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Synthesis of Optical Band-pass Chebyshev Filters

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Abstract:

Optical filters play a significant part in optical signal processing and communications systems. A systematic procedure for synthesising bandpass optical filters of Chebyshev types is described. Proposed structures for these filters in cascade or parallel forms are given using optical resonators exhibiting a single zero and single pole transfer function in the z-domain and a quasi all-pole and all-zero optical circuits are described for implementation of the synthesised filter functions.

1 INTRODUCTION

Recently optical filters and equalisers are attracting great interest due to the extension of the repeaterless transmission distance and their applications in wavelength division multiplexing systems and networks[1-2]. However only Butterworth-type optical filters have been considered[1][6].

In filters design, the Chebyshev types are also very important because it would generate a better filter passband and much improved stability of the filtering systems. In practice it is very often that the filter characteristics are specified and the designer has to tailor the optical filters accordingly. Several works have been published on the analysis of a certain type of optical configurations and from the characteristics obtained, some filters are proposed[3-4]. Thus there is an urgent need to develop a systematic procedure to synthesise optical filters from practical devices which are available in research laboratory and implemented devices.

This paper describes a synthesis for optical filters based on the digital filter technique following the requirement of a Chebyshev filter type. The problem background and an algorithm for synthesising the filters are given in Section 2. The transfer functions for these filters derived and described in Section 3 which are expressed in cascade and parallel forms as the fundamental structures for implementation of the filters. Essential optical components are analysed in Section 4 in which two optical resonators and an optical interferometer are described. In one resonator a 3x3 optical directional coupler is employed with two feedback back paths, one direct connection and the other with single or multiple order optical delay to obtain an optical transfer function having non-zero roots in both its numerator and denominator. The other resonator employs two 2x2 optical directional couplers and only one feedback path[1] to obtain an optical transfer having non-zero roots in the denominator. Optical implementation for the Chebyshev filters are proposed. in Section 5. Conclusions and properties of the Chebyshev filters are given in the last section.

2 Chebyshev Optical filter specification and synthesis algorithm

Optical filters can have the characteristics of all basic filter characteristics of several types such as low pass, high pass and band pass. The low pass filter is the fundamental filter and design algorithm is based on the design of this filter plus a further transformation such as bilinear transformation[5][7]. In this section the low pass type of Chebyshev filters is given then followed by an algorithm to develop band pass optical filters.

2.1 Basic characteristics of Chebyshev lowpass filters

Bandpass Chebyshev optical filters can be designed by transforming the characteristics of a low pass type which is given by [5]:

$$|H(\omega^2)|^2 = \frac{1}{1+\varepsilon^2 C_n^2(\omega)} \tag{1}$$

where ω is the optical frequency, $C_n(\omega)$ is the n^{th} order Chebyshev polynomial and ε < 1 is a real constant and specifies the amplitude of the ripple of the transfer function in the passband. Thus the n^{th} order Chebyshev polynomial is obtained as[5]

$$C_n(\omega) = \cos(n.\cos^{-1}\omega) \qquad \text{if } |\omega| < 1 \tag{2}$$

and

$$C_n(\omega) = \cosh(n.\cosh^{-1}\omega) \qquad \text{if } |\omega| > 1 \tag{3}$$

2.2 Chebyshev-type optical bandpass filter specification

A typical specification for photonic bandpass filter in the wavelength domain is shown in Figure 1 where λ_c is the centre wavelength, λ_l is the lower wavelength, λ_u upper wavelength and λ_{st} the stopband wavelength . Rp is the ripple of the pass band which is normally specified in dB. Rp corresponds to the parameter ε of (1) and Rs (in dB) is the overall transfer magnitude of the transfer function. Once the filter characteristics are specified the following steps are used to obtain the filter transfer function in the z-domain so that the filter hardware can be implemented. The z-domain is used for convenience in analysis and synthesis. Our algorithm is applicable in bot analog and digital domain. The z parameter is defined as usual as z = exp(jωT) = exp(jβL) where T in the sampling period and b is the propagation constant of the lightwaves and L is the optical delay length corresponding to T.

• Step 1: Converting the optical wavelengths to frequency domain from the above specification. This can be achieved by using $f = c/n\lambda$ with $n \approx 1.5$ for optical silica fibre, c is the speed of light in vacuum. This would give the optical frequencies f_c, f_u, f_l, f_{st} corresponding to the optical wavelengths at the centre, upper, lower and stop band of the filter as specified above.

• Step 2 : Choosing a sampling frequency to normalise and compute analog pre warped frequency. The Nyquist sampling rate is *2fc* for the narrow band-pass filter, then choosing sampling rate: fs=4fc to normalise for desired digital filter for each specified frequency by using $\theta = 2\pi f/f_s$, thus the pre warped analog frequencies θ_c, θ_l , θ_u , θ_{st} can be calculated.

• Step 3**:** Converting pre warped band-pass frequencies to equivalent low-pass by using

$$\omega_{Lp} = \frac{\omega_{Bp}{}^2 - \omega_0{}^2}{B\omega_{Bp}} \tag{3}$$

where the ω_{LP} and ω_{BP} denote the optical frequency for the lowpass and bandpass filters respectively. B is the optical 3-dB bandwidth of the transfer function and ω_o is the centre optical frequency of the filter. The bandpass ripple is Rp (in dB), it thus corresponds to $-10\log_{10}\frac{1}{1+\varepsilon^2} = Rp$. At the specified stopband if the maximum gain or loss is Rs (dB) we have

$$\left|H(j\omega)\right|^2 = \frac{1}{1+\varepsilon^2 Cn^2(\omega)} \le 10^{-\frac{Rs}{10}} \quad \Rightarrow Cn(\omega) = \left[\frac{\left(10^{\frac{Rs}{10}} - 1\right)}{\varepsilon^2}\right]^{1/2} \tag{4}$$

Since $\omega = \omega_{stLp} \rangle 1$, from (1) we have

$$C_n(\omega) = Cosh\left(nCosh^{-1}(\omega)\right) \qquad \Rightarrow n >= \left.\frac{Cosh^{-1}\left[Cn(\omega)\right]}{Cosh^{-1}(\omega)}\right|_{\omega=\omega_{stLp}} \tag{5}$$

(5) thus gives the order of the filter which is then chosen to be upper most nearest integer.

- Step 4: Obtaining the lowpass prototype transfer function corresponding to the defined filter order n above. This transfer function is then normalised such that H(j0) = 1. Transforming this lowpass transfer function back to band-pass filter by using $s = \frac{s^2 + \omega_0^2}{Bs}$ where s is defined as jω. We then obtain a **2n** order Chebychev analog band-pass filter transfer function

$$H_{Bp}(s) = H_{Lp}(s)\Big|_{s=\frac{s^2+\omega_0^2}{Bs}} \tag{6}$$

- Step 5: Applying the bilinear transformation to obtain required digital filter transfer function

$$H_{Bp}(z) = H_{Lp}(z)\Big|_{s=\frac{z-1}{z+1}} \tag{7}$$

where the z variable denotes the z transform of the transfer function. After this process converting the digital response to the optical wave length domain.

- Step 6: From this transfer function, the optical system consisting resonators using optical components, in particular resonators, interferometers, etc.[1]

2.3 Illustration of a Chebyshev bandpass optical filter

For sharper roll-off attenuation at stop band frequencies, one must require a higher order band pass filter or more hardware devices in implementation. In this work, an example is given for synthesising a sixth-order Chebychev band-pass filter (that is, a third-order low-pass is designed in the first step) for an arbitrary centre frequency in the useful optical frequency range. In present silica based optical fibre communications then the second and third windows at 1300 and 1550 nm respectively, are the working regions. Supposing that we want to synthesise an optical Chebyshev bandpass filter with the following specification :

Centre wave-length : 1310nm

Lower cut-off wave length : 1308nm

Upper cut-off wave length : 1312nm

Lower stop band wavelength : 1302nm

with a passband ripple of 1.0 dB and a -40 dB stopband.

It is can be shown easily by using equations (1) - (9) that for a sixth order Chebyshev bandpass filter the required transfer function is given by:

$$H_{BP}(z^{-1}) = \frac{-6.792372e-9(1-z^{-2})^3}{1+3.004723z^{-2}+3.009475z^{-4}+1.004752z^{-6}} \quad (8)$$

The magnitude and phase responses of the synthesised Chebyshev bandpass filter according to the above stringent specification is shown in Figure 2(a)-(b) and the poles and zeros positions are plotted in the z-plane as shown in Figure 2(c). This function can be decomposed into a sum of fractions or a multiplier of a number of subsystems which exhibit only a single root in the numerator or denominator. However if the roots are complex conjugate then the order of the subsystem can be quadratic. The partitioning of the transfer function is described in Section 5. In the Section 3 essential optical components for implementing this transfer function are given.

3 OPTICAL COMPONENTS FOR DESIGNING CHEBYSHEV FILTERS

Chebyshev filters can be implemented by using the single pole single zero resonator (SPSZR) which is formed by using a [3x3] optical directional coupler with a planar cross section and two optical feedback paths connecting two outputs to two inputs of the coupler. This type of resonator has been described in detail in another article[6], we outline very briefly its main characteristics for the sake of clarity. Further an all-pole and an all-zero optical circuits (APOC and AZOC) which are required for implementation of the filters are described.

3.1 The SPSZR

For a planar [3x3] optical directional coupler whose schematic diagram and its signal flow graph are shown in Figures 3(a)-(b) respectively, with a direct (or the order of the delay path is zero) shunt feedback from output port 3 to input port 3, the output-input transfer function is given as:

$$\frac{E_1(d)}{E_1(0)} = \frac{-\frac{1}{2}\sqrt{t_{1k}}e^{j\phi_{1k}}z^{-1} - \frac{1}{2}\sqrt{t_{2k}}e^{j\phi_{2k}} + \frac{1}{2}\sqrt{t_{1k}t_{2k}}e^{j(\phi_{1k}+\phi_{2k})}z^{-1}}{(1-\frac{1}{2}\sqrt{t_{2k}}e^{j\phi_{2k}})(1-\frac{1}{2}\sqrt{t_{1k}}e^{j\phi_{1k}}z^{-1})} \qquad (9)$$

where $E_1(d)$ and $E_1(0)$ are the optical field of the lightwaves at the output and input ports respectively. t_{1k} and t_{2k} are the intensity transmission coefficients in paths 1 and 2. ϕ_{1k} and ϕ_{2k} are the incorporated optical phase modulation in appropriate paths. The coefficients x_{ij} (i,j = 1,2,3) in Figure 3(b) are the coupling coefficient of the 3x3 coupler matrix. It is assumed that the 3x3 coupler has a planar cross section[3] with a coupling length d and a factor kd $=\pi\sqrt{2}\,\sqrt{2}/4$.

It can be easily seen that eqn.(9) has only one pole and one zero. Therefore the pole and zero can be independently adjusted by adjusting the coefficients t_{ik} and ϕ_{ik}, i.e. attenuators, optical amplifiers or optical phase modulators incorporated in the feedback paths. In designing optical Chebyshev filters the transfer function (9) can provide an arbitrary pair of pole-zero denoted by (a,b) given by the roots of its numerator and denominator as

$$a = \frac{1}{2}\sqrt{t_{1k}}e^{j\phi_{1k}} \qquad (10)$$

or $$\sqrt{t_{1k}}e^{j\phi_{1k}} = 2a \qquad (11)$$

or alternatively $$\sqrt{t_{2k}}e^{j\phi_{2k}} = -\frac{ab^{-1}}{0.5-ab^{-1}} \qquad (12)$$

with this set of chosen parameters, the transfer function in (9) becomes

$$\frac{E_1(d)}{E_1(0)} = \frac{\frac{ab^{-1}}{1-2ab^{-1}}(1-bz^{-1})}{(1-\frac{ab^{-1}}{1-2ab^{-1}})(1-az^{-1})} \qquad (13)$$

Again eqn.(13) clearly demonstrates that the resonator would exhibit only one pole and one zero which can be independently adjusted with each other. The gain of the transfer function is dependent on these values of the pole and zero. However this amplitude gain or loss can be compensated by an in-line optical amplifier.

The circuit of Figure 3(a) can be observed to exhibit only one pole due to the fact that there is only one loop with a single delay line in the graph. According to Mason's rule the number of poles is the roots of the graph determinant. The graph determinant order is the order of delay of the optical loop. Thus there is only one delay in the loop there must be only one pole.

The number of zeros of the resonator depends on the number of non-touching loops of the optical circuit. In this case there are two loops in this resonator and they are non touching, but only one unit delay in one loop, thus this ensures that the order of the numerator is one. It is therefore concluded that this identification of the double feedback optical resonator leads to implementation of an optical transfer function having a pole and zero pair. We can thus name this type of optical resonance circuit as the single-pole single zero resonator (SPSZR).

Since the SPSZR is the core component for designing Chebyshev optical filters, it is necessary to examine closely the feasibility of a direct optical feedback from the output to the input of the [3x3] optical coupler. This type of delay is termed as the delay-free feedback and thus a delay-free loop is formed at the upper part of Figure 3(a)-(b)[8]. It is stated in Ref.[8] that the necessary and sufficient condition for the signal flow graph of the structure to be computable for a digital filter is that there is no delay-free loop. We must make very clear here that the direct connecting shunt feedback path from the output port 3 to the input port 3 is extremely smaller than the delay of the other loop. Furthermore that direct connection loop is not operating under resonance at the operating wavelength. It is thus reasonable to assume that this loop does not have the same meaning as the delay-free loop defined in Ref.[8]. This ensures that our derivation for the transfer function (9) is valid. In practice, the delay path of the lower loop is much greater than that of the direct loop and that of the coupling length of the 3x3 directional coupler.

3.2 The APOC

Besides the SPSZR optical circuit described above, there must be optical circuits or components that exhibit a pole (or higher order multiple poles) characteristics so that it could form a set of optical components with the SPSZR to simulate the filter structure. The APOC is in fact an optical resonator using two 2x2 optical couplers with an optical feedback from the output of the second coupler to the input of the first coupler[1]. The schematic diagram of the APOC is given in Figures 4. The transmission coefficients are denoted as t_{ip} (i =1,2) with p and z denoting the all-pole or all-zero, .and the phases of each optical paths as γ.

The transfer function of the APOC with a first order delay in the feedback path can be obtained by using the graphical method[1] as :

$$H_{ap}(z^{-1}) = \frac{E_7}{E_1} = \frac{\sqrt{(1-k_1)(1-k_2)t_{1z}}\,e^{j\varphi_1}}{1+\sqrt{t_{1z}t_{2z}k_1k_2}\,e^{j(\varphi_{21}+\varphi_{11})}z^{-1}} \quad (14)$$

Thus the transfer function has a zero at origin and a pole at

$$z = -\sqrt{t_{1z}t_{2z}k_1k_2}\,e^{j(\phi_1+\phi_2)} \quad (15)$$

Thus this APOC is a quasi all-pole optical circuit, that is, the zero at the origin can be cancelled by an other optical circuit which would have a finite zero and a pole at the origin such as the AZOC to be considered next.

3.3 The AZOC

The AZOC is in fact an optical interferometer which has been studied in detail in [1]. The schematic diagram of the AZOC is shown in Figure . The transmission coefficients are denoted as t_{ip} or t_{iz} (i =1,2) with z denoting the all-zero type, .and the phases of each optical paths as γ and ψ. The transfer functions of the AZOC and its zero position are given in eqns.(16) and (17) respectively

$$H_{az}(z^{-1}) = \frac{E_{7p}}{E_{1p}}(z^{-1}) = \sqrt{(1-k_1)(1-k_2)t_{1p}}\,e^{j\gamma_1} - \sqrt{k_1k_2t_{2p}}\,e^{j\gamma_2}z^{-1} \quad (16)$$

which has one pole at the origin, p = 0 and one zero at

$$z = \sqrt{\frac{k_1k_2t_{2p}}{(1-k_1)(1-k_2)t_{1p}}}\,e^{j(\gamma_1-\gamma_2)} \quad (17)$$

Although the transfer function (16) of the AZOC contains a pole, it is at the origin in the z-plane. Thus the position of the zero can be changed to suit the needs for the design of optical systems. It is thus a quasi all-zero optical circuit.

It is interesting to note that if an APOC and an AZOC of the same order are cascaded then the overall transfer function exhibit a numerator and denominator of the same pole and zero order because the poles and zeros at the origin cancel each other. This is considered for implementing the Chebyshev filters in the next section.

4 Realisation of the Chebyshev optical bandpass filters:

In realising the optical filters of Chebyshev type there are two structures which can perform the same filtering functions, namely, the cascaded and the parallel types. The difference between these two types is that one is in tandem and one in parallel combination of each modular optical block. Ideally each modular optical block must have a single pole and single zero in its transfer function[8]. Two designs for the Chebyshev filters are considered in this section. One uses a combination of the SPSZRs and the APOC, called Chebyshev Optical Filter-type 1 (COF1) and the other combining the APOCs and AZOCs, called Chebyshev Optical Filter type 2 (COF2).

4.1 The COF1

4.1.1 Cascaded form Chebyshev filters

From the transfer function obtained above the design system should provide the following system of poles and zeros :

5 zeros at :

z1 = -1.00567002 + j0.0000, z2 = -0.99716505 + j0.0048946, z3 = -0.99761605 - j0.0048946, z4 = 1.00339252 + j0.0000, z5 = 0.99830373 + j0.00294813, z6 = 0.99830373 - j0.00294813

and 6 poles at :

p1 = -0.00000367 + j1.00118581, p2 = -0.00000367 - j1.00118581, p3 = 0.00231434 + j1.00059005, p4 = 0.00231434 - j1.00059005, p5 = -0.00232166 + j1.00059003, p6 = -0.00232166 - j1.00059003.

The poles are very closed to the unit circle, thus the system is marginally stable. However there are also equal number of zeros on the unit circle and clustered around the poles. This would generate a stable system as we can observed from the optical response in Figure 2(a). The poles and zeros of the systems are plotted in the z-plane as shown in Figure 2(c). The phase of the systems shown in Figure 2(b) indicate a quasi linear phase inside the optical passband. The poles and zeros are complex pole pairs.

The filter with the above system of poles and zeros can be implemented by cascading six SPSZR with the chosen parameters shown in the Table 1 :

SPSZR1	t11 = 4.009492	t21 = 0.800381366	ϕ11= 1.570799992	ϕ21 = 0.463174471	p = p1	z = -1

SPSZR2	t12 = 4.009492	t22 = 0.800381366	ϕ12 = -1.570799992	ϕ22 = 0.463174471	p = p2	z = 1
SPSZR3	t13 = 4.004721	t23 = 0.798711128	ϕ13 = 1.568483356	ϕ23 = 0.462948918	p = p3	z = -1
SPSZR4	t14 = 4.004721	t24 = 0.798711128	ϕ14 = -1.568483356	ϕ24 = 0.462948918	p = p4	z = 1
SPSZR5	t15 = 4.004743	t25 = 0.801677094	ϕ14 = 1.573116614	ϕ25 = 0.463873612	p = p5	z = -1
SPSZR6	t16 = 4.004743	t26 = 0.801677094	ϕ14 = -1.573116614	ϕ26 = 0.463873612	p = p6	z = 1

Table 1 : Chosen Parameters for Chebyshev bandpass optical filter

The filter system thus has the following transfer function :

$$H_{BP}(z^{-1}) = \frac{0.125(1-z^{-2})^3}{1+3.004723z^{-2}+3.009475z^{-4}+1.004752z^{-6}} \tag{18}$$

5.1.1 Parallel Realisation

For parallel realisation the transfer function of the Chebyshev bandpass filter (8) can be expressed as

$$H_{BP}(z^{-1}) = -6.7923e-9 + \frac{8.69874e-9(1-272.8e3z^{-1})}{(1-p1z^{-1})(1-p2z^{-1})} + \frac{-3.00551e-4(1+3.9499z^{-1})}{(1-p3z^{-1})(1-p4z^{-1})} + \frac{3.00551e-4(1+3.9477z^{-1})}{(1-p5z^{-1})(1-p6z^{-1})} \tag{19}$$

The system can be implemented by a parallel realisation as shown in the Figure 5. The sub systems H1, H2, H3 and H4 are implemented as followed:

(i) Sub-system H1: The sub-system H1 is simply implemented by cascading one optical device with gain 6.7923e-9 and an optical phase modulator with a phase π. H1 contribute to the system H1 = -6.7923e-9

(ii) Sub-system H2 : This subsystem H2 should provide a system of poles and zeros as follows: 2 poles at p = p1 and p = p2 and 2 zeros z1 = 272.8e03 and z2 = 0. This subsystem can be implemented by cascading a SPSZR and an APOC. The chosen parameters for these elements are shown in Table 2.

SPSZR1	t11= 4.009492	t21= 0.0135526	ϕ11= 1.570799999	ϕ21= 4.712404286	p = p1	z = 272.8e03
APOC1	k11=k21=0.5	t11 =t21 = 2.00237	ϕ11 = 0	ϕ21= -1.57079999	p = p2	z =0

Table 2 : Chosen parameters for subsystem H2

The two optical components in Table 2 are cascaded with an optical device with gain 0.0122456e-06 and an optical phase modular with phase -0.7848

(iii) Sub-system H3 :

This subsystem H3 should provide a system of poles and zeros as follows : 2 poles at p = p3 and p = p4 and 2 zeros at z = 3.9499 and z = 0. This subsystem can be implemented by cascading a SPSZR and an APOC. The chosen parameters for these elements are shown in Table 3.

SPSZR2	t12= 4.004721	t22= 0.2009535	ϕ12= 1.568483356	ϕ22= 1.099537311	p = p3	z = -3.9499
APOC2	k12=k22=0.5	t12=t22= 2.00118	ϕ12= 0	ϕ22= -1.568483356	p =p 4	z =0

Table 3 : Chosen parameters for subsystem H3

The two optical devices above are cascaded with an optical device with gain 1.254e-04 and an optical phase modular with phase -0.37841

(iv) Subsystem H4 :

This subsystem H4 should provide a system of poles and zeros as follows : 2 poles at p = p5 and p = p6 and 2 zeros at z = -3.9477 and z = 0. This subsystem can be implemented by cascading a SPSZR and an AZOC as described in Ref.[1]. The chosen parameters for these elements are shown in Table 4.

SPSZR3	t13= 4.004743	t23= 0.1543989	ϕ13= 1.57311662	ϕ23= 1.205039363	p = p5	z = -3.9477
APOC3	k13=k23=0.5	t13=t23= 2.0005926	ϕ13= 0	ϕ23= -1.57311662	p =p 6	z =0

Table 4 : Chosen parameters for subsystem H4

The two elements above are cascaded with an optical device with gain 1.152e-04 and an optical phase modular with a phase -0.379212

5.2 The COF2

5.2.1 Cascading Realisation

The Chebychev band-pass transfer function with the numbers of poles and zeros given in Section 4.1.1 above can be realised in the cascade configuration from the combination of all-poles and all-zeros basic elements. The overall system transfer function eqn. (18) can be expressed in the more general form which separates the factors containing the poles and zeros as:

$$H_{BP}(z) = \prod_{i=1}^{m} H_{azi}(z^{-1}) H_{api}(z^{-1}) \quad (20)$$

where each pole and each zero are realised from one basic element of the AZOC or APOC. The functions $H_{azi}(z^{-1})$ and $H_{api}(z^{-1})$ are first order function of z^{-1} numerator and denominator. The schematic diagram showing the cascade realisation for this transfer function is shown in Figure 6.

It is noted that if the poles or zeros appear in conjugate pairs of either real or imaginary then the numbers of subsystems can be reduced by using more delay coefficients (d≥2) for higher order subsystem realisation.

From eqns. (13) , (15) we obtain the required parameters with some arbitrary chosen values for each AZOC and APOC subsystems in the cascaded configuration in Figure 6. They are showed in Table 4 with parameters X_{pq} indicate p couplers and q subsystems. It is noted that the accuracy of parameters in the table is necessary and should not be rounded off. Additional amplifier gain may also be required to achieve a unity gain response.

Subsystem	**Coupling coefficient**	**Transmission coefficient**	**Phase shift modulator**		**Delay d**	**Poles or zeros**
H_{az1}	b11=b21 =0.5	t11=t21 =1	Φ11=0	Φ21=0	2	z = ±1
H_{az2}	b12=b22 =0.5	t12=t22 =1	Φ12=0	Φ22=0	2	z = ±1
H_{az3}	b13=b21 =0.5	t13=t23 =1	Φ13=0	Φ23=0	2	z = ±1
H_{ap1}	a11=a21 =0.5	t11=1 t21= 4.004743245	Φ11=0	Φ21= -1.5684760	1	p1
H_{ap2}	a12=a22 =0.5	t12=1 t22= 4.004743245	Φ12=0	Φ22= 1.56847603	1	p2
H_{ap3}	a13=a23 =0.5	t13=1 t23= 4.004743245	Φ13=0	Φ23= -1.5731092	1	p3
H_{ap4}	a14=a24 =0.5	t14=1 t24= 4.004743245	Φ14=0	Φ24= 1.57310929	1	p4
H_{ap5}	a15=a25 =0.5	t15=1 t25= 4.009492105	Φ15=0	Φ25= -1.5707926	1	p5
H_{ap6}	a16=a26 =0.5	t16=1 t26= 4.009492105	Φ16=0	Φ26= 1.57079266	1	p6

Table 4: Chosen System Parameters for Cascade Realisation

5.2.2 4.2.2. Parallel Realisation :

Using the transfer function for the Chebyshev bandpass filter given by (19) the system can be implemented by a parallel realisation as shown in Figure 5. This structures for the sub systems H1 to H4 are given as follows:

(i) Subsystem H1

Subsystem H1 is simply implemented by cascading one optical device with gain 6.7923e-9 and an optical phase modulator with phase biased at π. H1 contributes to the system H1 = -6.7923e^{-9}

(ii) Subsystem H2 :

This subsystem H2 should provide a system of poles and zeros of two poles at p = p1 and p = p2 and two zeros at z = 272.8e03 and z = 0. This subsystem can be implemented by cascading two APOCs and one AZOC with the chosen parameters shown in the Table 5 .An optical device with gain 1.5011e+6 is required to cascade with these optical components.

H_{az11}	b11=b21= 0.9996335	t21= 1000 t11= 0.1	ϕ11 = 0	ϕ21= 0	z = 272.8e3
H_{ap11}	a11=a21= 0.5	t11 =t21 = 2.00237	ϕ11 = 0	ϕ21= 1.57079999	p = p1
H_{ap21}	a12=a22= 0.5	t12 =t22 = 2.00237	ϕ12 = 0	ϕ22= -1.57079999	p = p2

Table 5 : Chosen parameters for subsytem H2

(iii) Subsystem H3 :

This subsystem H3 should provide a system of poles and zeros as follows: two poles at p = p3 and p = p4 and two zeros at z = -3.9499 and z = 0. This subsystem can be implemented by cascading two APOCs and one AZOC with the chosen parameters shown in the Table 6. These elements are cascaded with an optical device with gain 1.7882e-3 and an optical phase modulator with phase π.

H_{az12}	b11=b21= 0.66385	t21= 4 t11= 1	ϕ11 = π	ϕ21= 0	z = -3.9499
H_{ap12}	a11=a21= 0.5	t11 =t21 = 2.00237	ϕ11 = 0	ϕ21= 1.56848336	p = p3
H_{ap22}	a12=a22= 0.5	t12 =t22 = 2.00118	ϕ12 = 0	ϕ22= -1.56848336	p = p4

Table 6 : Chosen parameters for subsytem H3

(iv) Subsystem H4 :

Similarly the subsystem H4 should provide a system of poles and zeros as follows : two poles at p = p5 and p = p6 and two zeros at z = -3.9477 and z = 0. Again this subsystem can be implemented by cascading two all-pole and one all-zero subsystems with the chosen parameters shown in the Table 7. These elements are to be cascaded with an optical device with gain 1.787841e-3.

H_{az13}	b11=b21= 0.663735	t21= 4 t11= 1	ϕ11 = π	ϕ21= 0	z = -3.9477
H_{ap13}	a11=a21= 0.5	t11 =t21 = 2.0005926	ϕ11 = 0	ϕ21= 1.57311662	p = p5
H_{ap23}	a12=a22= 0.5	t12 =t22 = 2.0005926	ϕ12 = 0	ϕ22= -1.57311662	p = p6

Table 7 : Chosen Parameters for subsystem H4

5.3 Discussions

Although the use of the 3x3 optical directional coupler to form the SPSZR would reduce the required number of the couplers for structuring the filters type COF1, the direct feedback of the optical path delay restrict the operation frequency of the filter far below the resonance frequency range of the delay-free loop. On the other hand the COF2 employs the all-poles and all-zeros optical circuits would allow better stability as well as a much wider range of operating frequency or much narrow range of the optical bandpass filters. These filters can be implemented in optical fibre or integrated optical configuration. A much better technology would be the use of in-line fibre gratings in forward or reflection modes. We are currently implementing a number of optical filters such the Butterworth or Chebyshev types using UV written fibre gratings or photorefractive gratings in lithium niobate diffused optical waveguides.

6 CONCLUSIONS

We have demonstrated the synthesising process for a narrow Chebyshev bandpass filter according to a given set of specification. It can be seen that in practice the hardware implementations of these kind of filters should be very accurate due to the effects of optical elements parameters and optical phase modulators values in the network. Because the filters we described here have a very narrow bandpass in a very high frequency region thus they are very sensitive to any small change of optical elements. Care should be taken into account in these filters implementations. On the other hand this filter can be used as a sensitive optical sensor.

The employment of the SPSZRs as well as the two quasi all-pole and all-zero optical circuits has been proven to be compact for the implementation of the filters and thus would reduce the required number of the optical couplers. The quasi all-pole and all-zero optical circuits are also used and integrated into the optical systems for signal processing. We believe that these optical components described in this paper would find many applications in optical communications and signal processing networks.

However, it is believed that the equalisation of optical signals in high-speed data transmission can be implemented using fibre-optic resonators with some specific configuration to be feasible in the near future[9].

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FIGURE CAPTIONS

Figure 1 : Bandpass optical filter specification

Figure 2: Responses of the Chebyshev bandpass filters (a)-(b) magnitude and phase responses as a function of optical wavelength (c) poles and zeros positions in the z-plane.

Figure 3: The 3x3 optical coupler and optical feedback paths as the SPSZR (a) schematic diagram and (b) Graphical signal-flow representation

Figure 4: Optical resonance loop to obtain a quasi all-pole optical circuit (APOC).

Figure 5 : Hardware implementation diagram of Chebyshev filter

Figure 6 : Schematic Diagram showing Tandem all-pole and all-zero subsystems

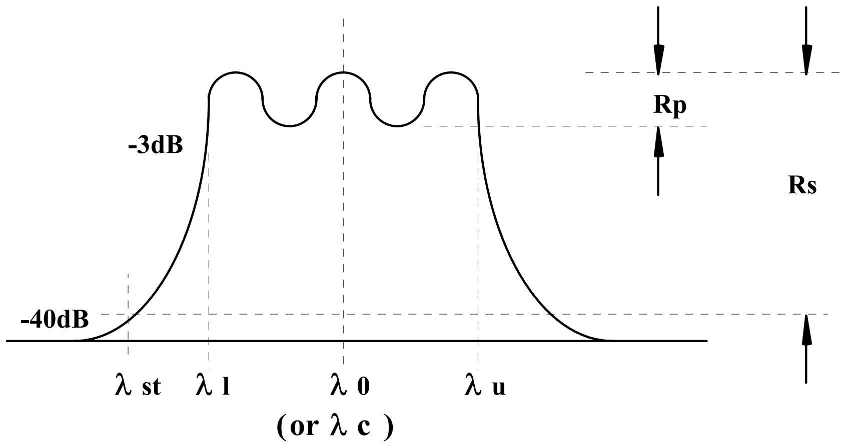
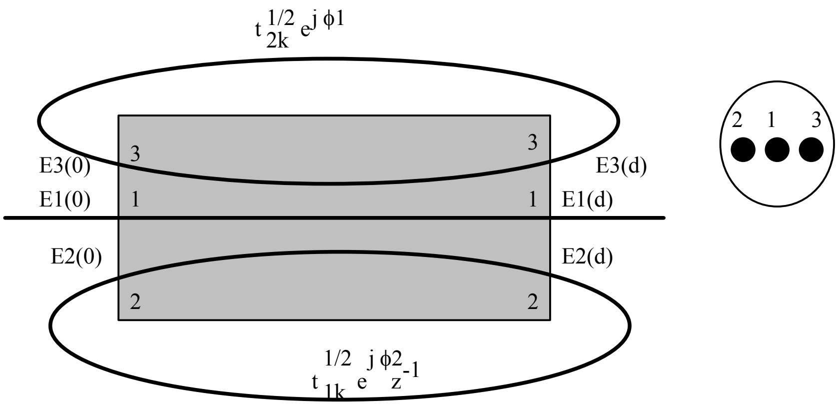


Figure 1 : Bandpass optical filter specification

Figure 2: Responses of the Chebyshev bandpass filter

(a)-(b) magnitude and phase responses as a function of optical wavelength (c) poles and zeros positions in the z-plane.


t 1/2 2k e j ϕ1
E3(0)
E1(0)
E2(0)
3
1
2
3
1
2
E3(d)
E1(d)
E2(d)
2 1 3
t 1/2 1k e j ϕ2 z -1

(a)

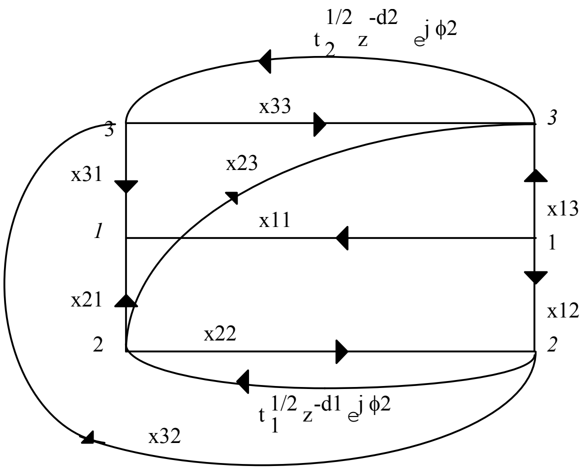

t 1/2 2 z -d2 e j ϕ2
x33
3
3
x31
x23
x13
1
x11
1
x21
x12
2
x22
2
t 1/2 1 z -d1 e j ϕ2
x32

Figure 3

The 3x3 optical coupler and optical feedback paths as the SPSZR (a) schematic diagram and (b) Graphical signal-flow representation

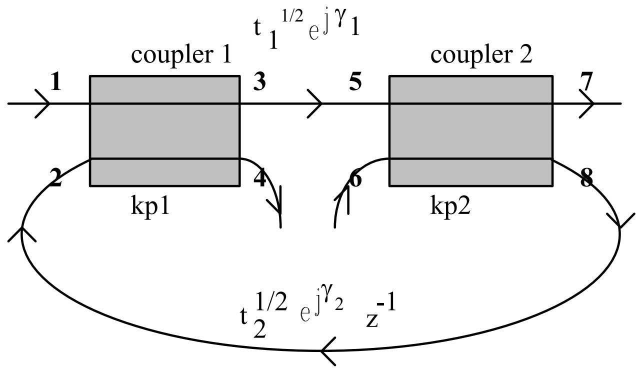


Figure 4 Optical resonance loop to obtain a quasi all-pole optical circuit (APOC).

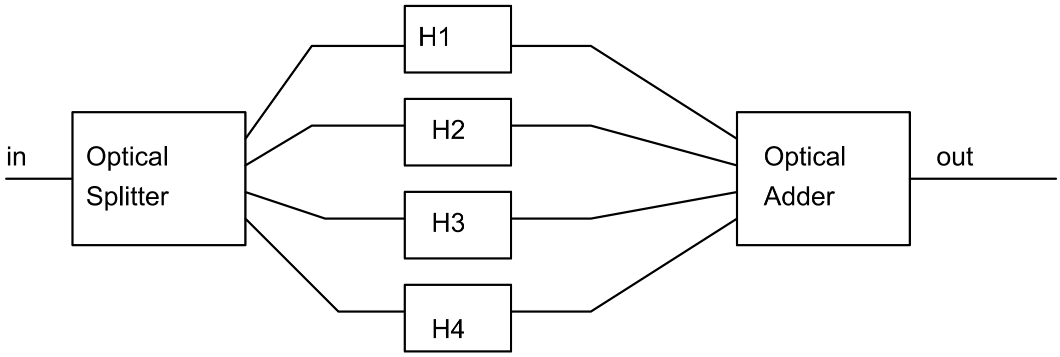


Figure 5 : Hardware implementation diagram of Chebyshev filter

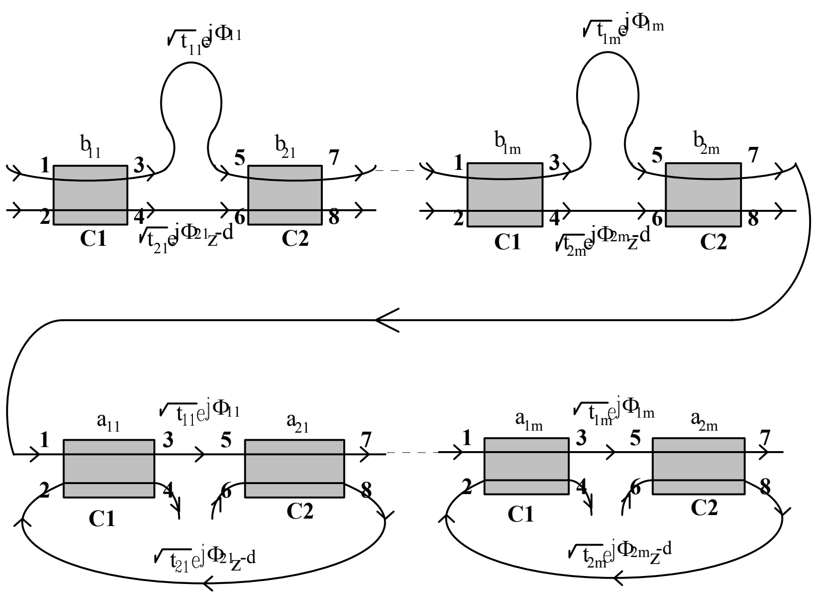


Figure 6 : Schematic Diagram showing Tandem all-pole and all-zero subsystems