논문 00-25-1B-13

한국통신학회논문지 '00-1 Vol.25 No.1B

한 개의 광증폭기를 이용한 광트랜스버셜 필터

정회원 이 채 욱*

Design method for optical transversal filter with an optical amplifier

Chae-wook Lee* *Regular Member*

요 약

광트랜스버셜 필터를 이용하여 희망하는 특성을 실현하기 위해서는 주어진 전달함수의 차수 만큼의 광섬유 증폭기를 사용하여야 한다. 본 논문에서는 단지 한 개의 광섬유 증폭기를 이용하여 주어진 전달함수의 정수 배를 실현할 수 있는 광트랜스버셜 필터에 대하여 논한다. 이때 광신호 에너지를 유효하게 사용하기 위하여 광신호 에너지를 최소로 하는 설계법을 적용하였다. 그리고 제안한 광트랜서버셜 필터를 이용한 몇 가지의 응용에 대하여 논하였다.

ABSTRACT

To realize a desired characteristics of an optical transversal filters, The number of optical amplifiers as same as the lentgh of a given transfer function is needed. In this paper, we consider an optical transversal filter that uses only one fiber amplifier, which can realize a constant($=a$) times of a given transfer function with a as large as possible in order to make use of optical signal energy. We also present some applications using this optical fiber filter.

Ⅰ. Introduction

It is generally recognized that all optical signal processing will be needed in order to fully exploit the high bandwidth properties of fiber optic point to point communication systems and networks. Although several approaches including opto-electronic, charge coupled, super conductor, surface acoustic wave and spatial optics based processors are feasible for their implementation [1], the low loss and large time-bandwidth product of optical fibers, together with the advances in various kinds of optical devices, provide attractive tools for high-speed and broadband signal processing. The use of optical fiber as a delay medium for signal processing applications has been demonstrated as with convolution, correlation pulse train generation, matched filtering and frequency filtering[1,2,3]. Fiber optic filters using silica-based waveguides and passive lattice structure have been proposed and noise analysis about delay line structure has been done[4,5].

Recently the advent of optical amplifiers has opened new prospects for all optical fiber communication systems and networks. The two main approaches followed to date towards optical amplification have concentrated on semiconductor laser (SLA) and fiber amplifiers (FA). Semiconductor laser amplifiers utilize the stimulated

---

* 대구대학교 정보통신공학부(cwlee@biho.taegu.ac.kr)

논문번호 : 99127-0328, 접수일자 : 1999년 3월 28일

※ 본 연구는 과학기술부에서 시행하는 중점연구개발 사업의 하나인 자연재해방재기술사업으로 수행되었습니다.

emission from injected carriers and are based on the conventional semiconductor laser structures. Fiber amplifiers can be implemented by doped, Raman, and Brillouin fiber amplifiers. Raman and Brillouin fiber amplifiers are based on nonlinear effects. Among doped fiber amplifiers, in general, Erbium-doped fiber amplifier (EDFA) in particular are perhaps the most interesting choice to be applied to fiber signal processors as they provide waveguide continuity, and hence lower insertion losses.

Fiber amplifiers have made new optical fiber signal processing possible in many fields. The use of fiber amplifiers in the context of optical fiber filtering has been proposed showing they can provide extra flexibility and filtering characteristics not available with their passive counterparts[6]. References[7,8] show feasibility of fiber optic programmable transversal filters, where the system parameters are changed by altering the amplifier pumping power electrically, using an optical amplifier in each stage. However, many fiber amplifiers have been used to implement optical transversal filters. Fiber amplifier, especially the Erbium-doped fiber amplifiers are still expensive and the multiplier programming can be achieved electrically. This can reduce the speed of operation of multiplier coefficients and the optical systems. Also, the spontaneous noise of fiber amplifier should be considered[9].

In this paper, we use the directional couplers to build the multipliers at each stage of optical fiber transversal filter, where we use only one fiber amplifier in cascade with optical transversal filter. Differing from the digital filters in which there is no essential restriction on the filter coefficient, the optical transversal filter considered in this paper has a restriction that the coupling coefficient of directional coupler for multipliers has to have a value between 0 and 1. We show how to effectively design the optical transversal filter using one fiber amplifier. We have shown an example on how to design the optical transversal filter. And we also have presented some applications using this optical transversal filter with one fiber amplifier.

Ⅱ. Components of optical fiber filter

We briefly describe the basic fundamental tools that are needed to construct optical fiber filter, such as optical fiber as delay elements, directional couplers as signal adders and tapping elements and fiber amplifiers as multipliers.

The implementation of the necessary delays can be achieved employing optical fibers, which provide a precise time. Time delays are on the order of 5ns/m. Their advantages in relation to signal processing can be summarized in terms of loss and bandwidth. Here z^{-1}represents a unit time delay.

Signal adders and tapping elements in guided-wave format can be implemented using 2x2 directional couplers. Directional couplers are the optical fiber equivalents of beam splitters, hence they have found widespread application in optical fiber communication systems and sensors. There are three kinds of directional couplers: fused, polished, and D-fiber. Both fixed and variable coupling ratio models are commercially available. In the latter, the coupling constant can be varied mechanically. Also, they were used as signal tapping elements for passive all fiber transversal filters.

The input-output relationship of a directional coupler can be described by a 2x2 transfer matrix as [1,2]

$$I_2^+ = (1-\gamma)(1-a)I_1^+ + (1-\gamma)aI_1^- \tag{1}$$

$$I_2^- = (1-\gamma)aI_1^+ + (1-\gamma)(1-a)I_1^- \tag{2}$$

where a, $0 \leq a \leq 1$, is the coupling coefficient, γ is the fractional loss of the directional coupler, and $I_1^+, I_1^-, I_2^+, I_2^-$ are the optical intensities at the input-output ports of the coupler, as shown in Fig.1. Considering the progress of techniques in realizing a directional coupler, we can assume $\gamma \simeq 0$.

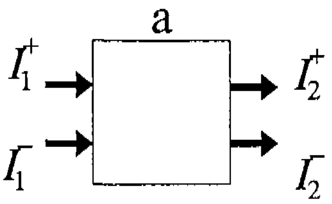

Fig. 1 Directional couper

We can construct the couplers by using the input $I_1^+ (I_1^- = 0)$ and the outputs I_2^+, I_2^-. The relationship between the input and the output is given by

$$I_2^+ = (1-a)I_1^+$$

$$I_2^- = aI_1^+$$

Signal multiplication in the optical domain can be accomplished with no conversion of photons to electrons by using optical amplifiers. There are two kinds of amplifiers, semiconductor laser and fiber amplifiers. Semiconductor lasers are very sensitive to signal polarization, as the single pass gain for the TE and TM modes are different. Fiber amplifiers can be implemented in various ways. In general, Erbium-doped fiber amplifiers are the most useful components of optical fiber signal processing. The multiplier programming can be understood by examining a typical signal gain in dB versus pump power curve of an Erbium doped fiber amplifier[8]. The output power of the pumping laser and its input current are related through the laser quantum efficiency η, $P=\eta I$, where P is the pump power required for the fiber amplifier and I is the required input current for the pumping laser diode. An efficient performance requires amplifier uniformity as related to pumping efficiency, high dynamic range and gain linearity outside the saturation region. The gains of fiber amplifiers can be achieved electronically by altering the value of the input current in the Erbium doped fiber amplifier pumping laser diode. Optical amplifiers have the advantage of providing signal amplification in the optical domain, therefore avoiding the need for optoelectronic and electrooptic conversion. However, many amplifiers can introduce much additional noises related to the spontaneous emission generated inside the amplifier and its subsequent amplification[8]. Furthermore, they are still expensive and the multiplier programming is achieved electrically, so the speed of the total optical system may be reduced.

Ⅲ. Optical transversal filter using one fiber amplifier

Capmany and Cascon[7,8] have proposed the fiber optic programmable FIR transversal filter shown in Fig.2, where T is the basic delay between adjacent taps. It is assumed that the signals add on an intensity basis.

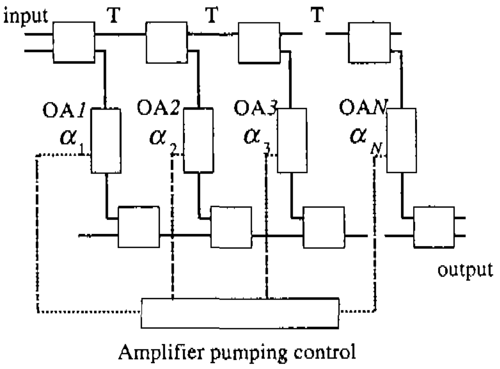

Fig. 2 Optical transversal filter using optical amplifiers

The upper couplers tap half of the incoming signal intensity into the fiber rings where the weighting operation is performed. The lower couplers have the same power splitting ratio and collect the weighted signals arising from each stage. In each ring, optical amplifier with power gain α_i can be used to perform the signal weighting. α_i can be achieved electronically by changing the values of the input current in the pump laser diode. This optical transversal filter as shown in Fig. 2 need many optical amplifiers (equal to the numbers of the upper couplers). However, the fiber amplifier is expensive and needs an amplifier pumping control system, which limits the speed of signal processing.

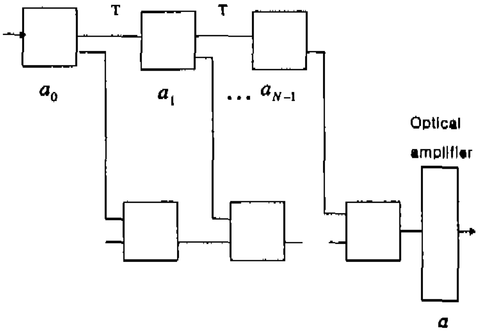

Fig. 3 Proposed optical transversal filter

We propose a simple optical transversal filter structure using one fiber amplifier. Fig.3 shows the proposed filter structure, where N represents the number of stages in the filter, T is a basic delay and parameter a is the fiber amplifier gain. As mentioned above, the coefficients of the directional couplers are restricted as follows:

$$0 \le a_k \le 1, \quad k=0,1,\cdots,N-1$$

We construct the upper couplers having the following relations:

$$I_k^+ = (1-a_k)I_{k-1}^+ \tag{3}$$

$$I_k^- = a_k I_{k-1}^+ \tag{4}$$

The lower couplers have the same power-splitting ratio as follows:

$$a_k = 1/2, \quad k=0,1,\cdots,N-1$$

These lower couplers collect the weighted signals arising from each stage. One of the two output intensities at the lower couplers is set to zero. Here, low coupler loss is given by $A = 2^{-N}$. This loss can be compensated for by a fiber amplifier at the filter output.

Since this structure has one amplifier at the filter output, we can avoid expensive amplifier pumping control systems and process high bandwidth signals at a high speed.

Next, we discuss how to design and realize the proposed optical transversal filter. The signals add on an intensity basis.

The impulse response is given as below.

0-th impulse response is

$$a_0$$

1-th impulse response is

$$a_1(1-a_0)$$

2-th impulse response is

$$a_2(1-a_1)(1-a_0)$$

Therefore, n-th impulse response is given by

$$h(nT) = a_n \prod_{k=0}^{n-1}(1-a_k) \tag{5}$$

Considering the amplifier gain a, the optical transversal transfer function $H(z)$ can be obtained directly from (5) yielding

$$H(z) = a\sum_{n=0}^{N-1}\left(a_n \prod_{k=0}^{n-1}(1-a_k)\right)z^{-n} \tag{6}$$

Assume that a desired (N-1)-th order transfer function is given as follows.

$$H(z) = \sum_{k=0}^{N-1} h_k z^{-k} \tag{7}$$

We can realize the desired transfer function using the optical transversal filter by equating the optical transfer function and the desired transfer function. Equating (5) and (6), we obtain

$$a a_k \prod_{l=0}^{k-1}(1-a_l) = h_k, \quad k=0,1,\cdots,N-1 \tag{8}$$

In order to increase the signal gain, we need more pump power, which is not desirable for the optical fiber filter. Therefore, we must minimize optical fiber amplifier gain.

Now, considering these design conditions, we explain how to determine the coupler coefficients

$a_0, a_1, \cdots, a_n$ with a as small as possible.

These can be easily seen as follows. From (8), we can obtain
for $i=0$;

$$a_0 = \frac{1}{a} h_0$$

for $i=1$;

$$a_1 = \frac{(1/a)h_1}{1-(1/a)h_0}$$

Now we can also get $(1-a_1)$, and substitute this term in (8) to obtain a_2. Therefore, repeating this operation, we can obtain coupler coefficients a_k $(k=0,1,\cdots,N-1)$ using the previous coefficients a_{k-1}.

We can arrange the general form as follows.

$$a_k = \frac{(1/a)h_k}{1-(1/a)\sum_{i=0}^{k-1} h_i} \tag{9}$$

Also, since $0 \le a_k \le 1$, from (9) we obtain

$$\frac{1}{a}\sum_{i=0}^{k} h_i \le 1$$

So, we can determine $a_{\min}$, the smallest value of a for (N-1)-th proposed optical fiber filter, as

$$a_{\min} = \sum_{i=0}^{N-1} h_i \tag{10}$$

From (9) and (10), the coefficients of the upper directional couplers of optical transversal filter are given by

$$a_k = \frac{(1/a_{\min})h_k}{1-(1/a_{\min})\sum_{i=0}^{k-1} h_i} \tag{11}$$

As a result, we have derived very simple design formulae for the proposed optical transversal filter using one amplifier, which can realize any FIR (Finite Impulse Response) transfer function. The design procedure for optical transversal filter is summarized as follows.

Step 1 : Given the coefficients $h_i (i=0 \sim N-1)$ of transfer function.

Step 2 : Solve $a_{\min}$ from (10).

Step 3 : Solve a_k from (11).

The fiber amplifier also can compensate for both the common coupler loss factor and the lower coupler loss. Here, the coefficients of lower couplers are set to be 1/2.

As an example, let the desired transfer function ($N-1=4$) be

$$H_d(z) = 0.1+0.2z^{-1}+0.3z^{-2}+0.2z^{-3}+0.1z^{-4}$$

Then, from the design formulae (10) and (11), we obtain

$$a_{\min} = 1.2,\ a_0 = \frac{0.1}{1.2},\ a_1 = \frac{0.166}{0.916}$$

$$a_2 = \frac{0.25}{0.75},\ a_3 = \frac{0.166}{0.5},\ a_4 = \frac{0.083}{0.333}$$

Setting the fiber amplifier gain $a=1.2$, we can realize the desired transfer function by the proposed optical transversal filter using one fiber amplifier.

The signals of the proposed optical fiber filter add on an intensity basis. Although intensity addition is assumed, it is possible to design the filter with negative coefficients using the scheme depicted in Fig.4, where differential detection is used to subtract positive signals. The positive and negative coefficients are implemented in the upper and lower transversal structures, respectively. The directional coupler preceding each of the fiber transversal filters may be replaced by an optical switch.

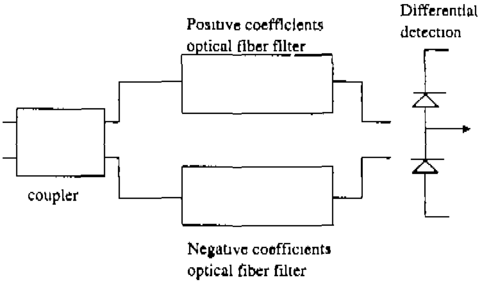

Fig. 4. System layout to perform filtering with negative coefficients

The procedure is as follows. If the desired impulse response h_t is non-negative, then the coefficient of the upper structure is set according to the design method, whereas the coefficient of the lower coupler is set so that $k_t = 0$. If $h_t < 0$, then we obtain the coefficients of the couplers by interchanging the upper and the low structures.

Next, in general, direct form I structure of filter is composed of the cascade of two blocks. So we can implement the IIR (Infinite Impulse Response) structure filter by connecting the same process for the transversal filter in the cascade. In this case, we notice that the feedforward part is the same as the optical transversal filter. The feedback part of the upper couplers has the same structure as the optical transversal filter and the coefficients of lower couplers are also set to be 1/2. But the direction from the upper to the lower couplers must be set opposite to the proposed optical transversal filter. We need one more coupler at the first stage of the feedback part because of the recirculation of the total system. Direct form II and canonic form of IIR filter also can be composed of the proposed optical transversal filter.

In an IIR filter, we must ensure stability, i.e., all the poles of the system transfer function must be inside the unit circle. However, the optical fiber filter in this paper consists of only passive elements, so unstability is not an issue.

Other applications are in the implementation of direct form optical discrete time signal processors using optical amplifiers and star couplers[8,9]. They have designed the canonic finite and infinite impulse response stages considering use of 2x2 directional couplers, NxM star couplers and non-blocking switching matrices. The all fiber discrete time signal processors are implemented, using 1xM, Mx1 star couplers, and M optical amplifiers are inserted between star couplers. Instead of the star couplers, if we use the same type coupler like the directional coupler we proposed, the discrete time signal processors may be realized using only one optical amplifier. We may also adopt this method for the all fiber discrete time signal processor using amplifiers and switch matrix.

The proposed type of directional coupler can be applied for other types of structures, such as lattice, ladder structure and for various types of digital filter structures.

Ⅳ. Conclusions

The demand for very high-speed and broadband signal processing, such as all optical signal processing has been increasing, continuously. Recently, optical fiber amplifiers that are still expensive have been used to implement optical fiber filters.

In this paper, we have proposed a new type of directional coupler, which is used as a multiplier, and we have shown a simple design method of optical transversal filter which uses the directional couplers and an optical amplifier. We have also shown some applications. As this optical transversal filter is a passive structure, it is not capable of performing programmable signal processing. This system is sensitive to environmental fluctuations such as pressure and temperature changes as well as frequency fluctuations of optical source. And we assume that the directional coupler has no error of implementation.

As for the topics related to this paper, we have been investigating reconfigurable directional couplers that can be made electrically or mechanically. For another type of optical fiber filter, such as ladder or lattice structure, we are considering effective and simple design methods and experimental results using this transversal model.

References

[1] K. P. Jackson, S. A. Newton, B. Moslehi, C. C. Cutler and H. J. Shaw, "Optical fiber delay line signal processing", IEEE Trans. Microwave Theory & Tec.,vol.MTT-33, No.3, pp.193-208, March 1985.

[2] B. Vizoso, C. Caren and A. Muriel, "Amplified

fiber optic recirculating delay lines", Journal of Lightwave Tec., vol.12, no.2, pp.294-308, Feb. 1994.

[3] B. Moslehi, J. W. Goodman, M. Tur and H. J. Shaw, "Fiber optic lattice signal processing," proc. IEEE, vol. 72, pp.909-930, 1984.

[4] K. Sasayama, M. Okuno and K. Habara, "Coherent optical transversal filter using silica based waveguides for high speed signal processing", Journal of Lightwave Tec., vol.9, No. 10, pp.1225-1230, Oct., 1991.

[5] E. C. Heyde, "General noise analysis of recirculating delay line structures," Journal of Lightwave Tec., vol.15, No.1, pp.102-111, Jan, 1997.

[6] B. Moslehi, "Fiber optic filters employing optical amplifiers to provide design flexibility," Electron Lett., vol. 28, no.3, pp.226-228, 1992.

[7] J. Capmany and J. Cascon, "Optical programmable transversal filter using fiber amplifiers," Electron Lett., vol. 28, no.13, pp.1245-1246, 1992.

[8] J. Capmany and J. Cascon, "Discrete time fiber optic signal processors using optical amplifiers", Journal of Lightwave Tec., vol.12, no.1, pp.106-117, Jan., 1994.

[9] M. Movassaghi, M. K. Jackson, V. M. Smith and W. J. Hallam, "Noise figure of Erbium Dopped fiber amplifibers in saturated operation," Journal of Lightwave Tec., vol.16, No.5, pp.812-817, May, 1998.

[10] M. Irshid and M. Kavehrad, "Star couplers with gain using fiber amplifiers," IEEE Photon, Tech. Lett., vol. 4, no.1, pp.58-60, 1992.

이 채 욱(Chael-wook Lee) 정회원
(통신학회 논문지 제 24권 제2B호 참조)
1980년 2월 : 한국항공대학교 통신공학과(공학사)
1987년 3월 : 동경공업대학 전기전자공학과(공학석사)
1990년 3월 : 동경공업대학 전기전자공학과(공학박사)
1990년 3월~현재 : 대구대학교 정보통신공학부 교수
<주관심 분야> 디지털신호처리, 광통신시스템, 적응신호처리