Progress In Electromagnetics Research B, Vol. 55, 217–240, 2013

32-CHANNEL OPTICAL INTERLEAVER/DEINTERLEAVER USING FIBONACCI QUASI-PERIODIC STRUCTURES

Saeed Golmohammadi*

Department of Engineering and Emerging Technologies, University of Tabriz, 51666-14761, Iran

Abstract—The design of Interleaver/Deinterleavers using Fibonacci-class quasistructures is proposed. We introduce an optical passive configuration composed of Fibonacci quasistructures and circulators which acts as interleaver and deinterleaver. Odd and even channels are interleaved/deinterleaved with dense wavelength-division multiplexing (DWDM) multichannel filter based on Fibonacci quasi-periodic structures. We use Fibonacci based DWDM filters in order to separate the odd and even wavelength channels. These quasi-periodic structures, with different geometrical and physical parameters, act as DWDM filters that reflect even and odd wavelengths. A modified numerical approach is presented to design the Fibonacci based DWDM filter. We demonstrate that it is possible to optimize DWDM filter response by varying the parameters of the Fibonacci structure, such as generation number, Fibonacci order and optical lengths of the layers. The proposed filter structures can separate 32 DWDM channels with 0.8 nm spacing into two 16 DWDM channels with 1.6 nm spacing. In order to eliminate the crosstalk between the adjacent channels, we apply the refractive index profile apodization. These structures are useful for multiplexing/demultiplexing of a high numbers of the channels.

1. INTRODUCTION

Next generation services and the high rate of internet growth, cause an explosion in the amount of the information transport in the communication networks. As network traffic continues to increase, more bandwidths are needed to accommodate the transmission of

Received 17 July 2013, Accepted 26 September 2013, Scheduled 4 October 2013
* Corresponding author: Saeed Golmohammadi (sgolmohammadi@tabrizu.ac.ir).

the information. DWDM is the most promising technology for increasing the information transmission capacity in the optical fiber communication networks. To meet the explosive bandwidth demand and make optimum use of the existing amplifier bandwidth, DWDM systems must offer more number of channels with narrower channel spacing. The optical interleaver/deinterleaver is shown to be an effective tool for increasing the capacity of the DWDM systems. Interleaver/deinterleavers have the advantage of lower insertion loss with respect to conventional multiplexer/demultiplexers [1].

Optical interleavers are needed for channel spacing of 50 GHz or smaller. An optical interleaver can provide a cost-effective method for increasing the capacity by doubling or quadrupling the number of channels and therefore lead to terabits capacities. Most optical interleaver designs are based on Michelson-Gires-Tournois interferometer [2–6], ring resonator type filters [8, 9], hybrid coupler and delay line on planar lightwave circuits [8, 9], hybrid filters and array waveguides [8], and birefringent crystals [7].

Improvements in the optical properties of the different interleaver structures have been reported in the literature [8–10].

Low insertion loss, wide −3 dB passband (flat-top), great −25 dB stopband, and higher −25 dB channel isolation are the important characteristics of the interleavers based on different technologies [11].

DWDM filters can be used to separate odd and even channels as interleavers/deinterleavers [12]. Available technologies for DWDM filters are multilayer dielectric thin film filters (TFFs) [13], arrayed waveguide gratings (AWGs) and fiber Bragg gratings (FBGs) [14].

Multilayer structures are one of the most suitable alternatives for DWDM filters. Fiber gratings (FG's) are also widely used as wavelength selective devices. High selectivity, low insertion loss, no polarization sensitivity, sharp and well-defined filter amplitude response (ideal rectangular shape) are critical characteristics for FG's in WDM communication systems [15].

Multiplexing/Demultiplexing of the large number of channels, with single wavelength multilayer filters requires a long cascade of the filters in DWDM systems. Reducing the number of the cascaded filters is of prime importance. The number of filters might be reduced if a series of the singleband filters is replaced with a multiband filter.

Wide band periodic filters based on the superimposed chirped fiber Bragg gratings have been designed for DWDM to provide flat amplitude response [16].

Gratings with periodic change of the refractive index, which have single stopband, behave as filters. Designing multi narrow band filters is possible by cascading a given number of the periodic structures with different periods. Here, we introduce quasi-periodic gratings based on Fibonacci sequence as multiband filters, where a single structure has several stopbands and hence results in ease of design and fabrication and also reduced insertion loss [31].

Study on Fibonacci multilayer structures started in 1987, when Kohmoto et al. introduced the first system based on optical Fibonacci multilayers capable of localizing photons [17]. Sibilia et al. demonstrated that the transmission spectrum produced by such structures are dense in wavelengths, displaying a self-similar pattern [18]. Gellermann et al. experimentally showed the existence of the bandgaps in the spectrum of these structures [19]. Omnidirectional bandgaps using Fibonacci quasi-periodic structures were also reported by Lusk et al. [20]. Peng et al. have reported the resonant transmission of light in the symmetric Fibonacci multilayers, characterized by many perfect transmission peaks and useful for narrow-band multi wavelength optical filtering applications [21].

Fibonacci sequences were used either as reflectors or as transmitters in designing microcavity structures [22–24]. Useful mathematical expressions for these structures were derived in [25, 26].

We introduce a new configuration which is composed of Fibonacci quasi-periodic DWDM standard filters and circulators, where the overall structure can be used as interleaver/deinterleaver. In the proposed structure, design of each DWDM filter is done using a single Fibonacci multilayer structure. For odd and even channels, DWDM filters with different geometrical and physical parameters are designed. Designed filters are according to the ITU grid, where two adjacent channels are spaced 1.6 nm from each other. DWDM filters are designed with single Fibonacci class FC(4, n). In the design process, numerical evaluation of the reflectance from the quasi-periodic structure is done using Transfer Matrix Method (TMM).

The organization of the paper is as follows. An overview of interleaver/deinterleaver is reviewed in Section 2. Section 3 is devoted to demonstration of the Fibonacci quasi-periodic structure layers arrangement. The theory of the light propagation in these structures is studied in Section 3. The interleaver/deinterleaver's proposed configuration is presented in Section 4. The structure response as interleaver and deinterleaver is simulated and results are expressed in Section 5. Finally, the paper ends with a short conclusion.

2. INTERLEAVER/DEINTERLEAVERS

Using an optical interleaver the transmission capacity can be increased by doubling or quadrupling the number of channels. These

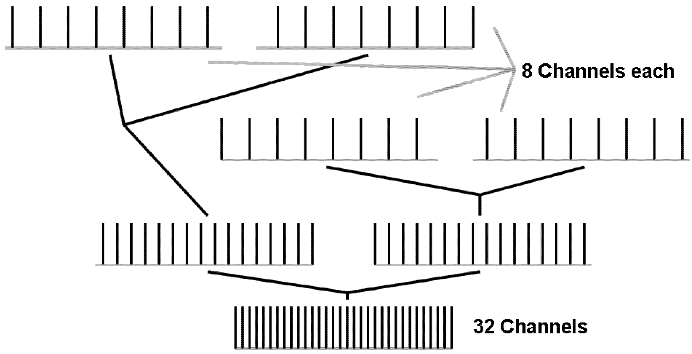


Figure 1. A interleaver combines two even and odd sets of 8 channels into one densely 16 channel, with half of the original channel spacing. Two 16 channels are cascaded to create a 32 channel set with narrower channel separation.

devices enable the practical implementation of DWDM systems by transforming the task of separating or combining a single set of very closely spaced channels into separating or combining multiple sets of widely spaced channels.

In the simplest case, the interleaver combines two sets of channels into one densely packed set with half of the channel spacing. In reverse, the deinterleaver routes the single input set of channels into two output streams with twice of the channel spacing. Single stage interleavers can be cascaded in a binary fashion to create devices with high number of channels (Fig. 1).

Several techniques, including dielectric thin-film filters, array waveguide gratings (AWGs), Fabry-Pérot filters, diffraction gratings, and unbalanced Mach-Zehnder interferometers can be employed in DWDM systems for packing as many channels as possible into fiber-optic networks. However, the channel spacing is limited to about 100 GHz using these techniques.

3. THEORY OF LIGHT PROPAGATION IN ONE DIMENSIONAL QUASI-PERIODIC STRUCTURE

In this section, the structure of the DWDM filter is introduced. After realization of the structure, we will declare the relations which are used in the calculation of the reflection and transmission spectrum. Fibonacci-class quasicrystals can be generated according to the mathematical recursive relations given by [26]:

$$\begin{cases} \mathrm{FC}(1,n) = S_1 = B \\ \mathrm{FC}(2,n) = S_2 = B^{n-1}A \\ \mathrm{FC}(3,n) = S_3 = (B^{n-1}A)^n B \\ \vdots \\ \mathrm{FC}(j,n) = S_j = S_{j-1}^n S_{j-2} \end{cases}, \tag{1}$$

where, n is a positive integer. For illustration of the explicit form of the proposed general relation for Fibonacci-class, the exact form for $j = 4$ is presented as:

$$\begin{aligned} &\mathrm{FC}(4,n) \\ &= S_3^n S_2 = \left[\left(B^{n-1}A\right)^n B\right]^n B^{n-1}A \\ &= \underbrace{\overbrace{(\underbrace{B\ldots B}_{n-1}A)\ldots(\underbrace{B\ldots B}_{n-1}A)}^{n} B \ldots \overbrace{(\underbrace{B\ldots B}_{n-1}A)\ldots(\underbrace{B\ldots B}_{n-1}A)}^{n} B}_{n} \underbrace{B\ldots B}_{n-1}A, \end{aligned} \tag{2}$$

In optical domain, we assume that Fibonacci class quasi-structures are constructed from A and B dielectric layers with constant index of refractions n_a and n_b and thicknesses d_a and d_b, respectively. In this structure, the layers which are arranged according to Eq. (2) show that the FC(4, n) is neither periodic nor disordered, but the layers are arranged in a regular pattern. One dimensional refractive index profile of the FC(4, n) can be applied on an optical waveguide active layer or an optical fiber core for optical communication usage. In this text, we mark the refractive index profiles of the FC(3, n) and FC(4, n) structures with $n_{s_3}(z)$ and $n_{s_4}(z)$.

The theoretical aspects related to electromagnetic wave propagation in any multilayer media have been widely studied using the coupled mode theory (CMT) [27], where the forward and backward propagating waves are related with coupled mode equations. The coupled-mode equations are usually derived heuristically, assuming the grating to be shallow, forming a weak modulation superimposed on a uniform background. This assumption allows expansion of the electric field simply in terms of the so-called forward and backward propagating modes of the uniform structure, each with slowly varying amplitude induced by the grating. Conventional coupled-mode theory can be applied to almost all fiber gratings, where the refractive index modulation is of order 10^{-4} [28]. In quasi-periodic structures such as FC(j, n), the refractive index changes are larger than the shallow gratings, hence, we can not apply ordinary coupled mode equations. In order to obtain a model for the light propagation in quasi-periodic structures, general coupled mode theory has been employed [29] .

The number of the forward and backward components is equal to the number of the eigenvalues (ω_μs). In the case of periodic gratings, ω_μ is the Bragg resonance frequency and is the forbidden frequency band.

In general, the essential property of any multilayer structure is the existence of forbidden frequency bands (ω_μ s), through which all the propagating modes are absent. These forbidden frequency bands can act as reflection band filters. For periodic multilayer structures, the bandgap can be calculated by analytical relations. For quasi-periodic multilayer structures, the forbidden frequency bands should be calculated numerically. We calculate the forbidden frequency bands for the case of FC(4, n) using the transfer matrix method (TMM) in a desired optical communication band. We calculate the number of the reflection bands, their central frequencies and bandwidths in an optical communication interval, e.g., C band. Here, μ is equal to the number of the reflection bands in the given interval. Assume that in the DWDM system the incident wavelengths, for example in the C band to be located around the λ_μ. These incident wavelengths cause μ forward and μ backward components due to the existence of the forbidden bandgaps.

4. PROPOSED INTERLEAVER/DEINTERLEAVER CONFIGURATION

In this section, we describe the operation of the proposed interleaver/deinterleaver structure. The configuration of the proposed structure is illustrated in Fig. 2. This figure shows that the overall structure is composed of three FC(j, n) structures and two circulators.

We first explain the structure's function as interleaver/deinterleaver. We assume that the 32-channels DWDM signal is as input to the deinterleaver from the port 1 of the circulator 1. These 32 channels must be separated into two sets of the odd and even channels. All 32 channels enter to the port 1 of the circulator 1, coming out from the port 2 of the circulator 1. The odd channels filter reflects the odd channels and passes even channels, so the odd channels enter to the port 2 of the circulator 1. The odd channels which have entered to the port 2, come out from the port 3 of the circulator 1. The even channels filter on the port 3 of the circulator 1 passes the odd channels, so the odd channels are separated from the even channels.

The even channels enter to the port 1 of the circulator 2, coming out from port 2 of this circulator and after reflection from the even

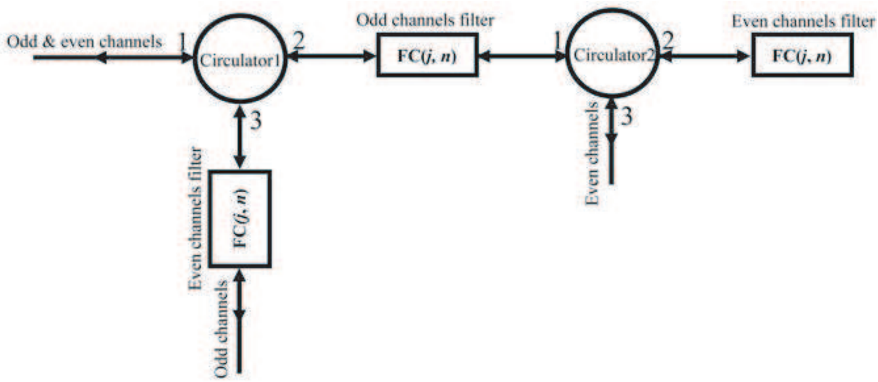


Figure 2. Interleaver/Deinterleaver configuration using FC(j, n) as odd and even filters.

channels filter, come back to the port 2 and finally come out from the port 3 of the circulator 2. Therefore, 16 odd channels appear on the port 3 of the circulator 1 and 16 even channels on the port 3 of the circulator 2. So, in the mentioned direction, the overall structure acts as deinterleaver.

The structure which is shown in Fig. 2 acts as interleaver in the opposite direction. The odd channels enter to the odd channels port of the structure, pass through the even channels filter, enter to the port 3 of the circulator 1, and come out from the port 1 of this circulator. The even channels enter to the port 3 of the circulator 2, come out from the port 1 of this circulator, pass through the odd channels filter, enter to the port 2 of the circulator 1, come out from the port 3 of this circulator, are reflected from the even channels filter, come back to the port 3, and finally come out from the port 1 of the circulator 1. In this way, the odd and even channels are interleaved and all are present at the port 1 of the circulator 1.

The above description shows that the overall structure acts as deinterleaver in one direction and interleaver in the opposite direction. The odd/even, odd and even input and output ports are the same either in the interleaver and the deinterleaver.

The odd/even channels filter should be able to reflect odd/even channels and pass the even/odd channels. The center wavelengths of these filters must be according to the ITU-T G.694.1 recommendation for optical DWDM systems. As mentioned before, we want to demonstrate that these filters can be built by the FC$(3, n)$ and FC$(4, n)$

quasi-periodic structures. In the next section, we will present a systematic procedure in order to designing the odd and even channel filters using these structures. Also, the simulation results for the reflection spectrum from these structures are presented in the C band.

5. FILTERING RESPONSE OF THE PROPOSED STRUCTURES

Here, we first present the structures of the proposed odd and even filters and their reflection spectrum. Then we will apply the refractive index apodization in order to have flat reflection bands without sidelobes. At the end, we will investigate the effects of the circulators losses on the response of the interleaver/deinterleaver, briefly.

Selection of the desired structure as odd or even filter for the interleaver/deinterleaver requires exact investigation of spectral reflectance for different generalized Fibonacci structures regarding free spectral range (FSR) and bandwidth as the main required properties of these filters. The desired filter should have bands that should be corresponding to ITU-T G.694.1 recommendation. This recommendation dictates that FSR $= 1.6\,\mathrm{nm}$ and $\Delta\lambda \geq 0.1$ at $-3\,\mathrm{dB}$. Some assumptions have been made in simulations of the optical reflectivity from these structures. Refractive indices of the layers A and B are assumed to be 1.65 and 1.45, respectively. The refractive indices of the materials in both sides of the structure are also assumed to be 1.45. These refractive indices are corresponding to various materials such as ... and SiO_2 respectively. Difference between two refractive indices must be at least 0.2 because at less than this value proper responses are not achieved. Optical thicknesses of all layers are assumed to be equal to odd multiple of the quarter of the central wavelength of the reflectivity, which is selected to be 1550.12 nm in all of the following simulations. The optical length of the layers A and B are assumed to be as the following equation:

$$D = n_{a,b} \times d_{a,b} = \frac{m\lambda_c}{4}, \tag{3}$$

where, $n_{a,b}$ and $d_{a,b}$ are refractive indices and physical thicknesses of layers, and m is an odd number, λ_C the central wavelength of the reflection spectrum.

In Fig. 3 spectral reflectance for two structures FC(3, 21, $m = 1$) and FC(3, 24, $m = 9$) are demonstrated. Figs. 3(a) and 3(b) show the reflection spectrum, which contains several optical reflective bands as optical filtering bands. The number and location of the reflection bands versus wavelength in Figs. 3(a) and 3(b) are different due to the different values of n and m for two structures. Fig. 3(a) illustrates

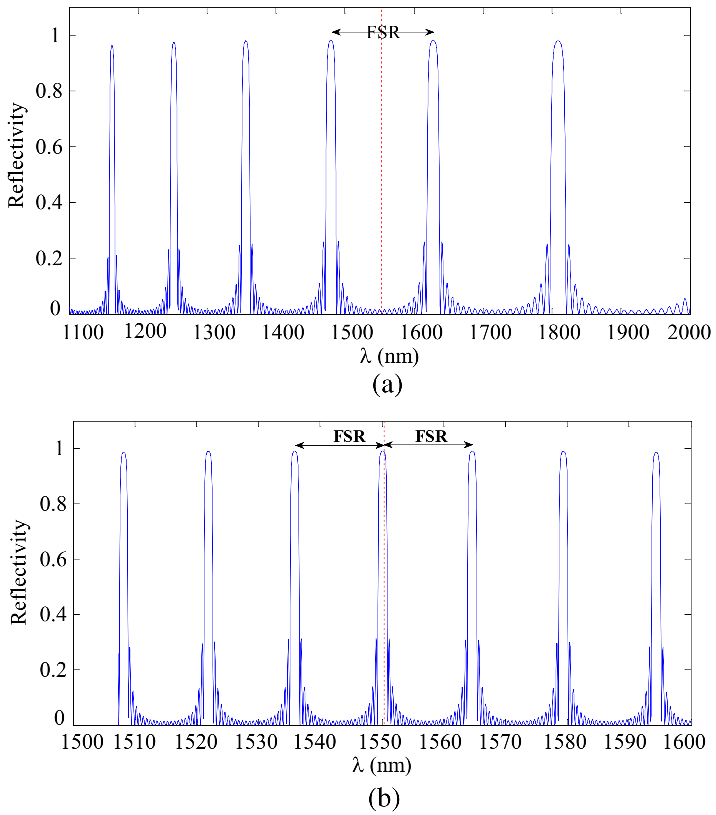


Figure 3. Spectral reflectivity for two sample structures based on, (a) FC(3, 21, $m = 1$) and (b) FC(3, 24, $m = 9$), λ_C is 1550.12 nm, represented by dashed line.

that FSR is so high (> 100 nm), since the structure is not desired for DWDM applications. Also, the FSR of illustrated spectrum in Fig. 3(b) is higher (> 10 nm) than the standard FSR defined by ITU-T. However, increasing the parameters m and n will led to smaller FSR and will make the structure more desired for DWDM applications.

In Table 1, the values of the FSR for FC(3, n) have been demonstrated for different values of n and m, the physical and geometrical parameters of the structures are the same as we have mentioned before. Since the number and shape of the reflection bands differ for odd and even values of n, in Table 1, the FSR for odd values of n is simply the distance between two central channels and for even values of n is the average of the distance for two central channels (as

Table 1. FSR in nm for the FC(3, n) for different values of m, $n_a = 1.65$, $n_b = 1.45$, $\lambda_C = 1550.12\,\text{nm}$.

structure	$\boldsymbol{m=1}$	$\boldsymbol{m=3}$	$\boldsymbol{m=5}$	$\boldsymbol{m=7}$	$\boldsymbol{m=9}$
FC(3, 21)	148.02	48.5	29.63	21.25	16.37
FC(3, 22)	142.25	47.01	28.21	20.20	15.7
FC(3, 23)	136.89	44.88	27.63	19	15
FC(3, 24)	130.14	43.01	25.9	18.5	14.40
FC(3, 25)	123.51	41	24.75	18	13.87

Table 2. FSR in nm for the FC(4, n) for different values of m, $n_a = 1.65$, $n_b = 1.45$, $\lambda_C = 1550.12\,\text{nm}$.

structure	$\boldsymbol{m=1}$	$\boldsymbol{m=3}$	**structure**	$\boldsymbol{m=1}$	$\boldsymbol{m=3}$
FC(4, 21)	6.95	2.31	FC(4, 29)	3.65	1.23
FC(4, 23)	5.79	1.92	FC(4, 31)	3.2	1.1
FC(4, 25)	4.9	1.63	FC(4, 33)	2.83	0.94
FC(4, 27)	4.2	1.41	FC(4, 35)	2.51	0.83

shown in Fig. 3).

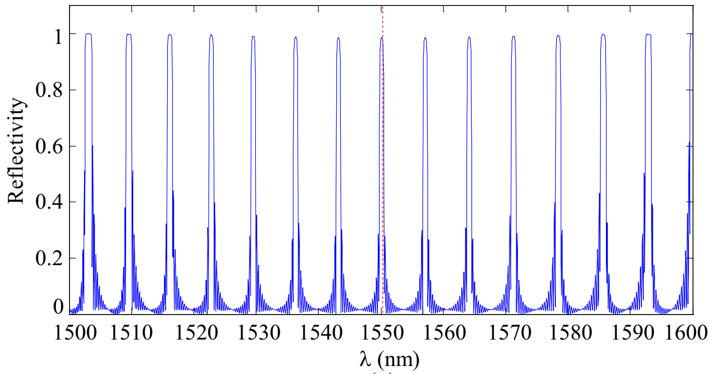
By investigation of the values of FSRs for the structures based on FC(3, n), we can suggest the following relation as a fitted curve for the given values of FSR in the Table 1.

$$\text{FSR(nm)} = \frac{2 \times \lambda_c(nm)}{m \times n}, \tag{4}$$

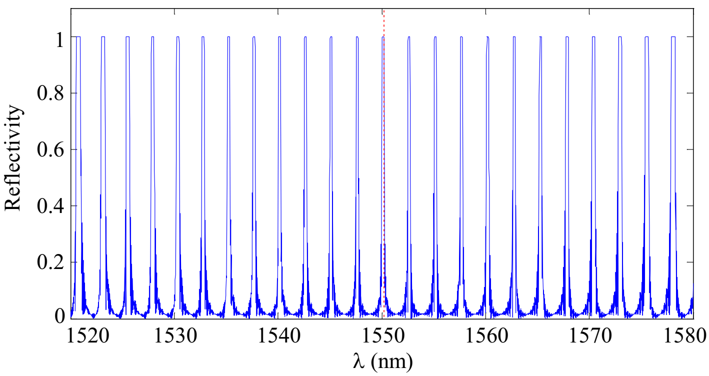
In Table 2 predicted values of FSR using Eq. (4) are presented and as it can be seen from tables there is small difference between corresponding values of the tables and hence in this case Eq. (5) is a good approximation for the FSR.

Figure 4 demonstrates the content of the spectral reflection for two FC(4, n) sample structures. Here the refractive indices of the layers are assumed to be the as before and the thicknesses of the layers are obtained from Eq. (3). Fig. 4 demonstrates the ability of the FC(4, n) to be used in multi-wavelength filtering applications. In order to use these structures in DWDM applications the bands should be according to the ITU-T grid. Comparing Figs. 3(a) and 3(b), we see that the FSR for FC(4, 21, m =1) is much smaller than the FC(3, 21, $m = 1$).

In Table 2(a), the values of the FSR for FC(4, n) have been given for different values of n and m, the physical and geometrical parameters of the structures are the same as mentioned before.



(a)



(b)

Figure 4. Spectral reflectance for two sample structures based on (a) FC(4, 21, $m = 1$) and (b) FC(4, 35, $m = 1$), λ_C is 1550.12 nm and is represented by dashed line.

Similar to Eq. (4), we can suggest the following approximated relation to calculate the FSR for FC(4, n, m) structure for different values of n and m.

$$\mathrm{FSR(nm)} = \frac{2 \times \lambda_c(nm)}{m \times n^2} \tag{5}$$

In Table 2(b) as in Table 1, predicted values of FSR using Eq. (5) are presented, and there is small difference between corresponding values of both tables. In this case, Eq. (5) is a good approximation for the FSR. It should be added that we do not need to generalize these empirical relations (Eq. (4) and Eq. (5)) because in high order quasiperiodic structures ($j > 4$) we did not find periodic behavior in spectral reflectance.

We can use Eqs. (4) and (5) to choose desired structures for odd and even channel filters, using the given values of FSR. In order to use these equations for DWDM filter design, we rewrite them in the following forms:

$$m = \frac{2 \times \lambda_c(nm)}{\text{FSR(nm)} \times n} \tag{6}$$

$$m = \frac{2 \times \lambda_c(nm)}{\text{FSR(nm)} \times n^2} \tag{7}$$

Now, by using Eqs. (6) and (7), we create two tables, in each table the value of m is calculated for different values of n and FSR. The values of FSRs are assumed to be 1.6 nm and 3.2 nm. For the case FSR = 3.2 nm, we will cascade two structures in order to achieve FSR = 1.6 nm. Using Tables 3 and 4, we will discover the odd integer values of m, and then we will calculate the reflection spectrum for these values of m. With comparison of the reflection bands of the spectrum with ITU-T G.694.1 recommendation grids, we can determine the desired structure for odd and even channel filtering purposes. Table 3 is made using Eq. (6) and six odd integer values for m is indicated in the table.

The values of m for different values of n ($11 < n < 49$) and FSR (1.6 and 3.2) are demonstrated in Table 4 for the FC(4, n) structure. Only one odd integer value is obtained for m, which has been highlighted in Table 4.

In order to check the best compatibility between the reflection spectrum and ITU-T grid, we calculate these spectrums using TMM.

The reflection spectrum for odd integer values of m in the Table 3 is demonstrated in Fig. 5. The vertical dotted grids in these figures demonstrate the central wavelengths of the channels recommended by ITU-T G.694.1.

Figure 5(a) demonstrates reflection spectrum for FC(3, 17, $m =$ 57). As seen from this figure, the lateral bands of the filter can not be used in filtering application because of its small bandwidth and large insertion loss. According to Figs. 5(b) and 5(c), FC(3, 19, $m = 51$) and FC(3, 34, $m = 57$) structures are not proper to be used as DWDM filters. Figs. 5(d), 5(e) and 5(f) demonstrate the reflection spectrum of the structures FC(3, 51, $m = 19$), FC(3, 57, $m = 17$) and FC(3, 88, $m = 11$), respectively. For these structures the value of FSR is 3.2 nm, we can use two cascaded structures for odd or even channel filters. Central wavelengths of the resulted cascaded structure would be 1.6 nm.

In Table 4, there is only one odd integer value of m ($m = 1.008$), which is for the FC(4, 31) structure. Reflection spectrum of FC(4, 31, m =1) structure is illustrated in Fig. 6, where the FSR for this filter

Table 3. Values of m for different values of n and FSR ($\lambda_C = 1550.12\,\text{nm}$) for FC(3, n) structure.

n	FSR (nm)		n	FSR (nm)		n	FSR (nm)	
	1.6	3.2		1.6	3.2		1.6	3.2
11	176.150	88.075	41	47.260	23.630	71	27.291	13.645
12	161.471	80.735	42	46.135	23.067	72	26.912	13.456
13	149.050	74.525	43	45.062	22.531	73	26.543	13.272
14	138.404	69.202	44	44.038	22.019	74	26.184	13.092
15	129.177	64.588	45	43.059	21.529	75	25.835	12.918
16	121.103	60.552	46	42.123	21.061	76	25.495	12.748
17	113.979	**56.990**	47	41.227	20.613	77	25.164	12.582
18	107.647	53.824	48	40.368	20.184	78	24.842	12.421
19	101.982	**50.991**	49	39.544	19.772	79	24.527	12.264
20	96.883	48.441	50	38.753	19.377	80	24.221	12.110
21	92.269	46.135	51	37.993	**18.997**	81	23.922	11.961
22	88.075	44.038	52	37.263	18.631	82	23.630	11.815
23	84.246	42.123	53	36.559	18.280	83	23.345	11.673
24	80.735	40.368	54	35.882	17.941	84	23.067	11.534
25	77.506	38.753	55	35.230	17.615	85	22.796	11.398
26	74.525	37.263	56	34.601	17.300	86	22.531	11.265
27	71.765	35.882	57	33.994	**16.997**	87	22.272	11.136
28	69.202	34.601	58	33.408	16.704	88	22.019	**11.009**
29	66.816	33.408	59	32.842	16.421	89	21.771	10.886
30	64.588	32.294	60	32.294	16.147	90	21.529	10.765
31	62.505	31.252	61	31.765	15.882	91	21.293	10.646
32	60.552	30.276	62	31.252	15.626	92	21.061	10.531
33	58.717	29.358	63	30.756	15.378	93	20.835	10.417
34	**56.990**	28.495	64	30.276	15.138	94	20.613	10.307
35	55.361	27.681	65	29.810	14.905	95	20.396	10.198
36	53.824	26.912	66	29.358	14.679	96	20.184	10.092
37	52.369	26.184	67	28.920	14.460	97	19.976	9.988
38	50.991	25.495	68	28.495	14.247	98	19.772	9.886
39	49.683	24.842	69	28.082	14.041	99	19.572	9.786
40	48.441	24.221	70	27.681	13.840	100	19.377	9.688

Table 4. Values of m for different values of n and FSR ($\lambda_C = 1550.12\,\text{nm}$) for FC(4, n) structure.

n	FSR (nm)		n	FSR (nm)	
	1.6	3.2		1.6	3.2
11	16.014	8.007	31	2.016	**1.008**
13	11.465	5.733	33	1.779	0.890
15	8.612	4.306	35	1.582	0.791
17	6.705	3.352	37	1.415	0.708
19	5.367	2.684	39	1.274	0.637
21	4.394	2.197	41	1.153	0.576
23	3.663	1.831	43	1.048	0.524
25	3.100	1.550	45	0.957	0.478
27	2.658	1.329	47	0.877	0.439
29	2.304	1.152	49	0.807	0.404

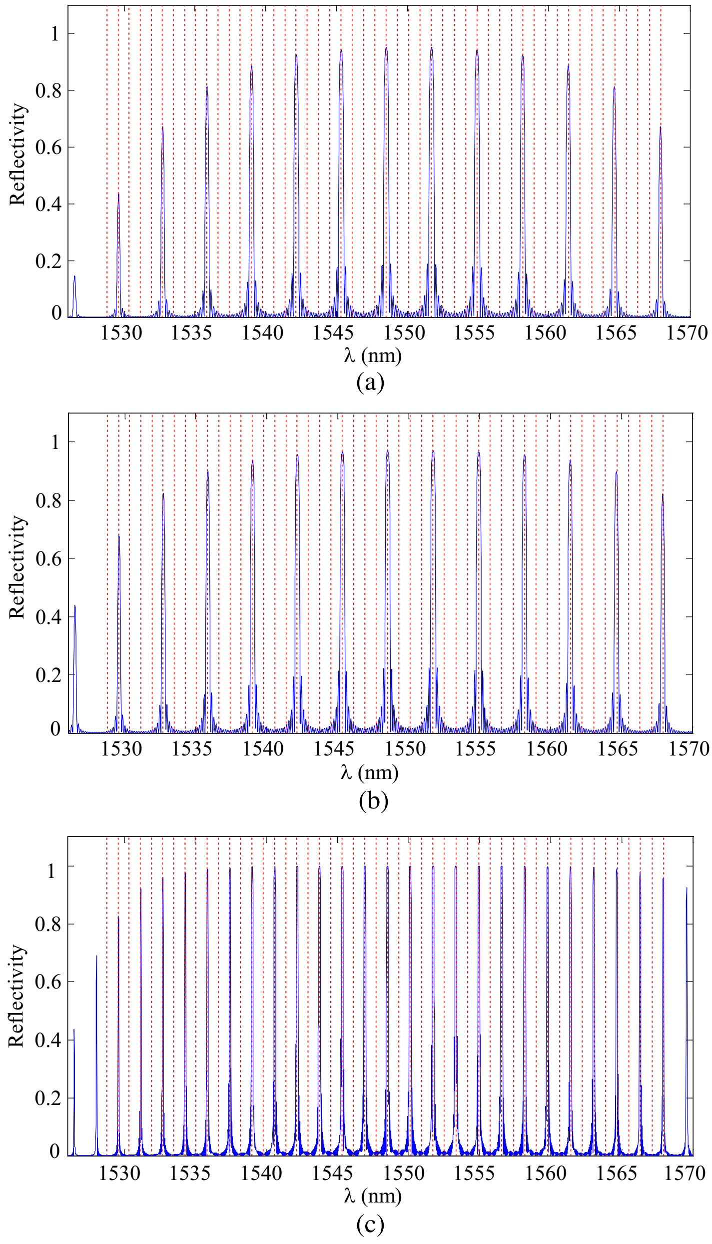
Table 5. Two physical parameters of selected structures from Table 3 and Table 4.

Structure	Length (mm)	Number of A layers
FC(3, 51, $m = 19$)	13.182	51
FC(3, 57, $m = 17$)	14.735	57
FC(3, 88, $m = 11$)	22.738	88
FC(4, 31, $m = 1$)	7.947	962

structure is 3.2 nm.

Similar to selected structures of the Table 3, two FC(4, 31, $m = 1$) should be cascaded in order to achieving 1.6 nm for the FSR. In order to comparison the selected FC(j, n, m) filter structures, two physical parameters of these structures are presented in Table 5. The structures with smaller lengths and layer numbers are preferred from the fabrication view. Short length of the filter may be an advantage from manufacturing and insertion loss point of views.

In Figs. 5 and 6, another important problem is the high reflection sidelobes in the reflection bands which can cause a high crosstalk between the adjacent channels, so they should be eliminated in these filters. These sidelobes are due to large Δn, which causes resonance in the reflectivity, and occur on the both sides of each stop band in the reflection spectrum. An appropriate method for reduction of the sidelobes in the reflection spectrum is the refractive index profile apodization [30]. The apodization is done by multiplying the index



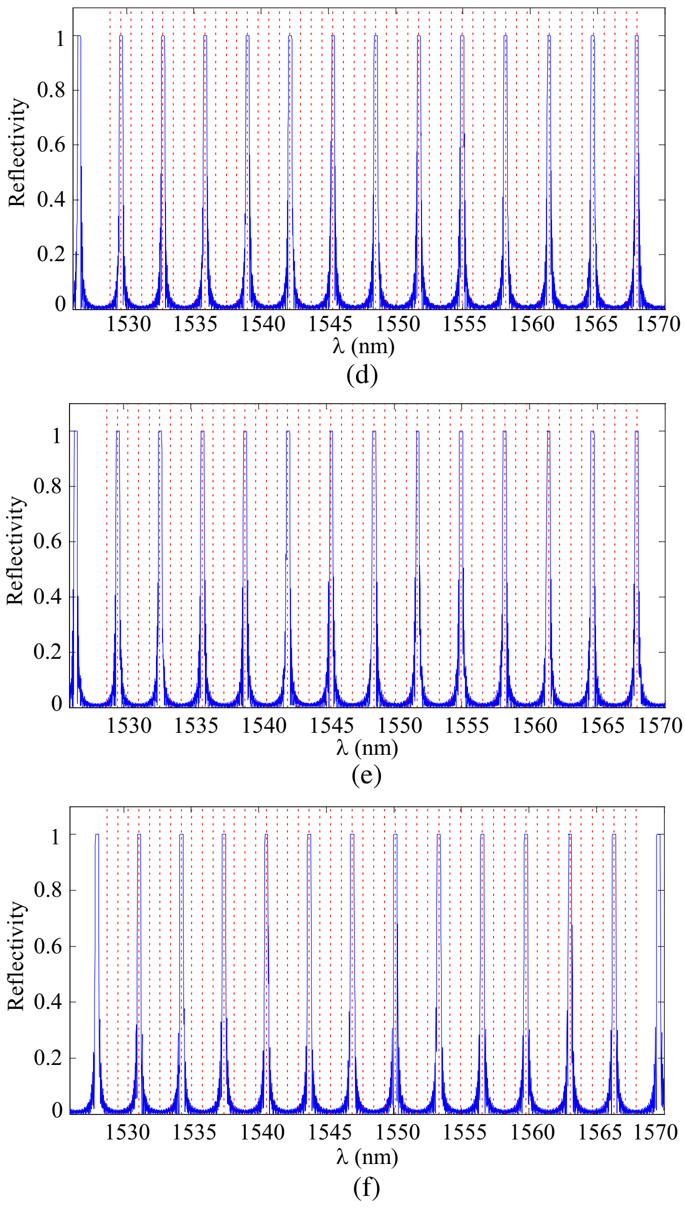


Figure 5. Reflection spectrum of the chosen structures from Table 3, $n_a = 1.65$, $n_b = 1.45$, $\lambda_C = 1550.12$. (a) FC(3, 17, $m = 57$), (b) FC(3, 19, $m = 51$), (c) FC(3, 34, $m = 57$), (d) FC(3, 51, $m = 19$), (e) FC(3, 57, $m = 17$), and (f) FC(3, 88, $m = 11$).

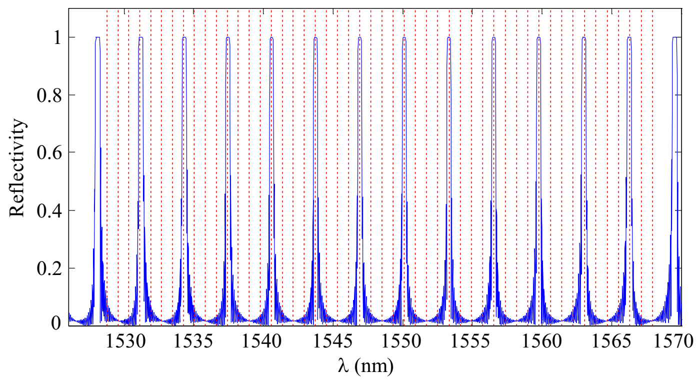


Figure 6. Reflection spectra of the FC(4, 31, $m = 1$), $n_a = 1.65$, $n_b = 1.45$, $\lambda_C = 1550.12\,\text{nm}$.

profile by an envelope function, such as Gaussian:

$$g(z) = h \times \exp\left[-\left(\frac{z - 0.5L}{\sigma L}\right)^2\right], \tag{8}$$

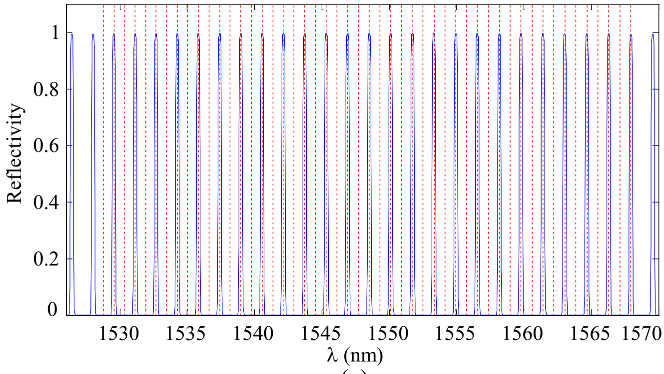
where, z is the coordinate along which the apodization is performed, L is the length of the structure, and h and σ are the amplitude and the standard deviation of the apodization function, respectively. We have assumed that the apodized indices $n_a(z)$ and $n_b(z)$ have the general form of

$$n_{a,\,b}(z) = n_0 + \Delta n_{a,\,b} \times g(z) \tag{9}$$

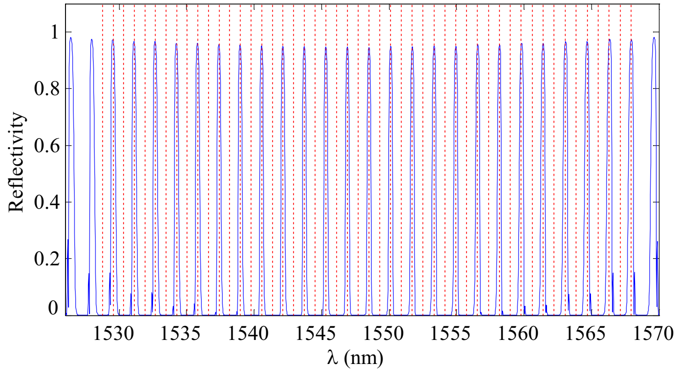
in which, n_0 is the reference refractive index and $\Delta n_{a,b}$ are the apodized portion of the refractive indices of the layers A and B.

Figure 7 demonstrates the result of apodization applied on two cascaded FC(3, 51, $m = 19$) and FC(4, 31, $m = 1$) structures, which dedicated to the even channels filter. This figure illustrates that the sidelobes have been sufficiently reduced, and as can be seen from Fig. 8, the maximum crosstalk between the adjacent channels is about $-35\,\text{dB}$, which is an acceptable value.

As seen from Fig. 7, the apodization process will led to a reduction in the maximum reflectance of the filter, specially in the middle bands. This reduction cause more insertion loss in the overall interleaver/deinterleaver structure. The insertion loss due to the apodization, for the FC(4, 31, $m = 1$) structure is more than the FC(3, 51, $m = 19$) structure. Figs. 8(a) and 8(b) show enlarged central part of the Figs. 7(a) and 7(b), respectively. Using these figures, we can see the induced apodization insertion loss to the apodized FC(3, 51, $m = 19$) and FC(4, 31, $m = 1$) structures. comparison of physical



(a)



(b)

Figure 7. Spectral reflectance of two cascaded, (a) FC(3, 51, $m = 19$) and (b) FC(4, 31, $m = 1$) after apodization. The parameters are: $n_0 = 1.43$, $\Delta n_a = 0.2$, $\Delta n_b = 0$, $\sigma = 0.3$, $h = 1.0$, $\lambda_{C1} = 1546.92\,\text{nm}$, $\lambda_{C2} = 1548.512\,\text{nm}$.

structures in selected filters (FC(3, 51, $m = 19$) and FC(4, 31, $m = 1$)) shows that the first one is indeed a periodic structure but the later one is in some degree a quasiperiodic structure and this quasiperiodicity leads to increase in layers count and hence the complexity of the filter and a reduction in length of the filter. While the later one is an advantage, the first one is a disadvantage and leads to difficulty in fabrication. Although the second filter shows that we can achieve a periodic response from a quasiperiodic structure, but it can be guessed that due to increase in complexity of structure fabrication costs of filters based on this quasiperiodic structure will be more than those based on periodic structure.

Now, we can make the final decision to choose the desired structure, between the suggested structures. Using Table 5 and

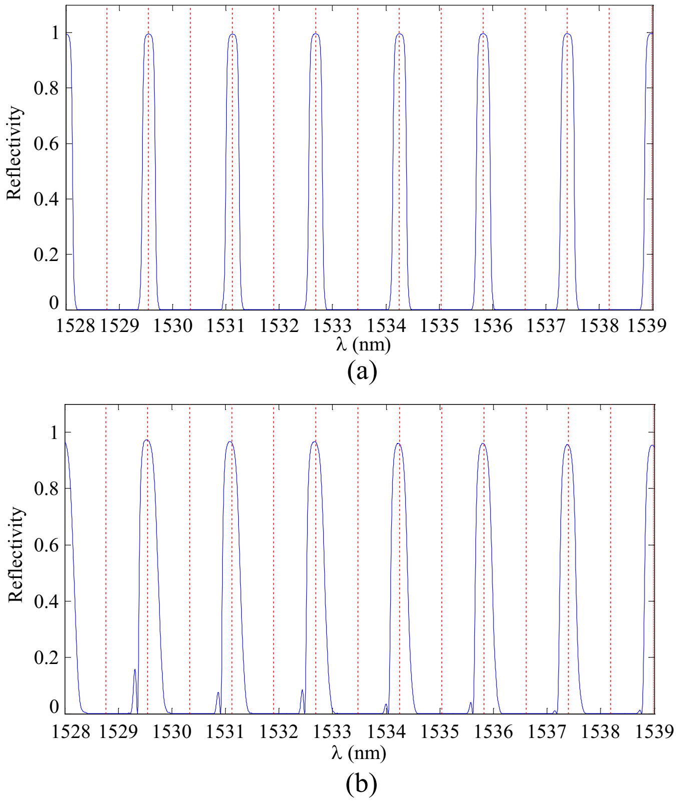


Figure 8. Closer look at spectral reflectance of two cascaded (a) FC(3, 51, $m = 19$) and (b) FC(4, 31, $m = 1$) in left side of the C-band after apodization. The parameters are: $n_0 = 1.43$, $\Delta n_a = 0.2$, $\Delta n_b = 0$, $\sigma = 0.3$, $h = 1.0$, $\lambda_{C1} = 1546.92\,\text{nm}$, $\lambda_{C2} = 1548.51\,\text{nm}$.

Fig. 8 we choose two cascaded FC(3, 51, $m = 19$) structures for odd and even channel filtering in the proposed interleaver/deinterleaver configuration.

In Fig. 9 reflection responses of two filters designed for odd and even channels are shown on the same axis before and after apodization. This figure illustrates that the central wavelengths of the proposed filter bands are according to ITU-T grid. In order to have a closer view, Fig. 10 demonstrates an enlarged part of Figs. 9(a) and 9(b), respectively.

So far, we have designed the reflective filters with the FC(3, 51, $m = 19$) structure, which can reflect the odd and even channels in a optical DWDM system. Now, we are going to evaluate the response

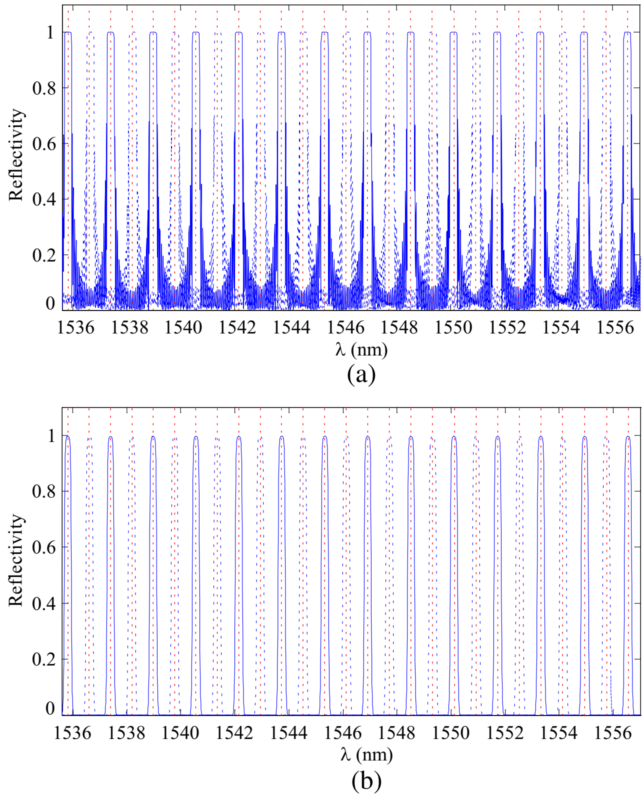


Figure 9. Spectral reflectance of two filters designed by FC(3, 51, $m = 19$) for odd (solid line) and even (dashed line) channels in the C-band (a) before and (b) after apodization. The parameters are: $n_0 = 1.43$, $\Delta n_a = 0.2$, $\Delta n_b = 0$, $\sigma = 0.3$, $h = 1.0$, $\lambda_{C1} = 1546.92\,\text{nm}$, $\lambda_{C2} = 1548.51\,\text{nm}$ for odd channels filter and $\lambda_{C1} = 1546.12\,\text{nm}$, $\lambda_{C2} = 1547.72\,\text{nm}$ for even channels filter.

of the proposed interleaver/deinterleaver structure. The proposed structure is composed of the passive filters and circulators, which have no induced time delay but have some induced insertion loss, typically in the range of 0.5 to 0.8 dB.

In our proposed structure, deinterleaving of the channels contains two and three circulation process for the odd and even channels, respectively. This means that the odd and even channels experience 1.2 and 1.8 dB circulation loss, respectively, thus all channels do not arrive the receiver with the same level of the power.

In the proposed structure, interleaving of the channels contains one and three circulation process for the odd and even channels,

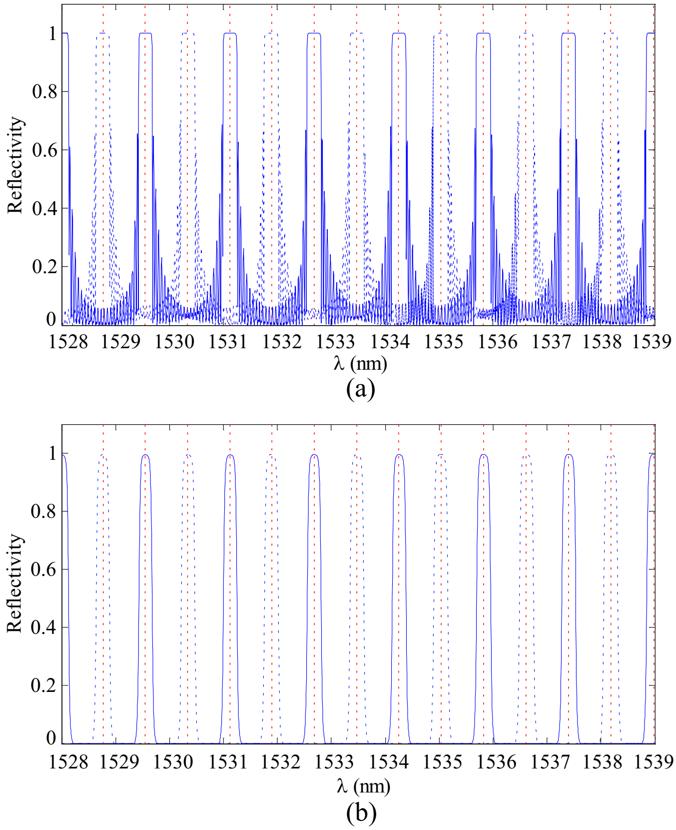


Figure 10. Closer look at spectral reflectance of two filters designed by FC(3, 51, $m = 19$) for odd (solid line) and even (dashed line) channels in the C-band (a) before and (b) after apodization. The parameters are: $n_0 = 1.43$, $\Delta n_a = 0.2$, $\Delta n_b = 0$, $\sigma = 0.3$, $h = 1.0$, $\lambda_{C1} = 1546.92\,\text{nm}$, $\lambda_{C2} = 1548.51\,\text{nm}$ for odd channels filter and $\lambda_{C1} = 1546.12\,\text{nm}$, $\lambda_{C2} = 1547.72\,\text{nm}$ for even channels filter.

respectively. This means that the odd and even channels experience 0.6 and 1.8 dB circulation loss, respectively, thus all channels do not arrive the end station with the same level of the power. This seems to be a drawback of the proposed structure in Fig. 2, but using highly sensitive detectors with lower thresholds this problem will be solved.

6. CONCLUSIONS

We have proposed an interleaver/deinterleaver based on Fibonacci-class quasi-periodic structures and circulators. The odd and even channels are interleaved/deinterleaved with DWDM multichannel filters constructed from Fibonacci quasi-periodic structures. We have used three DWDM filters in order to separate the odd and even wavelength channels. We have shown that FC(3, 51, $m = 19$) structure with different geometrical and physical parameters can act as DWDM filters. In order to have odd and even channels filter, different central wavelengths for two FC(3, 51, $m = 19$) structures have been chosen. For 32 transmission channels with 0.8 nm spacing the filters parameters are specified. It is shown that the proposed structure can separate these 32 channels into two 16-channel sets with 1.6 nm channel spacing and in the opposite direction combine two 16-channel sets with 1.6 nm channel spacing into 32 channels with 0.8 nm spacing. In order to eliminate the crosstalk between the adjacent channels, we have applied refractive index profile apodization in the FC(3, 51, $m = 19$)'s refractive index profile and shown the filter response. The ability of the quasi-periodic structures in comb filtering of the high channel count DWDM systems has been demonstrated. These structures are useful for multiplexing/demultiplexing of the high number of the channels. The length of the proposed DWDM multichannel filters is about 13 mm, which is very high for using deposition technologies as a fabrication method because in the best case speed of these technologies such as thermal evaporation, ion-assisted deposition or sputtering is about 5–10 nm/s. Therefore, we recommend photolithographic method for fabrication of these filters [31].

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