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A NEW APPROACH TO DESIGN DIGITALLY TUNABLE OPTICAL FILTER SYSTEM FOR DWDM OPTICAL NETWORKS

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Abstract—A new approach to design digitally tunable optical filter system for DWDM (Dense Wavelength Division Multiplexed) optical networks is presented. This digitally tunable optical filter system uses semiconductor optical amplifiers (SOAs) and DWDM thin film filter based wavelength selection elements. The design is very easy to configure, expand and reduce. This digitally tunable optical filter system is smaller in size, lesser in weight, cheaper in cost, consumes low power and has better timing performance as compared to digitally tunable optical filter suggested by researchers recently.

1. INTRODUCTION

DWDM (Dense Wavelength Division Multiplexing) has currently taken over as the leading technology in point-to-point optical transmission links. At the dynamic network level, however, DWDM is still in its R & D stage. This is due to the fact that network functionality requires dynamic elements to perform signal-processing manipulations at different levels of networks. This includes filtering, routing, add-drop multiplexing and wavelength conversion etc. One major dynamic network functionality in the DWDM environment is optical filtering, that is, channel selection. Since in DWDM systems each channel is related to a different wavelength, channel manipulations and particularly channel selection require optical wavelength selection (i.e., optical filtering). Therefore for optical implementation of DWDM networks, logical functionalities such as wavelength (channel) selection should be carried out in the wavelength domain; thus, development

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of dynamic optical devices is required. One key device is a tunable optical filter.

In past, consistent efforts have been made by various researchers to design different types of optical filters that are dynamically tunable over a certain band of wavelengths. Such devices include tunable multiple electrode asymmetric directional couplers [1], tunable Mach Zehnder interferometers [2, 3], fiber Fabry-Perot filters [4, 5], tunable waveguide arrays [6, 7], liquid crystal Fabry-Perot filters [8, 9], tunable multigrating filters [10], acousto-optic tunable filters [11], and electro-optic tunable filters [12] etc. Tunable 2 × 2 directional couplers work on the principle that application of a specific voltage to the electrodes changes the refractive index of the waveguides thereby selecting one of the wavelengths say λ_i, to be coupled to the second waveguide. Tunable Mach Zehnder interferometers (MZI) use either thermo-optic or electro-optic control mechanisms to change the length of the interferometer arms which varies the path difference to select a channel in each MZI stage. Fiber Fabry-Perot filters work on the principle of partial interference of the incident beam with itself in a mirrored resonant cavity to produce transmission peaks and nulls in the frequency domain. In tunable waveguide arrays, by appropriately biasing the optical amplifiers to increase or attenuate spectral components, or through specific on/off settings of optical switches, each channel can be selected to pass through the filter. Liquid crystal Fabry-Perot filters are tuned by applying a voltage across a crystal, which changes the refractive index, and hence the optical path length, in the cavity material. Tunable multigrating filters use two three-port circulators with a series of N electrically tunable fiber-based reflection gratings placed between them. Acousto-optic tunable filters operate through the interaction of photons and acoustic waves in a solid lithium niobate. Here, an acoustic transducer is modulated by an RF signal to produce a surface acoustic wave in the lithium niobate crystal. This wave sets up an artificial grating in the solid, the grating period being determined by the frequency of the RF signal. In Electro-optic wavelength-tunable fiber ring laser based on cascaded composite Sagnac loop filters [12], filtering function is electrically tunable through an electro-optic modulator.

Recently, a digitally tunable optical filter was suggested by Li et al. [13]. This digitally tunable optical filter was based on Semiconductor Optical Amplifiers (SOAs) and DWDM thin film filter wavelength selection elements. In this system, the desired wavelength was routed to the output through transmission and/or reflection from thin film filters with the help of a particular SOA on-off combination. It had the advantages of fast tuning speed, large tuning range, good temperature stability and simple control mechanism. It was also easily scalable. The pass band wavelengths were in consistency with those suggested by ITU-T (International Telecommunication Union Telecommunication). Recently, in another research work [14], a different, easier, simpler and more efficient approach to design a digitally tunable optical filter system based on thin film filters and SOAs for application in DWDM optical networks was demonstrated. This design carried all the advantages of the design reported in reference [13], as it utilized the same components and subsystems. In addition, when the total numbers of wavelength channels were greater than 8, the design required [14] lesser number of SOAs for a more number of channels to be tuned, which reduced the system cost, size, weight, and power consumption. Further, the use of only one kind of wavelength selection element (i.e., a two-bytwo wavelength selection element for each channel) in the proposed structure made this structure easy to assemble, expand and reduce. In this paper, another new approach to design digitally tunable optical filter based on Semiconductor Optical Amplifiers (SOAs) and DWDM thin film filter wavelength selection elements is presented. The current design approach not only retains all the advantages of the previous design approach [14], but in addition, it removes the timing disparity between the upper and lower set of four channels present in the previous design; thereby, improving the timing performance of the system. This issue is very important in high speed optical networks. A comparison between this design and the previous designs [13, 14] is given in Section 4, in this paper.

2. SYSTEM DESCRIPTION AND WORKING

The system uses a (1×2) splitter, 8 two-by-two (2×2) wavelength-selection elements with DWDM thin-film filters for different channels, 6 SOAs, connecting fibers and 1 four-by-one (4×1) combiner. The complete system designed by using these subsystems and components is shown in Figure 1. The two-by-two wavelength selection element is shown in Figure 2, it uses a thin-film filter as depicted in figure, such that, all the wavelengths from input 1 and input 2 fiber will be reflected to output 1 and output 2, respectively, except for the wavelength that is equal to the center wavelength, λ_i, of the thin-film filter. This wavelength will pass through the filter and arrive at the diagonally opposite output port.

The input light to this system is divided into two portions via splitter that arrive at semiconductor optical amplifiers SOA_{11} and SOA_{12}. When SOA_{11} is turned on (SOA_{12} is off), all the wavelengths will arrive at the thin-film filter with center wavelength λ_1. All the wavelengths except λ_1 will be reflected and will arrive at the thin-film filter with center wavelength λ_2. SOA_{2i} ($i = 1, 2, 3$ and 4) will perform second selection of the wavelength. In the above case, λ_1 will arrive at the output through the 4×1 combiner if SOA_{21} is on (SOA_{22}, SOA_{23} and SOA_{24} are off). If in this case, SOA_{21} is off and SOA_{22} is on, then λ_2 will arrive at the output through the 4×1 combiner. The on-off

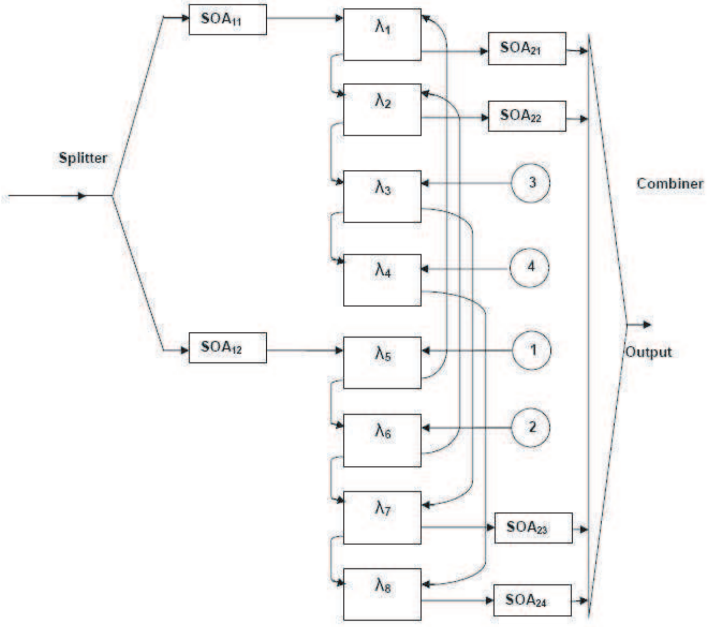

Figure 1. Configuration of 8 channel tunable optical filter system.

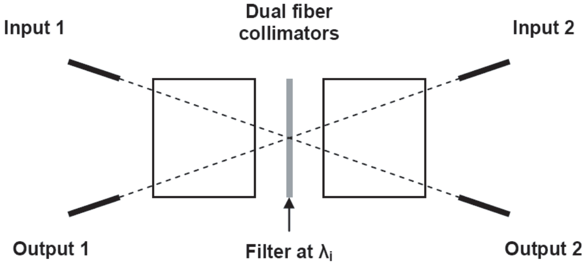

Figure 2. Structure of a 2×2 wavelength selection element.

Table 1. SOA control combinations for filtering different wavelengths.

SOA_{11}	SOA_{12}	SOA_{21}	SOA_{22}	SOA_{23}	SOA_{24}	Selected Wavelength
1	0	1	0	0	0	λ_1
1	0	0	1	0	0	λ_2
1	0	0	0	1	0	λ_3
1	0	0	0	0	1	λ_4
0	1	1	0	0	0	λ_5
0	1	0	1	0	0	λ_6
0	1	0	0	1	0	λ_7
0	1	0	0	0	1	λ_8

combinations of SOAs will decide which wavelength will be routed to the output. Suppose, if only SOA_{11} and SOA_{23} are on, then λ_3 will arrive at the output after reflection from side 2 of thin film filter with center wavelength λ_7, via 4×1 combiner. The control combinations for filtering different wavelengths through this system are given in Table 1. In this table, 1 means that the SOA is turned on and 0 means that the SOA is turned off. It is evident that this structure allows the desired center wavelength to be arbitrarily selected from the 8 thin-film filter center wavelengths.

3. MODELING AND SIMULATION

For gain based modeling of this system, output power equations were derived for different wavelengths filtered through this system as given below

$$P_{O\lambda_1} = G_{21\lambda_1}\left(G_{11\lambda_1}P_{i\lambda_1} - P_{lt\lambda_1}\right) - P_{lc\lambda_1} \tag{1}$$

$$P_{O\lambda_2} = G_{22\lambda_2}\left(G_{11\lambda_2}P_{i\lambda_2} - P_{lr\lambda_2 f_1} - P_{lt\lambda_2}\right) - P_{lc\lambda_2} \tag{2}$$

$$P_{O\lambda_3} = G_{23\lambda_3}\left(G_{11\lambda_3}P_{i\lambda_3} - P_{lr\lambda_3 f_1} - P_{lr\lambda_3 f_2} - P_{lt\lambda_3} - P_{lr\lambda_3 f_7}\right) - P_{lc\lambda_3} \tag{3}$$

$$P_{O\lambda_4} = G_{24\lambda_4}\left(G_{11\lambda_4}P_{i\lambda_4} - P_{lr\lambda_4 f_1} - P_{lr\lambda_4 f_2} - P_{lr\lambda_4 f_3} - P_{lt\lambda_4} - P_{lr\lambda_4 f_8}\right) - P_{lc\lambda_4} \tag{4}$$

$$P_{O\lambda_5} = G_{21\lambda_5}\left(G_{12\lambda_5}P_{i\lambda_5} - P_{lt\lambda_5} - P_{lr\lambda_5 f_1}\right) - P_{lc\lambda_5} \tag{5}$$

$$P_{O\lambda_6} = G_{22\lambda_6}\left(G_{12\lambda_6}P_{i\lambda_6} - P_{lr\lambda_6 f_5} - P_{lt\lambda_6} - P_{lr\lambda_6 f_2}\right) - P_{lc\lambda_6} \tag{6}$$

$$P_{O\lambda_7} = G_{23\lambda_7}\left(G_{12\lambda_7}P_{i\lambda_7} - P_{lr\lambda_7 f_5} - P_{lr\lambda_7 f_6} - P_{lt\lambda_7}\right) - P_{lc\lambda_7} \tag{7}$$

$$P_{O\lambda_8} = G_{24\lambda_8}\left(G_{12\lambda_8}P_{i\lambda_8} - P_{lr\lambda_8 f_5} - P_{lr\lambda_8 f_6} - P_{lr\lambda_8 f_7} - P_{lt\lambda_8}\right) - P_{lc\lambda_8} \tag{8}$$

where, $P_{O\lambda_j}$ and $P_{i\lambda_j}$ are the output and input powers respectively for the wavelength λ_j $(j = 1, 2, 3 \ldots, 8)$. $G_{hi\lambda_j}$ is the optical gain of the SOA$_{hi}$ ($h = 1, 2$ and $i = 1, 2, 3, 4$) for the wavelength λ_j. $P_{lt\lambda_j}$ is the power loss in transmission through thin film filter with λ_j center wavelength. $P_{lr\lambda_j f_k}$ is the power loss due to reflection from thin film filter with center wavelength λ_k $(k = 1, 2, 3 \ldots, 8)$ for the wavelength λ_j. $P_{lc\lambda_j}$ is the power loss introduced by the combiner for the wavelength λ_j.

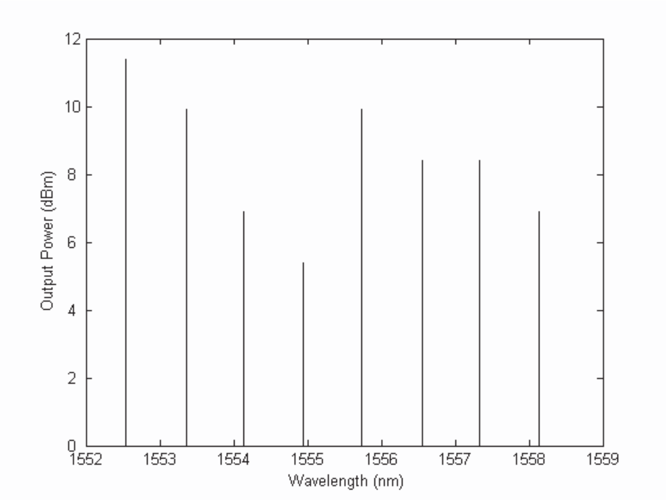

Figure 3. Transmission spectrum of the simulated system.

Table 2. List of center wavelengths.

Channel	**Wavelength (nm)**
1	1552.54
2	1553.36
3	1554.14
4	1554.95
5	1555.74
6	1556.55
7	1557.33
8	1558.14

To demonstrate the performance of the proposed system, simulation of the system was carried out. Figure 3 shows the result of the simulation. The stair-step patterns in the transmission spectrum arise from the fact that more successive reflections take place for certain wavelengths in its routing path. The 8 wavelengths range from 1552.54 to 1558.14 nm as listed in Table 2. The loss introduced by combiner was taken to be 0.1 dB. The SOA considered was operative across the entire optical bandwidth with a single-pass gain of 5 dB. A loss of 0.2 dB due to transmission and 0.3 dB due to reflection was taken in the wavelength-selection element.

4. COMPARISON

Suppose the number of channels to be tuned in the proposed system is n, then the number of SOAs required on the input side i.e., $N_{SOAINPUT} = n/4$. Number of SOAs required on the output side is $N_{SOAOUTPUT} = 4$ (fixed). Therefore, the total number of SOAs required is given by $N_{SOATOTAL} = N_{SOAINPUT} + N_{SOAOUPUT} = (n/4 + 4)$. A comparison of the number of SOAs required in the proposed structure with the structure suggested in reference [13] is shown in Figure 4. Circular dots show the number of SOAs required for the different number of channels to be tuned in case of reference [13] and triangles show the number of SOAs required for different number of channels to be tuned, in case of the proposed structure. Figure 4 clearly shows that the proposed design approach requires fewer SOAs in comparison to the approach suggested in reference [13], for greater number of channels to be tuned. The requirement of SOAs in design

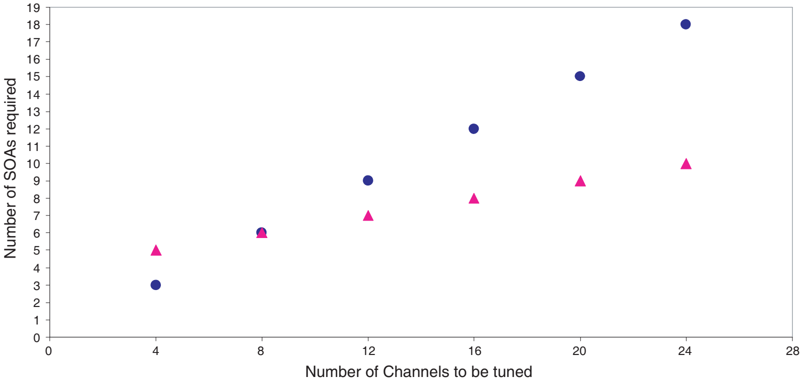

Figure 4. Comparison of systems.

suggested in reference [13] drastically increases with increase in number of channels, while in the case of current system it rises slowly and gradually. This significant reduction in the number of SOAs drastically reduces the system cost, size, weight and power budget. The approach suggested in the current paper is very simple and easy as compared to that suggested in reference [13]. The proposed design can be very easily expanded to accommodate more number of channels. For a new set of four channels (say λ_9, λ_{10}, λ_{11} and λ_{12}) only one additional semiconductor optical amplifier (SOA_{13}) will be required at the side1 (input side) while at the side 2, outputs of the λ_9, λ_{10}, λ_{11} and λ_{12} wavelength selection elements have to be connected at side 2 inputs 1, 2, 3 and 4 respectively (marked in Figure 1). Similarly, the proposed system can be expanded for desired new sets of channels. Further, the use of only one kind of wavelength selection element (i.e., only two-by-two wavelength selection element for each channel) as compared to two kinds in reference [13] makes this system not only easy to expand, but also easy to reduce. The design allows using subsystems used in this system as a separate system, when they are not in use.

In the configuration of 8 channel digitally tunable optical filter system (Figure 1) suggested in the work [14]. Different paths are followed by the different wavelengths. If, $t_{\lambda i}$ is the delay time for the λ_i wavelength between input side (left) and output side (right) SOAs; $t_{r\lambda_i\lambda_j}$ is the time taken by the λ_i wavelength to go into the wavelength selection element with λ_j center wavelength filter, and coming back after reflection; t_t is the time taken by the λ_i wavelength in passing through the wavelength selection element with λ_i center wavelength filter and to appear at the diagonally opposite output port; t_f is the time taken by the λ_i wavelength in passing through the fibers. Where, $i = 1, 2, 3, \dots 8$; $j = 1, 2, 3, \dots 8$. By looking into the paths followed by each wavelength, the time delay for each wavelength between input SOA and output SOA can be written as

$$t_{\lambda_1} = t_t + t_f \tag{9}$$

$$t_{\lambda_2} = t_t + t_{r\lambda_2\lambda_1} + t_f \tag{10}$$

$$t_{\lambda_3} = t_t + t_{r\lambda_3\lambda_2} + t_{r\lambda_3\lambda_1} + t_f \tag{11}$$

$$t_{\lambda_4} = t_t + t_{r\lambda_4\lambda_3} + t_{r\lambda_4\lambda_2} + t_{r\lambda_4\lambda_1} + t_f \tag{12}$$

$$t_{\lambda_5} = t_{r\lambda_5\lambda_1} + t_t + t_f \tag{13}$$

$$t_{\lambda_6} = t_{r\lambda_6\lambda_2} + t_t + t_{r\lambda_6\lambda_5} + t_f \tag{14}$$

$$t_{\lambda_7} = t_{r\lambda_7\lambda_3} + t_t + t_{r\lambda_7\lambda_6} + t_{r\lambda_7\lambda_5} + t_f \tag{15}$$

$$t_{\lambda_8} = t_{r\lambda_8\lambda_4} + t_t + t_{r\lambda_8\lambda_7} + t_{r\lambda_8\lambda_6} + t_{r\lambda_8\lambda_5} + t_f \tag{16}$$

If $t_{r\lambda_i\lambda_j} = t_t = t_f = 10\,\mathrm{ps}$; for $i = 1, 2, 3, \dots 8$; $j = 1, 2, 3, \dots 8$. The delay times for the upper group of four wavelengths are $t_{\lambda_1} = 20\,\mathrm{ps}$,

$t_{\lambda_2} = 30\,\mathrm{ps}$, $t_{\lambda_3} = 40\,\mathrm{ps}$ and $t_{\lambda_4} = 50\,\mathrm{ps}$. Therefore, the average delay time for the upper group of four wavelengths comes out to be 35 ps.

For the lower group of four wavelengths the delay times are $t_{\lambda_5} = 30\,\mathrm{ps}$, $t_{\lambda_6} = 40\,\mathrm{ps}$, $t_{\lambda_7} = 50\,\mathrm{ps}$ and $t_{\lambda_8} = 60\,\mathrm{ps}$. Therefore, the average delay time for the lower group of four wavelengths comes out to be 45 ps.

Similarly, in the current configuration of 8 channel digitally tunable optical filter system, shown in Figure 1. By looking into the paths followed by each wavelength, the time delay for each wavelength between input SOA and output SOA can be written as

$$t_{\lambda_1} = t_t + t_f \tag{17}$$

$$t_{\lambda_2} = t_{r\lambda_2\lambda_1} + t_t + t_f \tag{18}$$

$$t_{\lambda_3} = t_{r\lambda_3\lambda_1} + t_{r\lambda_3\lambda_2} + t_t + t_{r\lambda_3\lambda_7} + t_f \tag{19}$$

$$t_{\lambda_4} = t_{r\lambda_4\lambda_1} + t_{r\lambda_4\lambda_2} + t_{r\lambda_4\lambda_3} + t_t + t_{r\lambda_4\lambda_8} + t_f \tag{20}$$

$$t_{\lambda_5} = t_t + t_{r\lambda_5\lambda_1} + t_f \tag{21}$$

$$t_{\lambda_6} = t_{r\lambda_6\lambda_5} + t_t + t_{r\lambda_6\lambda_2} + t_f \tag{22}$$

$$t_{\lambda_7} = t_{r\lambda_7\lambda_5} + t_{r\lambda_7\lambda_6} + t_t + t_f \tag{23}$$

$$t_{\lambda_8} = t_{r\lambda_8\lambda_5} + t_{r\lambda_8\lambda_6} + t_{r\lambda_8\lambda_7} + t_t + t_f \tag{24}$$

Now, if $t_{r\lambda_i\lambda_j} = t_t = t_f = 10\,\mathrm{ps}$ for $i = 1, 2, 3, \ldots 8$; $j = 1, 2, 3, \ldots 8$.

The delay times for the upper group of four wavelengths are $t_{\lambda_1} = 20\,\mathrm{ps}$, $t_{\lambda_2} = 30\,\mathrm{ps}$, $t_{\lambda_3} = 50\,\mathrm{ps}$ and $t_{\lambda_4} = 60\,\mathrm{ps}$. Therefore, the average delay time for the upper group of four wavelengths comes out to be 40 ps.

The delay times for the lower group of four wavelengths are $t_{\lambda_5} = 30\,\mathrm{ps}$, $t_{\lambda_6} = 40\,\mathrm{ps}$, $t_{\lambda_7} = 40\,\mathrm{ps}$ and $t_{\lambda_8} = 50\,\mathrm{ps}$. Therefore, the average delay time for the lower group of four wavelengths comes out to be 40 ps.

The disparity between average delay time in the upper and the lower group of four wavelengths is 10 ps in the previous design approach [14] and the disparity between average delay time in the upper and the lower group of four wavelengths is zero in the current design approach.

In the previous design approach [14], on an average, the lower group of four wavelengths (λ_5, λ_6, λ_7 and λ_8) were getting more delayed as compared to the upper group of four wavelengths (λ_1, λ_2, λ_3 and λ_4). So, the timing performance of the current design approach is superior to the previous design approach [14], due to design balance. This timing performance is very important in high speed optical networks.

5. CONCLUSION

A simple and novel approach to design digitally tunable optical filter system is presented. The design is easy to configure and assemble, smaller in size, lesser in weight, cheaper in cost and consumes less power. Only four SOAs are required on the output side, while the input side requires one SOA for each set of four channels, due to which, the design can be easily expanded for filtering more number of channels. The center wavelengths of the thin-film filters can be selected from the International Telecommunication Union Telecommunication (ITU-T) recommended wavelength grid for either DWDM or CWDM. The system can be used in optical networks based on any of the two techniques DWDM and CWDM. This kind of filter finds potential application in DWDM or CWDM wavelength selective switching based optical networks.

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