Progress In Electromagnetics Research Letters, Vol. 9, 93–100, 2009

NEW APPROACH TO DESIGN DIGITALLY TUNABLE OPTICAL FILTER SYSTEM FOR WAVELENGTH SELECTIVE SWITCHING BASED OPTICAL NETWORKS

A. Banerjee

Department of Electronics and Communication
Amity University
Lucknow 226010, U.P., India

Abstract—A new approach to design digitally tunable optical filter system by using semiconductor optical amplifiers (SOAs) and Dense Wavelength Division Multiplexed (D.W.D.M.) thin film filter based wavelength selection elements is presented. The system designed with this approach is very easy to configure and expand, smaller in size, lesser in weight, cheaper in cost and consuming less power as compared to design suggested by other researchers recently.

1. INTRODUCTION

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

---

Corresponding author: A. Banerjee (anirudhelectronics@yahoo.com).

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 new type of tunable optical filter design was suggested by Li et al. [13]. This digitally tunable optical filter was based on Semiconductor Optical Amplifiers (SOAs) and DWDM thin film filter based wavelength selection elements. In this system, it was possible to route desired wavelength to the output through reflection and/or transmission by thin film filters, by selecting particular SOA on-off combination. The major advantages of this system were that it was easy to configure; it was expandable; the same system was usable for whole new set of wavelengths (either DWDM or CWDM) by just changing center wavelength filters. Such design flexibility and multi utility are of great use in optical networking environment.

In this paper, a different, easier, simpler, more efficient and low cost approach is presented to design digitally tunable optical filter system by using the components and the subsystems used in reference [13]. The design not only carries all the advantages of the design suggested in reference [13], but also is easier to assemble and configure, smaller in size, lesser in weight, consuming less power and cheaper in cost.

2. SYSTEM DESCRIPTION AND WORKING

The system uses a (1 × 4) splitter, 8 two-by-two (2 × 2) wavelength-selection elements with DWDM thin-film filters for different channels, 6 SOAs, connecting fibers and 1 two-by-one (2 × 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

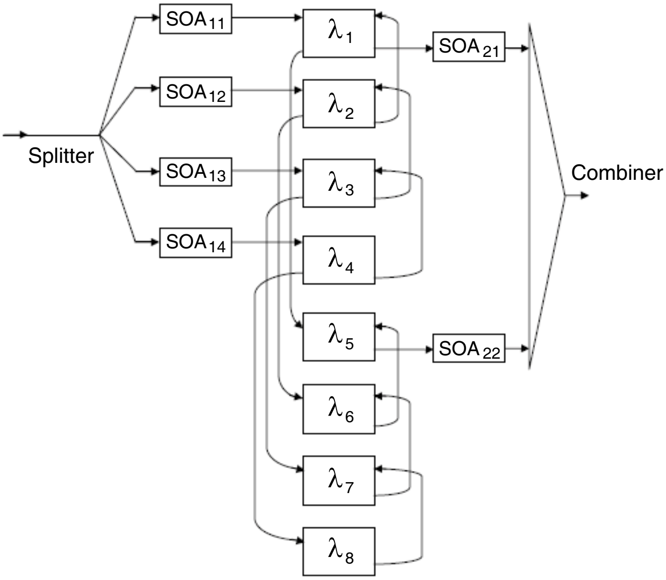

Figure 1. Configuration of 8 channel tunable optical filter system.

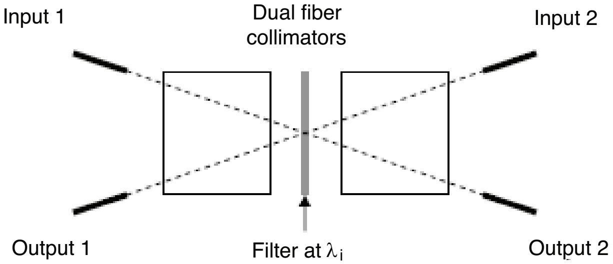

Figure 2. Structure of a 2 × 2 wavelength selection element.

opposite output port.

The input light to this system is divided into four portions via splitter, which arrive at semiconductor optical amplifiers SOA_{11}, SOA_{12}, SOA_{13} and SOA_{14}. When SOA_{11} is turned on (SOA_{12}, SOA_{13} and SOA_{14} are 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 arrive at the thin-film filter with center wavelength λ_5. SOA_{2i} $(i = 1, 2)$ will perform second selection of the wavelength. In the above case, λ_1 will arrive at the output through the 2 × 1 combiner if SOA_{21} is on and SOA_{22} is off. If in this case, SOA_{21} is off and SOA_{22} is on, then λ_5 will arrive at the output through the 2 × 1 combiner. The on-off combinations of SOAs will decide which wavelength will be routed to the output. Suppose, if only SOA_{12} and SOA_{21} are on, then λ_2 will arrive at the output after one reflection from side 2 of thin film filter with center wavelength λ_1, via 2 × 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

Table 1. SOA control combinations for filtering different wavelengths.

SOA_{11}	SOA_{12}	SOA_{13}	SOA_{14}	SOA_{21}	SOA_{22}	Selected Wavelength
1	0	0	0	1	0	λ_1
0	1	0	0	1	0	λ_2
0	0	1	0	1	0	λ_3
0	0	0	1	1	0	λ_4
1	0	0	0	0	1	λ_5
0	1	0	0	0	1	λ_6
0	0	1	0	0	1	λ_7
0	0	0	1	0	1	λ_8

below

$$
\begin{aligned}
P_{O\lambda_1} &= G_{21\lambda_1}\left(P_{i\lambda_1}G_{11\lambda_1} - P_{lt\lambda_1}\right) - P_{lc\lambda_1} \qquad (1)\\
P_{O\lambda_2} &= G_{21\lambda_2}\left(P_{i\lambda_2}G_{12\lambda_2} - \left(P_{lt\lambda_2} + P_{lr\lambda_2 viaf_1}\right)\right) - P_{lc\lambda_2} \qquad (2)\\
P_{O\lambda_3} &= G_{21\lambda_3}\left(P_{i\lambda_3}G_{13\lambda_3} - \left(P_{lt\lambda_3} + P_{lr\lambda_3 viaf_2} + P_{lr\lambda_3 viaf_1}\right)\right) - P_{lc\lambda_3} \qquad (3)\\
P_{O\lambda_4} &= G_{21\lambda_4}\left(P_{i\lambda_4}G_{14\lambda_4} - \left(P_{lt\lambda_4} + P_{lr\lambda_4 viaf_3} + P_{lr\lambda_4 viaf_2} + P_{lr\lambda_4 viaf_1}\right)\right) - P_{lc\lambda_4} \qquad (4)\\
P_{O\lambda_5} &= G_{22\lambda_5}\left(P_{i\lambda_5}G_{11\lambda_5} - \left(P_{lr\lambda_5 viaf_1} + P_{lt\lambda_5}\right)\right) - P_{lc\lambda_5} \qquad (5)\\
P_{O\lambda_6} &= G_{22\lambda_6}\left(P_{i\lambda_6}G_{12\lambda_6} - \left(P_{lr\lambda_6 viaf_2} + P_{lt\lambda_6} + P_{lr\lambda_6 viaf_5}\right)\right) - P_{lc\lambda_6} \qquad (6)\\
P_{O\lambda_7} &= G_{22\lambda_7}\left(P_{i\lambda_7}G_{13\lambda_7} - \left(P_{lr\lambda_7 viaf_3} + P_{lt\lambda_7} + P_{lr\lambda_7 viaf_6} + P_{lr\lambda_7 viaf_5}\right)\right) - P_{lc\lambda_7} \qquad (7)\\
P_{O\lambda_8} &= G_{22\lambda_8}\left(P_{i\lambda_8}G_{14\lambda_8} - \left(P_{lr\lambda_8 viaf_4} + P_{lt\lambda_8} + P_{lr\lambda_8 viaf_7}\right.\right.\\
&\qquad \left.\left. + P_{lr\lambda_8 viaf_6} + P_{lr\lambda_8 viaf_5}\right)\right) - P_{lc\lambda_8} \qquad (8)
\end{aligned}
$$

where $P_{O\lambda_j}$, $P_{i\lambda_j}$ 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. $P_{lr\lambda_j viaf_k}$ 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.

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

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

Table 2. List of center wavelengths.

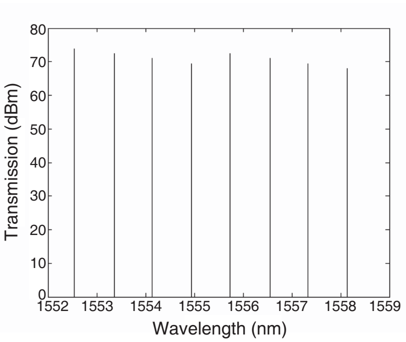

Figure 3. Transmission spectrum of the simulated system.

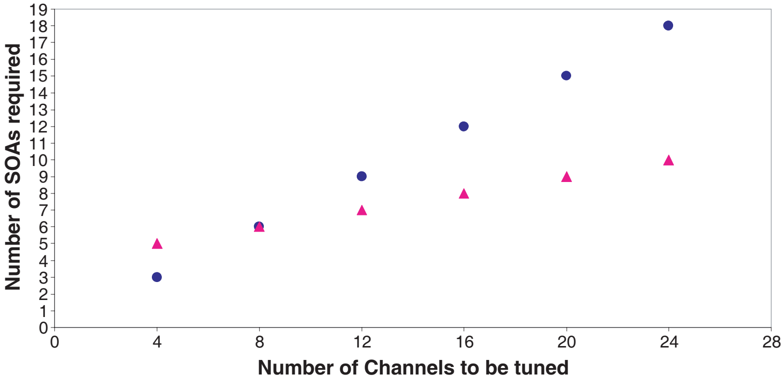

Figure 4. Comparison of systems.

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 is n, then the number of SOAs required on the input side i.e., $N_{SOAINPUT} = 4$ (fixed). Number of SOAs required on the output side is $N_{SOAOUTPUT} = n/4$. Therefore, the total number of SOAs required is given by $N_{SOATOTAL} = N_{SOAINPUT} + N_{SOAOUPUT} = (4 + n/4)$. 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 different numbers of channels to be tuned in case of reference [13], and triangles show the number of SOAs required for different numbers of channels to be tuned, in case of proposed structure. Figure 4 clearly shows that the proposed design approach requires fewer SOAs in comparison to the approach suggested in [13], for greater number of channels to be tuned. The requirement of SOAs in design suggested in [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 [13]. The proposed design can be very easily expanded to accommodate more number of channels. 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 [13] makes this system not only easy to expand, but also easy to reduce. This design also allows to subsystems in this system as a separate system, when they are not in use.

5. CONCLUSIONS

A simple and novel approach to design digitally tunable optical filter system is presented. The design is very easy to configure and assemble, smaller in size, lesser in weight, cheaper in cost and consuming less power. Only four SOAs are required on the input side, while output 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. The DWDM center wavelengths for this proposed 8 channel system are listed in Table 2. This kind of filter finds potential application in wavelength selective switching based optical networks.

ACKNOWLEDGMENT

I would like to express my heartfelt gratitude to Sri. Aseem Chauhan, Maj. Gen. K. K. Ohri, Prof. S. T. H. Abidi, Prof. N. Ram of Amity University, Lucknow for their constant encouragement and support throughout this research work.

REFERENCES

1. Brooks, D. and S. Ruschin, “Integrated electro-optic multielectrode tunable filter,” *J. Lightwave Tech.*, Vol. 13, 1508–1513, 1995.
2. Wooten, E. L., R. L. Stone, E. W. Miles, and E. M. Bradely, “Rapidly tunable narrowband wavelength filter using $LiNbO_3$ unbalanced Mach-Zehnder interferometers,” *J. Lightwave Tech.*, Vol. 14, 2530–2536, 1996.
3. Oda, K., N. Yakato, T. Kominato, and H. Toba, “A 16-channel frequency selection switch for optical FDM distribution systems,” *IEEE Journal on Selected Areas in Communications*, Vol. 8, 1132–1140, 1990.

4. Stone, J. and L. W. Stulz, "High-performance fiber Fabry-Perot filters," *Electron. Lett.*, Vol. 27, 2239–2240, 1991.
5. Born, M. and E. Wolf, *Principles of Optics*, 6th edition, Pergamon, New York, 1980.
6. Zirngibl, M., C. H. Joyner, and B. Glance, "Digitally tunable channel dropping filter/equalizer based on wave guide grating router and optical amplifier integration," *IEEE Photonics Technology Letters*, Vol. 6, 513–515, 1994.
7. Ishida, O., H. Takahashi, and Y. Inoue, "Digitally tunable optical filters using arrayed wave guide grating (AWG) multiplexers and optical switches," *J. Lightwave Tech.*, Vol. 15, 321–327, 1997.
8. Sneh, A. and K. M. Johnson, "High-speed tunable liquid crystal filter for WDM networks," *J. Lightwave Tech.*, Vol. 14, 1067–1080, 1996.
9. Chen, P. L., K. C. Lin, W. C. Chuang, Y. C. Tzeng, K. Y. Lee, and W. Y. Lee, "Analysis of a liquid crystal Fabry-Perot etalon filter: A novel model," *IEEE Photonics Technology Letters*, Vol. 9, 467–469, 1997.
10. Fujii, Y., "High-isolation polarization-independent optical circulator coupled with singlemode fibers," *J. Lightwave Tech.*, Vol. 9, 456–460, 1991.
11. Smith, D. A., J. E. Baran, J. J. Johnson, and K. W. Cheung, "Integrated-optic acoustically tunable filters for WDM networks," *IEEE Journal on Selected Areas in Communications*, Vol. 8, 1151–1159, 1990.
12. Kim, C.-S., F. N. Farokhrooz, and J. U. Kang, "Electro-optic wavelength-tunable fiber ring laser based on cascaded composite Sagnac loop filters," *Opt. Lett.*, Vol. 29, 1677–1679, 2004.
13. Li, X., J. Chen, G. Wu, and A. Ye, "Digitally tunable optical filter based on DWDM thin film filters and semiconductor optical amplifiers," *Optics Express*, Vol. 13, 1346–1350, 2005.