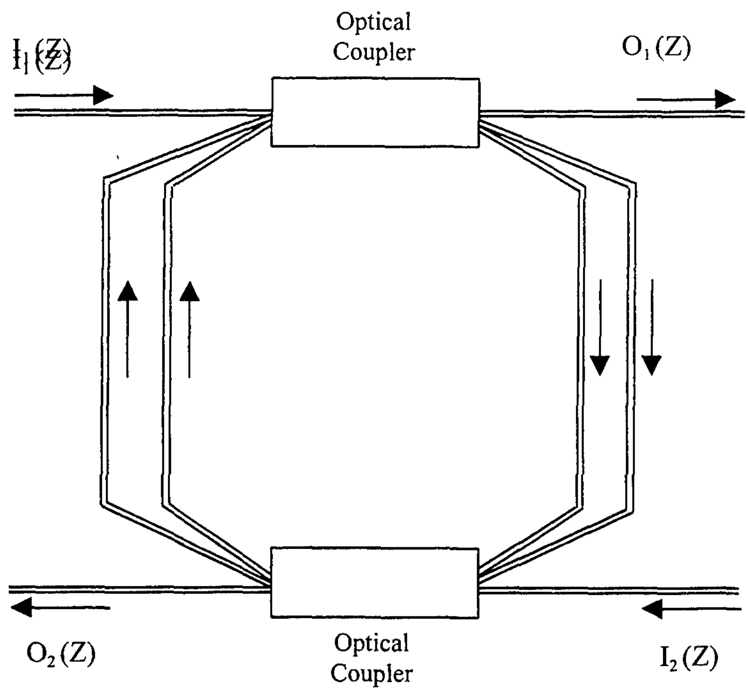

Fig.2 The schematic diagram of a two-loops optical IIR band-pass filter

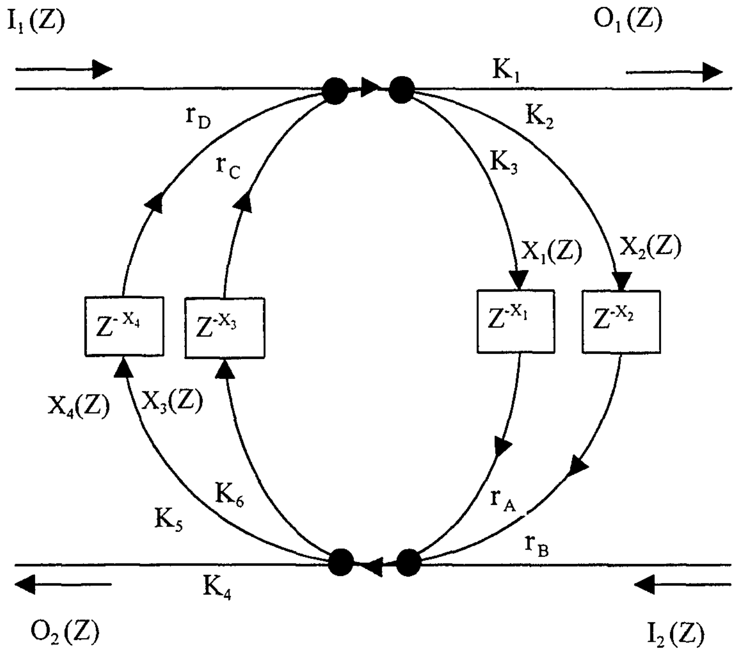

Fig.3 Two-loops optical IIR band-pass filter signal flow chart

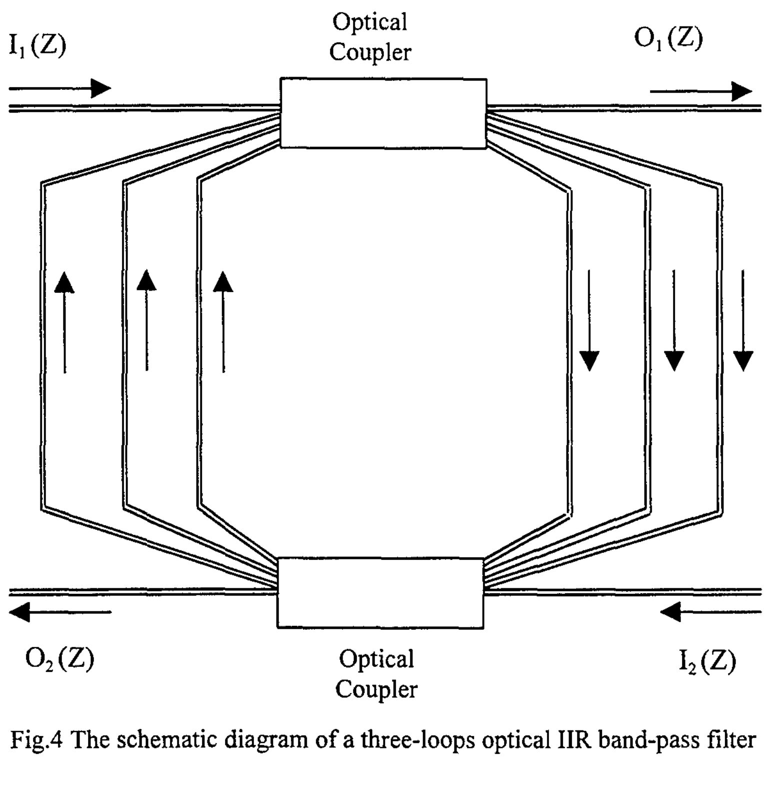

Fig.4 The schematic diagram of a three-loops optical IIR band-pass filter

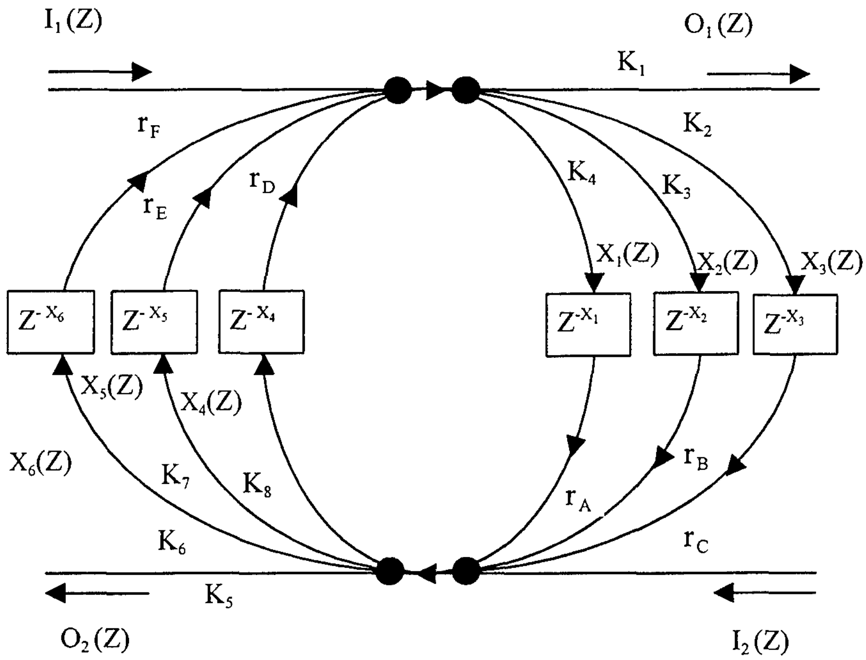

Fig.5 Three-loops optical IIR band-pass filter signal flow chart

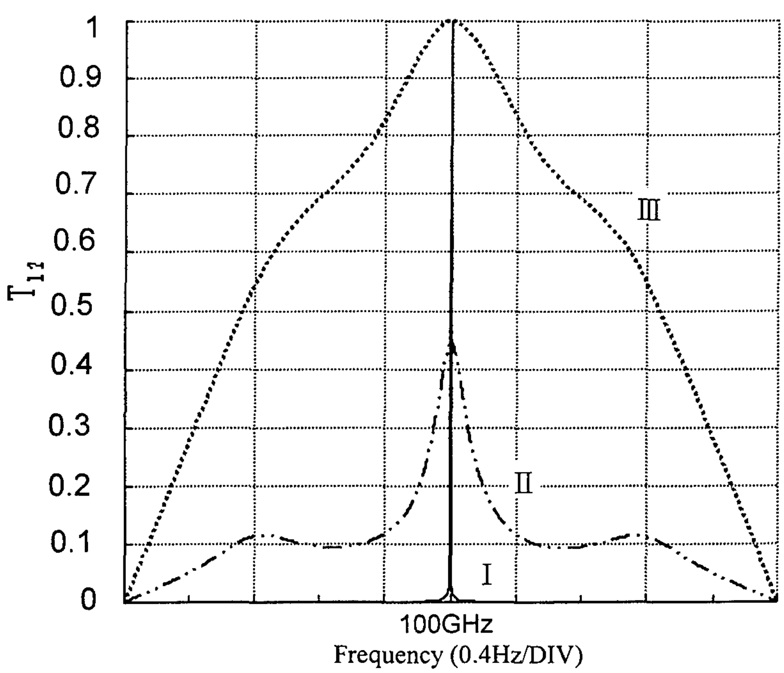

Fig.6 Frequency response T_{12} of two- loops optical IIR band-pass filter

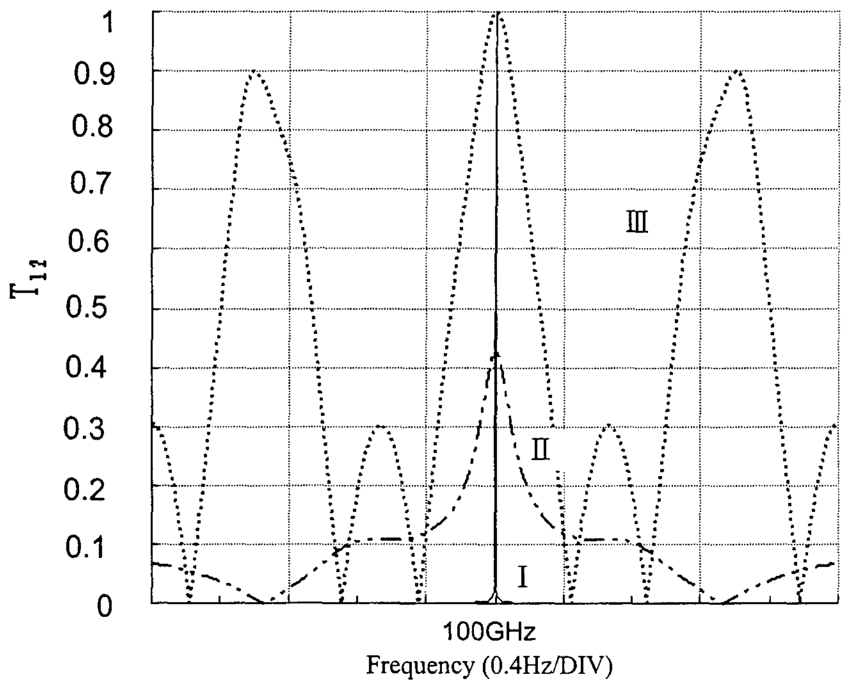

Fig.7 Frequency response T_{12} of three- loops optical IIR band-pass filter

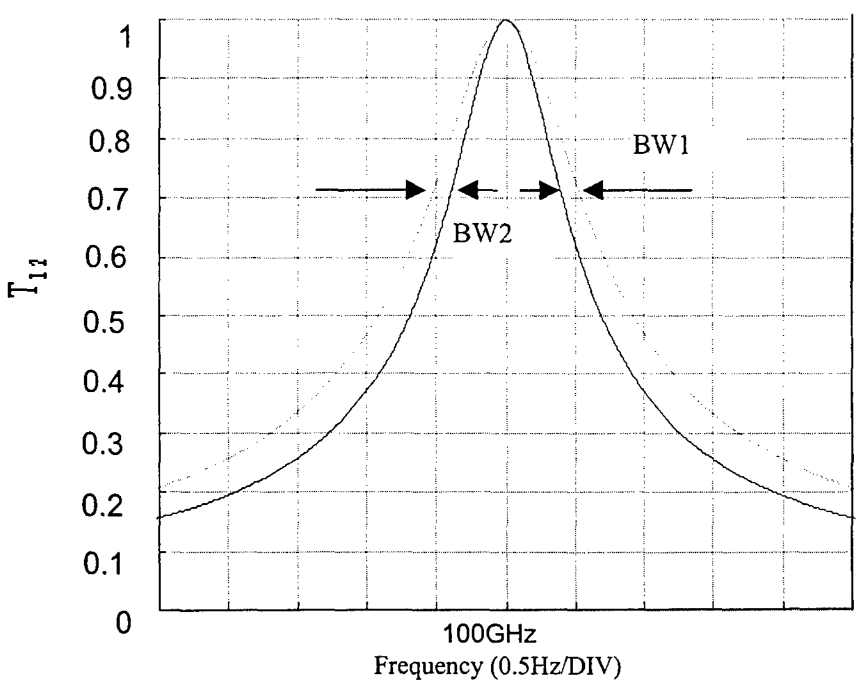

Fig.8 Comparison of Two and Three-loops optical IIR narrow band-pass filter frequency responses