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DESIGN OF LATTICE FORM OPTICAL DELAY LINE STRUCTURE FOR MICROWAVE BAND PASS FILTER APPLICATIONS

P. Prakash and M. Ganesh Madhan*

Department of Electronics Engineering, MIT Campus, Anna University, Chennai, India

Abstract—The design of a multi-channel ($M = 5$) lattice form band pass optical delay line filter is reported. The filter synthesis is based on the division of total transfer function into unit blocks and the circuit parameters are obtained by constrained least square method. This band pass filter has better performance compared with the results obtained in the conventional design techniques. For a filter of order 35, a stop band attenuation greater than 50 dB is achieved. Further, the band pass filter is introduced in a optical fiber link and simulated in Optisystem software, to verify its characteristics.

1. INTRODUCTION

Digital filters such as finite-impulse response (FIR) and Infinite-impulse response (IIR) are well known from the digital signal processing applications. These filters consist of delay elements, weighting factors and adders. Similar filters can be realized using fiber optic components due to their periodic transfer function, which is used for filtering several adjacent channels simultaneously [1, 2].

In recent times, optical delay line filters are finding increased application in optical processing of microwave and RF signals [3–5]. These filters offer several channels of phase shifted bandpass transmission simultaneously. The design of 1×3, 3×3 filters have already been proposed in the literature [6, 7]. In these design techniques, the passbands of the filter were found to be nonoverlapping and the delay time was about 0.01 ns which corresponds to the free

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* Corresponding author: Muthu Ganesh Madhan (mganesh@annauniv.edu).

spectral range (FSR) of 100 GHz. The number of stages used in the 1×3 filter design is 21. The 3×3 filter is designed with a circuit, which consists of two ports of lattice structures that respectively, consist of N and two stages of 3×3 directional couplers linked by differential delay lines. By choosing differential delay lines in the lattice structures, the resultant filter is capable of producing three channels of $2\pi/3$ phase-shifted interleaved transmissions.

Jinguji and Yasui [8] in their work, have designed a $1 \times M$ ($M \geq 2$) optical lattice filter with a $M \times M$ diagonal delay circuit with a modified inverse discrete Fourier transform. The synthesis algorithm was based on polyphase decomposition with $N = 39$ and 1 dB bandwidth of the pass band was about 0.16 FSR and attenuation of stopband was greater than 28 dB.

Azam et al. [9] have proposed a synthesis algorithm of a multichannel lattice form optical delay line circuit. The method consists of $1 \times M$ optical delay line circuit which offers same characteristics as $1 \times M$ FIR digital filter.

In this paper, a 1×5 lattice form band pass optical delay line filter is proposed to meet the multi-channel bandpass filter characteristics. The circuit is composed of directional couplers and phase shifters. The synthesis algorithm is based on the division of total transfer function into unit blocks and the circuit parameters are obtained by constrained least square method. This algorithm increases the speed of execution and improves the numerical accuracy of the result and does not require transition band region and it is globally concave. The scheme proposed in this work greatly reduces the computational complexity and improves the performance of the interlever. The main advantage of this method is that it can be used to design the band pass filter without specifying the transition regions.

2. CIRCUIT CONFIGURATION

The circuit configuration of (1×5) lattice form $(M = 5)$ lattice form band pass optical delay line filter is presented in this section. Figure 1 shows the circuit configuration of a 1×5 lattice form band pass optical delay line filter. The circuit consists of M waveguides, $(M-1) \times (N+1)$ directional couplers, $(M-1) \times (N+1)$ phase shifters and an external phase shifter φ_{ex}. The delay line with delay time is shown in the first waveguide. The time difference $\Delta\tau$ is maintained by the wave guide present in the first path. In each block, there are $(M-1)$ directional couplers, $(M-1)$ phase shifters and one delay line.

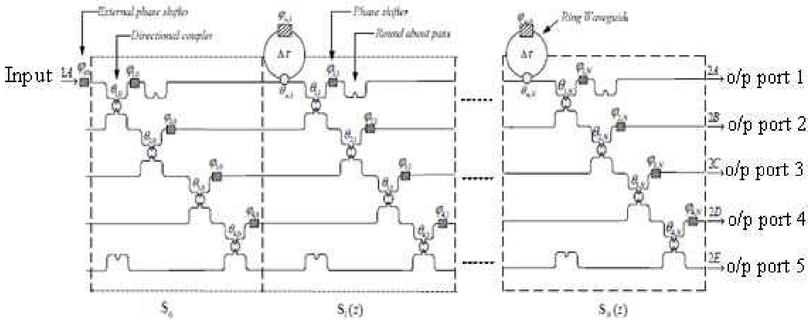


Figure 1. Circuit configuration of a 1×5 lattice form band pass optical delay line filter.

3. SYNTHESIS ALGORITHM

The synthesis algorithm is mainly used to calculate the unknown parameters like optimum coefficients a_k, b_k, c_k $(k = 0 \sim N)$, coupling coefficient angles θ_{ka}, $\theta_{kb}\,(k = 0 \sim N)$, phase shift values ϕ_{ka}, ϕ_{kb} $(k = 0 \sim N)$ and one external phase shifter [9, 11]. The steps involved in this synthesis algorithm are given below:

Step 1. The initial step is to get the constant delay time difference $\Delta\tau$ from desired periodic frequency f_0. It is calculated by $\Delta\tau = 1/f_0$.

Step 2. Obtain the approximate optimum coefficients a_k, b_k and c_k using constrained linear least square method.

Step 3. Calculate the transfer function of each block and derive the equations to obtain the coupling coefficient angles of directional couplers and phase shift angles of phase shifters. The recursion equations can be obtained by factorizing the total transfer matrix $S(z)$. Transfer matrix $S(z)$ can be decomposed into the following form:

$$S_k(Z) = S_d S_{ca} S_{pa} S_{cb} S_{pb} \tag{1}$$

$S_k(z)$ is obtained by multiplying the transfer functions of all basic components.

$$S_l(Z) = \begin{pmatrix} \cos\theta_{lA} e^{-j\varphi_{lA}} z^{-1} & -j\sin\theta_{lA} e^{-j\varphi_{lA}} & 0 \\ -j\sin\theta_{lA}\cos\theta_{lB} e^{-j\varphi_{lB}} z^{-1} & \cos\theta_{lA}\cos\theta_{lB} e^{-j\varphi_{lB}} & -j\sin\theta_{lA}\sin\theta_{lB} z^{-1} \\ -\sin\theta_{lA}\sin\theta_{lB} z^{-1} & -j\cos\theta_{lA}\sin\theta_{lB} & \cos\theta_{lB} \end{pmatrix} \tag{2}$$

The following expressions are used to find the circuit parameters and the Equation (3) is used to find the coupling coefficient and phase shift

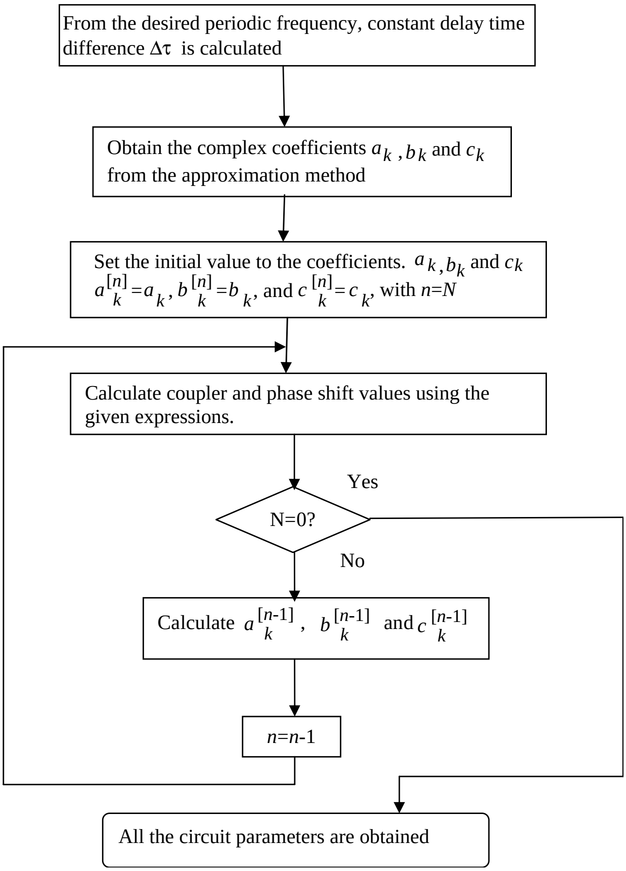


Figure 2. Flowchart of the algorithm.

values of the delay line filter.

$$\begin{cases} a_k^{[n-1]} = \left(a_{k+1}^{[n]} \cos\theta_{na} e^{j\varphi_{na}} + jb_{k+1}^{[n]} \sin\theta_{na} \cos_{nb} e^{j\varphi_{nb}} - c_{k+1}^{[n]} \sin\theta_{na} \sin\theta_{nb}\right) \\ b_k^{[n-1]} = \left(ja_k^{[n]} \sin\theta_{na} e^{j\varphi_{na}} + b_k^{[n]} \cos\theta_{na} \cos_{nb} e^{j\varphi_{nb}} + jc_k^{[n]} \cos\theta_{na} \sin\theta_{nb}\right) \\ c_k^{[n-1]} = \left(jb_k^{[n]} \sin\theta_{nb} e^{j\varphi_{nb}} + c_k^{[n]} \cos\theta_{nb}\right) \end{cases} \tag{3}$$

$$\begin{cases} \varphi_{nB} = \arg\left(\frac{jc_n^{[n]}}{b_n^{[n]}}\right) \\ \theta_{nB} = \tan^{-1}\left(\frac{jc_n^{[n]} e^{-j\varphi_{nB}}}{b_n^{[n]}}\right) \\ \varphi_{nA} = \arg\left\{\frac{\left(jb_n^{[n]} \cos\theta_{nB} e^{j\varphi_{nB}} - c_n^{[n]} \sin\theta_{nB}\right)}{a_n^{[n]}}\right\} \\ \theta_{nA} = \tan^{-1}\left\{\frac{\left(jb_n^{[n]} \cos\theta_{nB} e^{j\varphi_{nB}} - c_n^{[n]} \sin\theta_{nB}\right) e^{-j\varphi_{nA}}}{a_n^{[n]}}\right\} \end{cases} \tag{4}$$

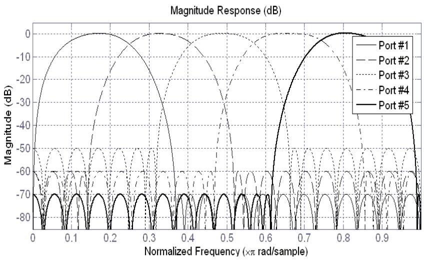


Figure 3. Magnitude response of 1×5 band pass optical delay line filter.

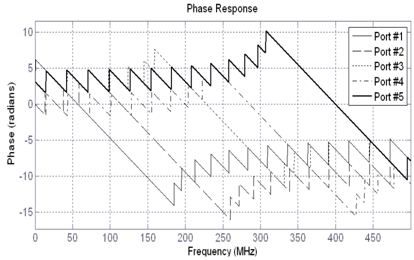


Figure 4. Phase response of 1×5 band pass optical delay line filter.

Figure 2 shows the flowchart of various steps involved in the synthesis algorithm.

4. DESIGN EXAMPLE

In this design example, delay time is set to 0.2 ns, which corresponds to the free spectral range of 5 GHz. The number of expansion coefficients is set at 35. The wavelength of operation is fixed as 1550 nm and the delay time is calculated accordingly [8]. The center frequency of the mth passband is shifted by $2\pi(m-1)/(M\Delta\tau)$, where $\Delta\tau$ is the unit delay time (the FSR corresponds to $1/\Delta\tau$). The constrained least square algorithm [10] is used to synthesize a $M = 5$ lattice form band pass optical delay line filter and the various parameters are calculated. Table 1 shows the calculated circuit parameters of coupling coefficient angles of directional couplers and the phase shift values of the phase shifters (θ_{nA}, θ_{nB}, φ_{nA} and φ_{nB}) with number of stages $k = 35$.

5. RESULTS AND DISCUSSION

The magnitude and phase response of the 1×5 lattice form band pass optical delay line filter are shown in Figures 3 and 4 respectively. The response obtained in Figure 3 shows the 0 dB at the center frequency of each band while the stop band attenuation is less than 50 dB. The maximum number of stages used to design this multi-channel filter (1×5) is 35 ($k = 35$), which is less than that reported by Azam et al. [9], where an order of 39 is registered to realize a stop band attenuation of 26 dB.

Figure 4 shows the phase response of 1×5 lattice form band pass optical delay line filter. The variation of 3 dB bandwidth for different output ports are shown in Figure 5. The 3 dB bandwidth obtained from the filter shows almost constant bandwidth of 65 MHz for all

Table 1. Expansion coefficients and calculated circuit parameters of a 1×5 optical filter.

Stage number	Expansion coefficients (a_k)	Expansion coefficients (b_k)	Expansion coefficients (c_k)	Coupling coefficient angle (θ_{nA})	Coupling coefficient angle (θ_{nB})	Phase shift value (φ_{nA})	Phase shift value (φ_{nB})
1	0.0051	0.0033	−0.00008	−0.8151	−2.1547	2.103	1.4827
2	0.0096	0.0070	−0.00007	1.9263	0.4278	2.453	1.0261
3	0.0112	0.0041	−0.0063	1.2273	2.3870	1.563	1.6732
4	0.0059	−0.0082	−0.0077	0.6553	−1.1882	0.826	3.0837
5	−0.0058	−0.00193	0.0098	0.2978	0.5217	0.386	0.9065
6	−0.0173	−0.0145	0.0251	−0.9982	−2.2846	27.00	1.3381
7	−0.0192	0.0034	0.0040	−1.4922	0.6544	1.238	0.7376
8	−0.0095	0.0127	−0.0270	−1.6976	0.9787	0.981	0.3247
9	0.00009	0.0036	−0.0173	0.3365	−1.2914	0.428	0.0735
10	−0.0067	0.00001	0.0038	0.5082	−1.3108	0.658	3.2397
11	−0.0424	0.0287	−0.0139	1.7160	−2.1955	2.191	10.641
12	−0.0920	0.0642	−0.0095	−0.5587	−1.9118	2.440	0.8634
13	−0.1184	0.0401	0.0729	1.5552	0.4311	1.960	1.0220
14	−0.0858	−0.0635	0.0976	−1.8258	0.4560	0.806	4.1318
15	0.0109	−0.1605	−0.0610	1.5154	−2.0173	0.121	0.9978
16	0.1333	−0.1308	−0.2059	−2.2701	0.5934	3.396	0.8153
17	0.2184	0.0348	−0.0670	1.8382	−2.4250	21.12	1.5169
18	0.2184	0.1947	0.2016	1.8382	2.4250	21.12	1.5169
19	0.1333	0.1947	−0.0670	−2.2701	0.5934	3.396	0.8153
20	0.0109	0.0348	−0.2059	1.5754	−2.0173	0.121	0.9978
21	−0.0858	−0.1308	−0.0610	−1.8258	0.4560	0.806	4.1318
22	−0.1184	−0.1605	0.0976	1.5552	0.4311	1.960	1.0220
23	−0.0920	−0.0635	0.0729	−0.5587	−1.9118	2.440	0.8634
24	−0.0424	0.0401	−0.0095	1.7160	−2.1955	2.191	10.649
25	−0.0067	0.0642	−0.0139	0.5082	−1.3108	0.658	3.2397
26	0.00009	0.0287	0.0038	1.7160	−1.2914	0.428	0.0735
27	−0.0095	0.00001	−0.0173	0.5082	0.9787	0.981	0.3247
28	−0.0192	0.0036	−0.0270	0.3365	0.6544	1.238	0.7376
29	−0.0173	0.0127	0.0040	−1.6976	−2.2846	27.00	1.3381
30	−0.0058	0.0034	0.0251	−1.4922	0.5217	0.386	0.9065
31	0.0059	−0.0145	0.0098	−0.9982	−1.1882	0.826	3.0837
32	0.0112	−0.0193	−0.0077	0.2978	2.3870	1.565	1.6732
33	0.0096	−0.0082	−0.0063	0.6553	0.4278	2.453	1.026
34	0.0051	0.0041	−0.0007	1.2273	−2.1547	2.103	148.82
35	0.0015	0.0070	−0.0008	1.9263	1.1350	1.430	6.4088

the output ports. The variation of stopband attenuation for centre frequency of different output ports is presented in Figure 6. The stopband attenuation shows a periodic variation with the maximum attenuation of 70 dB for the first and last output ports; however the minimum stopband attenuation is around 50 dB for the center band.

A system level simulation of an optical link is carried out using Optisystem software to verify the characteristics of the microwave band

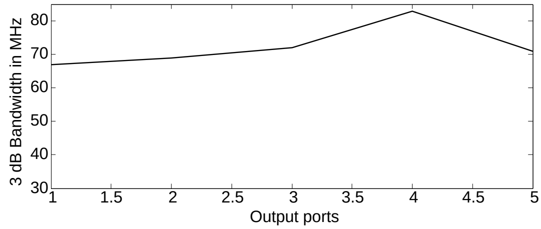


Figure 5. Variation of 3 dB bandwidth for different output ports.

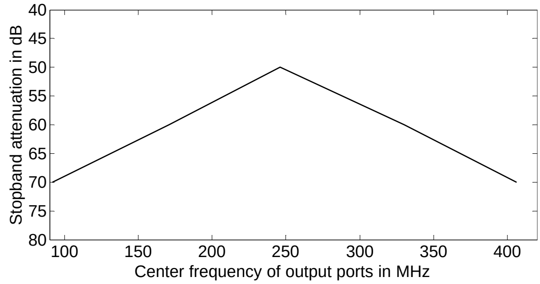


Figure 6. Variation of stopband attenuation for centre frequency of different output ports.

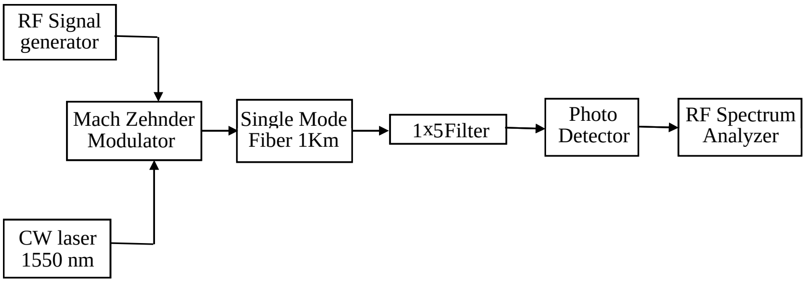
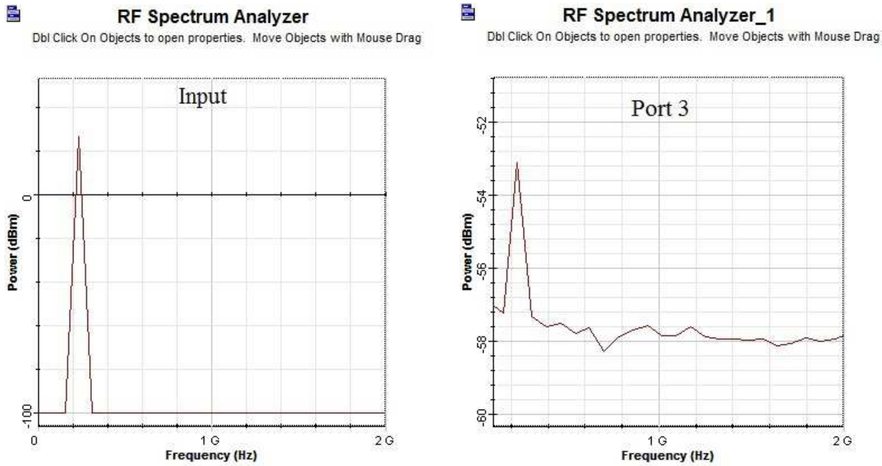


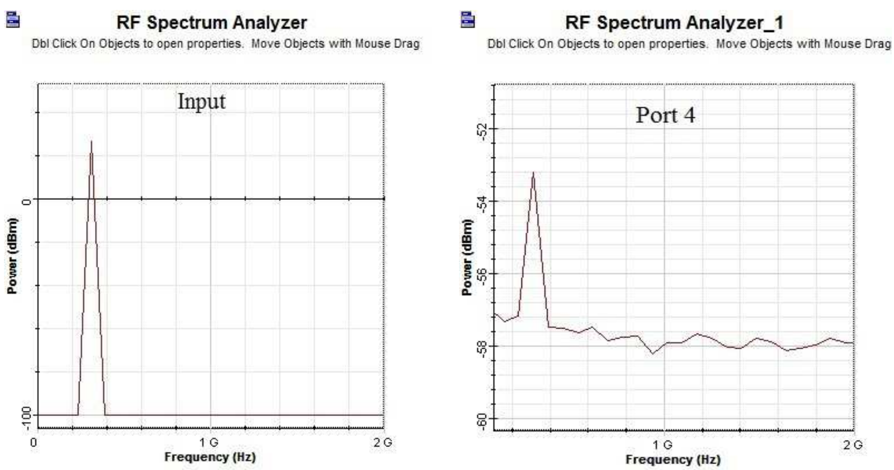
Figure 7. System simulation of optical link with bandpass filter.

pass filter. The system comprises of a 1550 nm Laser diode and a Mach Zehnder external modulator, driven by a RF signal source. The optical filter output is fed to a photodetector and a RF spectrum analyzer. A RF amplifier is also added to the photo detector to provide an amplified RF signal. The RF modulated optical signal is passed through the delay line filter, implemented in MATLAB, through a co-simulation option available in Optisystem software. The entire block diagram is shown in Figure 7. The input RF signal spectrum of a 246 MHz RF signal and the corresponding output is shown in Figures 8(a) and



(a) (b)

Figure 8. Results obtained using system simulation (a) input and (b) output spectrum for port 3.



(a) (b)

Figure 9. Results obtained using system simulation (a) input and (b) output spectrum for port 4.

(b) respectively. The output is available only in the port 3, which corresponds to that centre frequency (246 MHz). The other ports showed no output. The simulation is also repeated for 330 MHz centre frequency and output showed the desired response [Figures 9(a) (b)].

6. CONCLUSION

The design of lattice form multi-channel ($M = 5$) optical delay line filter is proposed in this paper. The design approaches the similar filter characteristics of the digital FIR filter. An algorithm for synthesizing the multichannel optical delay line is also derived. Constrained least square method is used to obtain the circuit parameters which have less number of complexities compared to the set of recursion equations. This proposed algorithm has been tested with an example. It is observed that the maximum number of stages used to design the multi-channel filter is 35. It is found that the lattice form multi-channel optical delay line filter can be mostly used in all microwave applications. The performance of the designed filter is also verified in a optical fiber link, using Optisystem simulation software.

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