

Design of Equalized ROADMs Devices with Flexible Bandwidth Based on LCoS Technology

Mónica Carrero Mora, Alfredo Martín Mínguez, Paloma R. Horche,

Abstract— This paper describes the theory, design, applications and performance of a new Reconfigurable Add-drop Multiplexer (ROADM) with flexible bandwidth allocation. The device can address several wavelengths at the input to four output fibers, according to the holograms stored in a SLM (Spatial Light Modulator), where all the outputs are equalized in power. All combinations of the input wavelengths are possible at the different output fibers. Each fiber has assigned all the signals with the same bandwidth; the possible bandwidths are 12.5GHz, 25GHz, 50GHz and 100GHz, according to ITU-T 694.1 Recommendation. It is possible to route several signals with different bandwidth in real time thanks to Liquid Crystal over Silicon (LCoS) technology.

Keywords— ROADMs; LCoS technology; Flexible bandwidth selection; Mixed holograms; Cascaded ROADM effect.

I. INTRODUCTION

The increment of high speed services requires DWDM optical transport networks in order to transport them. Currently, these networks are able to carry 10/40/100Gbps channels and in a near future, 400Gbps and 1Tbps channels. The evolution towards 400Gbps/1Tbps channels produces the increment of the bandwidth per channel. To ensure the coexistence of channels with different speed and bandwidth, ROADM devices are the key components.

Different technologies have been proposed for the implementation of ROADMs, like MEMS or LC; each one has its own advantages and drawbacks, but neither is able to route channels with flexible bandwidth, only they can route with a fixed grid due to the size of the pixel. The main characteristic of holographic ROADMs is the easy way of changing the tuning and power level of the signal at the output fiber by the implementation of different holograms in real time.

In section 2 of this paper the operation principle of the device is described, based on the diffraction produced when the light passes through a fixed grating and SLM where phase holograms are stored. Section 3 is dealing with the design of the holographic device, taking into account the focal distance for the lens, spatial period for the fixed grating, position of output fibers, and the number of pixels in the SLM. Section 4 shows the transfer function of the ROADM and the operational limitations. Section 5 studies the possibilities of mixed holograms for different

wavelengths. In Section 6 it is developed an equalized solution with SOA. And, finally, Section 7 gives an explanation about the effects of cascaded ROADMs transfer function in optical networks.

II. BASIC OPERATION PRINCIPLE

The working principle of our device is based on the angular dispersion (diffraction) of the incident wavelength when a polychromatic light reaches a diffraction grating. Considering the incident light perpendicular to the grating, the relationship between the diffraction angle, β , and the wavelength, λ , is given by

$$\sin\beta = \frac{m\lambda}{d} \quad (1)$$

where m is the diffraction order and d the grating spatial period. For dynamic hologram applications, $m = +1$ is usually considered because it is the first diffraction order with the maximum intensity; in (1) $d > \lambda$ has to be reached. According to (1), if there is a change in the spatial period d or in the incident light wavelength, λ , the diffraction angle, β will also change. Consequently, we can implement an optical router by using this phenomenon.

A. Implementation with a SLM

Most of the diffraction gratings have a fixed period, which prevents the implementation of tunable devices. A way to allow these variations is to use a Spatial Light Modulator (SLM) to implement Computer Generated Holograms (CGH). The pixelated structure of the SLM produces the effect of a two-dimensional diffraction grating when the device is illuminated with coherent light. In the SLM every Liquid Crystal over Silicon (LCoS) micropixel can be electro-optically configured to provide a phase modulation for the incident light.

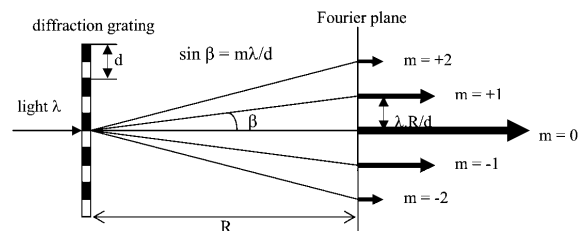


Fig. 1 Diffraction grating effect

Therefore, by managing the hologram on the SLM and its spatial period, we obtain a programmable diffraction grating [1]. The micropixel size is supposed to be thousands times lower than the typical pixel size (10 μm), about 10 nm. In order to obtain enough resolution it is necessary to use a fixed diffraction grating, with a high spatial frequency (low spatial period), together with the SLM giving a high resolution filter. The two parameters that impact strongly on the size of the optical device are the focal distance of the lens, f , and the product ND , where D is the size of the micropixel and N is the number of micropixels in one dimension of the SLM.

The relationship between the hologram spatial period and ND is:

$$H = \frac{N \cdot D}{n} < n < \frac{N}{2} \quad (2)$$

where n is an integer number which depends on the type of hologram (pattern), typically black/white bars for this application.

III. DESIGN OF A FLEXIBLE BANDWIDTH HOLOGRAPHIC DEVICE

A. ROADM structure

In order to design a holographic optical device, a “4f-folded” structure is chosen using transmissive SLM and transmissive fixed grating. We have chosen this type of structure due to the reduced size of the device in comparison with other possible structures, like “lineal 4f”, where the dimension in the optical axis is four times the local distance of the lens used. Fig. 2 illustrates the holographic structure selected for the present device. The holograms (black and white bars) are uploaded via a PC-based interface. The SLM-LCoS and fixed grating are illuminated by a collimated light coming from a single mode optical fiber by means of a lens. At the SLM the light is reflected and comes back through a convergent lens that couples the first order or the diffracted light in the output optical fibers. The output fibers are placed at the lens focal plane where the Fourier Transform of the hologram stored in the SLM is located.

The relationship between the system diffraction angles is in agreement with the expression:

$$\arctg\left(\frac{x}{f}\right) = \arcsin\left(\frac{\lambda}{d}\right) - \Phi + \left(\frac{2n\lambda}{N \cdot D}\right) \quad (3)$$

where x is the distance of the output optical fiber to the optical axis, f is the local distance of the lens, d is the spatial period of the fixed grating and ND/n is the hologram spatial period.

For small angles, equation (3) can be simplified as follows:

$$\lambda \approx \frac{x}{f} * \frac{1}{\left(\frac{n}{N \cdot D} + \frac{1}{d}\right)} \quad (4)$$

B. Bandwidth selection

Starting from the previous scheme, we can design a tunable filter with an operating wavelength range $\Delta\lambda = \lambda(n=0) - \lambda(n=N/2)$ and a central wavelength channel for the filter, λ_0 is obtained for $n = N/4$ from (4).

The 3dB passband width, BW, for each wavelength channel tuned is limited by the output optical fiber characteristics and

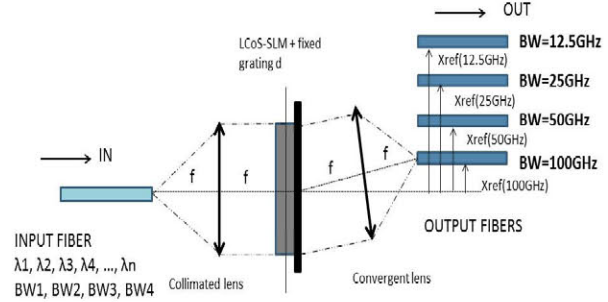


Fig. 2. Structure of a ROADM with Flexible Bandwidth

the wavelength coupled inside the core fiber diameter Φ_{core} (for a single mode fiber, $\Phi_{core} = 9 \mu\text{m}$). According to 3 dB passband expression of [2] for SLM-FLC and taking into account the size of LCoS pixel instead of FLC pixel, we obtain the following equation:

$$\Delta\lambda_{BW} = \frac{\Phi_{core} \left(1 - \left(\frac{\lambda_0}{d} + \frac{\lambda_0}{H}\right)^2\right)}{f \left\{ \frac{1}{H} + \frac{1}{d \sqrt{1 - \frac{\lambda_0^2}{d^2}}} \right\}} \quad (5)$$

where λ_0 is the central wavelength, H is the hologram spatial period, d is the spatial period of fixed grating and f is the lens focal distance.

The purpose of our new design is transmitting DWDM signals with spectral bandwidth according to ITU-T G.694.1: 12.5GHz, 25GHz, 50GHz and 100GHz. Therefore, each bandwidth is routed towards one specific output fiber. This assignment is showed in Fig. 2; Table I is in agreement with that.

TABLE I. SELECTED BANDWIDTH

Selected Bandwidth		
Output Fiber	BW(GHz)	BW(nm)
1	12.5	0.1
2	25	0.2
3	50	0.4
4	100	0.8

C. Selection of focal distance and ND values

The collimated light through SLM has to illuminate the maximum area to achieve minimum losses. In order to obtain it and considering optical Gaussian laws, the following condition must be reached:

$$\frac{f}{N \cdot D} = \frac{\pi \cdot \Phi_{core}}{4 \cdot \lambda_o} = 4,56, = 4,56 N \cdot D, \quad (6)$$

where $\Phi_{core} = 9 \mu m$. In DWDM systems channels are allocated between $\lambda_{min}=1530$ nm and $\lambda_{max}=1625$ nm, with central wavelength channel $\lambda_o = 1550$ nm.

In Fig. 3, we can observe the former situation; when $f'_{opt} > f_{opt}$, just a part of the ND surface is illuminated and some losses are produced.

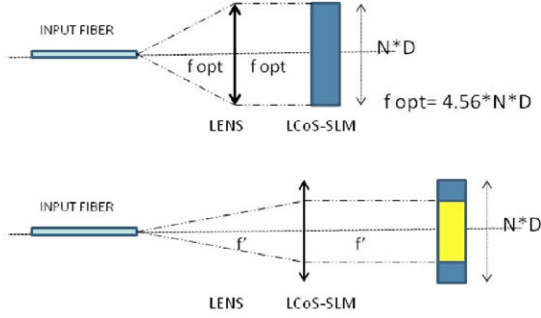


Fig.3. SLM illumination by the input light according focal distance value

As a practical value we assume $f = 8$ mm; and thus, from (6) a value of 1.75mm for ND is obtained. Taken $D = 10$ nm (it is supposed 1000 times lower than FLC pixel size) for SLM pixel size, $N = 1.75 \cdot 10^5$.

D. Selection of the spatial period d of fixed grating

The spatial period of fixed grating follows the diffraction laws, $\sin \alpha = \frac{\lambda}{d}$, where α is the output angle of the incident beam. The sin of whatever angle cannot be higher than one, therefore, $d \geq \lambda_o = 1550$ nm.

Due to (5), we found other limitation:

$\left(1 - \lambda_o^2 \cdot \left(\frac{1}{d} + \frac{1}{H}\right)^2\right) > 0$, where we extract that $H \geq \frac{\lambda_o}{1 - (\lambda_o/d)^2}$. The minimum size of spatial period H depends on the size of spatial period of fixed grating and central wavelength.

An inverse relationship between spatial period of the grating fixed d and spatial period H is reached, this implies the need of high resolution to get the desired bandwidth.

For this reason, the most recommended d is bounded between $2.0 \mu m \leq d \leq 2.6 \mu m$, which ensures a lower required resolution, less system size and wavelength limitation. The first value of d which covers the entire bandwidth is $d = 2.3 \mu m$. In the Fig. 4 we can observe the result of (5) with $\lambda_o = 1550$ nm, the value of H to obtain a bandwidth.

The bandwidth graph introduces two sections; the first one can be approximated by a line with a high slope for short H values. The second section grows asymptotically, it is being necessary to increase large H values in order to obtain a short bandwidth difference.

The hologram spatial period has the following equation:

$$H = \frac{N \cdot D}{n} \quad (7)$$

where ND is the size of one dimension of the SLM and n is an integer number which depends on the type of hologram (pattern). We can choose the hologram in the computer depends on the value of n . In the Table II, it can be found the values of n to obtain a specific bandwidth for $\lambda_o = 1550$ nm.

TABLE II. H, N AND n VALUES FOR 12.5, 25, 50 AND 100GHZ

H, N and n values for 12.5, 25, 50 and 100 GHz			
BW (GHz)	H (μm)	Number of micropixel	$n = N \cdot D / H$
12,5	5,33	533	329
25,0	6,04	604	290
50,0	8,14	814	215
100,0	22,82	2282	77

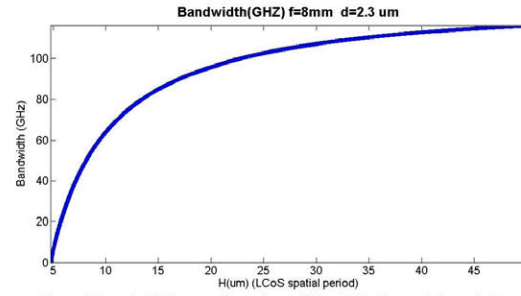


Fig. 4 Bandwidth as a function of the LCoS spatial period

E. Position of the output fibers

The design includes four output single mode fibers to route signal with bandwidths: 12.5GHz, 25GHz, 50GHz and 100GHz. Thus, signals which have 50GHz bandwidth will be directed to the same output fiber. In order to obtain this situation, each output fiber has to be located on a different x distance to the optical axis. The x position will be defined by:

$$x_n = \lambda_{ref} \cdot f \cdot \left(\frac{n}{N \cdot D} + \frac{1}{d}\right) = \lambda_{ref} \cdot f \cdot \left(\frac{1}{H_{BW}} + \frac{1}{d}\right) \quad (8)$$

where λ_{ref} is the central wavelength, f is the focal distance of lens, H is the hologram spatial period fixed by the bandwidth and λ_{ref} and d is the spatial period of fixed grating.

If the fibers used are $9/125 \mu m$, contiguous output optical fibers have to be separated more than $\Delta x = 125 \mu m$ in the line perpendicular (x) to the optical axis due to the cladding diameter of single mode fibers. Table III summarizes the position of each output fiber depending on the bandwidth.

F. Wavelength working range

The maximum wavelength range which our device is able to work depends on the n values to select in the computer. Thereafter, these parameters have the following expression:

$$\lambda_{max} = \frac{x_{ref}(50GHz)}{f} \cdot \frac{1}{\left(\frac{n_{min}+1}{N.D}\right)} \quad (9)$$

$$\lambda_{min} = \frac{x_{ref}(50GHz)}{f} \cdot \frac{1}{\left(\frac{n_{max}+1}{N.D}\right)} \quad (10)$$

where n_{min} is the minimum number of bar pairs in the hologram spatial period of SLM which corresponds with maximum BW (100GHz) and n_{max} corresponds with the minimum BW (12.5GHz). The x_{ref} value is the position of the output fiber with the 50GHz bandwidth, because it is the typical bandwidth in DWDM signals.

TABLE III POSITION OF THE FOUR OUTPUT FIBERS DEPENDING ON THE BANDWIDTH

Output Fiber	Position of the four output fiber	
	Output fiber bandwidth (GHz)	Output fiber position x (mm)
1	12.5	7,7178
2	25	7,4443
3	50	6,9146
4	100	5,9347

Table IV shows the maximum and minimum wavelength values. The wavelength range is 417.4 nm which includes the DWDM range from 1530.0413 nm to 1624.8914 nm.

TABLE IV WAVELENGTH WORKING RANGE AT THE INPUT

Parameter	Wavelength working range at the input			
	λ (nm)	n	BW (GHz)	x_{min}/x_{max} (mm)
λ_{max}	1805	77	100	6,9146
λ_{min}	1387	329	12.5	6,9146

The device will get the tuning of a specific wavelength changing the hologram spatial period of SLM, $H = N.D/n$, through the n parameter. The output fiber positions are proper to assign the central wavelength $\lambda_0 = 1550$ nm depending on the bandwidth. In order to tune whatever wavelength according to its bandwidth goes to the correct fiber and maintaining them in the same place, it is necessary to adapt the hologram spatial period. This value is calculated with (5), but with the correct wavelength value. Table V includes two wavelength examples with different bandwidths.

TABLE V H AND n VALUES ASSIGNMENT DEPENDING ON WAVELENGTH AND BANDWIDTH

Wavelength (nm)	H and n values assignment depending on wavelength and bandwidth				
	Output fiber	BW (GHz)	H (μ m)	n	x (mm)
1520	1	12.5	5,01	350	7,7133
1520	2	25	5,65	310	7,4459
1560	3	50	8,39	209	6,9165
1560	4	100	24,55	72	5,9395

It is highlighted that our device switches the input wavelengths depending on the signal bandwidth and all

signals with the same bandwidth are sent to the same output fiber.

IV. TRANSFER FUNCTION OF THE HOLOGRAPHIC FILTER

In [2] the spectral function of a SLM-FLC filter was measured. They obtained until -3dB, a passband which can be approximated for a 1st order Gaussian shape. However, it presented, from 20-30 dB, larger "tails" and the shape is like a Bessel function, which goes to zero slower than a Gaussian filter.

The holographic filter based on SLM-LCoS presents an analogous spectral function like a SLM-FLC device. Therefore, we consider that the spectral function at -3dB can be approximated by Gaussian filter and its tails by Bessel filter. It does not know exactly the Gaussian filter order, but the most common orders are 1st, 2nd and 3rd. The power characteristic of n order Gaussian filter has the following expression:

$$H(f) = \alpha * e^{-\ln(\sqrt{2}) * \left(\frac{f-f_c}{\frac{B}{2}}\right)^{2*N}} \quad (10)$$

where α is the insertion loss, f_c is the central frequency of the filter, B is the bandwidth and N is the filter order. The power characteristic of n order Bessel filter is the following:

$$H(s) = \alpha \frac{d_0}{B_n(s)}, s = j\left(\frac{z(f-f_c)w_b}{B}\right) \quad (11)$$

where B_n is an n th-order Bessel polynomial, $B_n = \sum_{k=0}^n d_k s^k$; d_0 is a normalizing constant, $d_0 = \frac{(2n)!}{2^{2n} n!}$, w_b denotes the normalized -3 dB bandwidth.

The transfer function of the SLM-LCoS filter appears in the Fig. 5. The central wavelength is 1550nm with 0.4nm bandwidth.

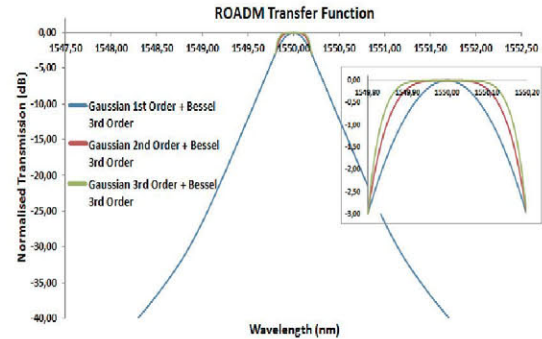


Fig. 5 Transfer function of a SLM-LCoS filter

A. Wavelength resolution for input signals

The minimum distance between central wavelengths of input signals is limited by wavelength resolution of the filters. There are two factors which influence in the resolution $\Delta\lambda$:

- Attenuation limitation: in order to avoid interference between signals it is necessary that the central wavelength of each filter should coincide in the tails

of the right and left filters. 30dB attenuation is a suitable value.

- Paramter n limitation: the n value allows selecting the hologram spatial period for each wavelength and bandwidth. The wavelength resolution will be limited by the minimum variation of n that it is possible to achieve. Equation (12) present the expression of n and how it changes depends on wavelength

$$n = \left(\frac{x_{\text{ref}}}{\lambda * f} - \frac{1}{d} \right) * N * D$$

$$\frac{\Delta n}{\Delta \lambda} = \frac{-x_{\text{ref}} * N * D}{\lambda^2 * f} \quad (12)$$

The minimum n variation which we can achieve in the computer is 1. Table VI summarizes the resolution wavelength $\Delta\lambda$ depending on the limitation factor.

TABLE VI LIMITATION FACTORS FOR FILTER RESOLUTION

BW (GHz)	Limitation factors for filter resolution	
	Attenuation value $\Delta\lambda$ (nm)	n value $\Delta\lambda$ (nm)
12.5	0,42	1,4222
25	0,8	1,4750
50	1,2	1,5883
100	3,0	1,8499

Finally, the limitation factor is the attenuation and each central wavelength has to be separated $\Delta\lambda = 3$ nm to assure even that a 100 GHz signals do not have interference.

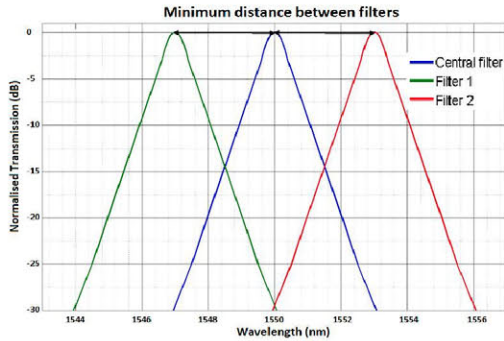


Fig. 6 Separation between input signals for not interference

V. MIXED HOLOGRAMS OPERATION

In order to get wavelengths switching towards the proper output fiber depending on the bandwidths, it is necessary the mixed hologram implementation. This operation mode is done by the selection in the SLM of a mixed hologram composed of all individual holograms corresponding to each input wavelength and bandwidth. Fig 7 shows an example for three input wavelengths and its holograms, formed, in this case, by black and white bars.

Table VII shows an application example of mixed holograms. Using a mixed hologram with different n values 329+290+215+77, a 1550 nm wavelength appears in the output of the four fibers, f_1 , f_2 , f_3 and f_4 , having the

following bandwidth: 12.5 GHz in f_1 , 25 GHz in f_2 , 50 GHz in f_3 and 100 GHz in f_4 .

VI. HOLOGRAPHIC DEVICE LOSSES AND EQUALIZATION

The losses produced in a holographic router are due to different causes:

- Diffraction losses: the total optimized loss is 4.5dB.
- Intrinsic SLM losses: a typical value of 1dB is considered.
- Fiber/lens coupling losses: for 90% efficiency, 0.5 dB is added.
- Losses for adding holograms: the number of channels is 4 and therefore the additional loss is 6dB.

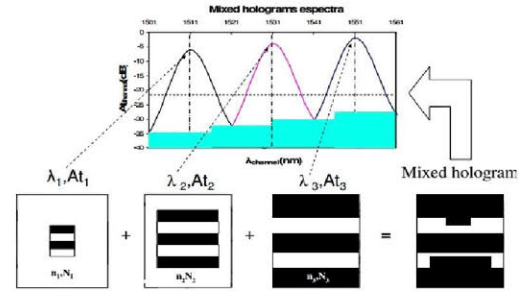


Fig. 7. Mixed holograms building

TABLE VII H AND n VALUES FOR MIXED HOLOGRAMS OPERATION

λ_{in} (nm)	H and n values for mixed holograms operation					
	Output Fiber	BW (GHz)	x (mm)	n	H (μm)	λ_{out} (nm)
1550	1	12,5	7,7177	329	5,33	1550
1550	2	25	7,4442	290	6,04	1550
1550	3	50	6,9146	215	8,14	1550
1550	4	100	5,9346	77	22,82	1550

There are 12 dB of total losses in the holographic device which is necessary to compensate. In order to reach it and to compensate the different response of the network components and distances for the used channel wavelength, a gain component, like a Semiconductor Optical Amplifier (SOA) has to be employed. The total equalization takes into account the gain-wavelength variation of this amplifier, ΔG_A . The target is to have at the output fibers a net loss of 0dB.

$$G_T = G_A - \Delta G_A - 10 * \log(n^{\circ}\text{channels}) - L_{HR} - \Delta At \quad (13)$$

where ΔAt is the total attenuation range for channel to be equalized at the input of the device; L_{HR} is the intrinsic holographic router losses and the term $10 * \log(n^{\circ}\text{channels})$ is due to the mixed holograms. According to the chosen SOA characteristics, we talk of typical gain of 17-22dB, bandwidth of 60nm with central wavelength 1550nm, noise figure of 7dB and low

polarization sensitivity (1.0 dB). Fig. 8 shows the final design of our equalized ROADM.

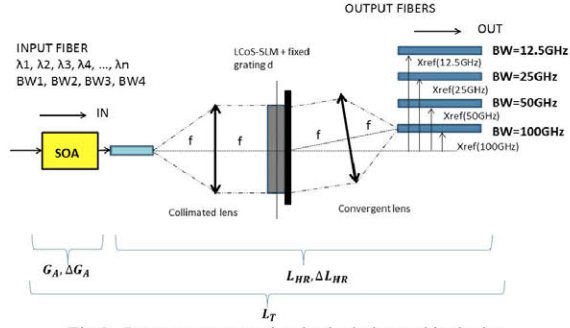


Fig. 8. Losses compensation in the holographic device

VII. STUDY OF CASCADED ROADMS

Each ROADM behaves as an optical filter. In the transparent optical network, an optical signal may be passing through several ROADMs before it has reached its destination. When the signal passes through cascaded ROADMs its influence towards the signal can be referred as a filter concatenation effect. This effect produces a narrowed passband filtering and clipping signal effect, and also it introduces strong chromatic dispersion because of the variations in filter phase, loss and group delay ripples.

The effective transfer function of cascaded filter is the product of every individual filter. Therefore, the effective transmission bandwidth of cascaded filters will be narrower than the bandwidth of an individual filter. Furthermore, when the center frequency of the cascaded filters is misalignment, it will further narrow the effective bandwidth. According to the studied transfer function, our ROADM has a Gaussian shape within passband -3dB and Bessel shape from -30dB. In this case, we want to characterize the narrowed effect of bandwidth of the signal when it passes through n ROADMs. We have only considered 1st and 3rd order Gaussian filters because we are interested in the bandwidth and these order are the most typical in optical network. The chosen bandwidth is 50GHz with central frequency of 193.1THz and offset of ± 2 GHz.

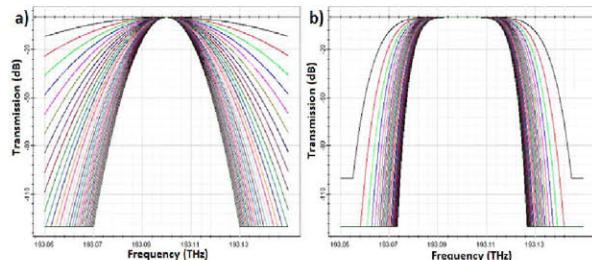


Fig. 9. Effect of cascaded ROADMs, a) 1st and b) 3rd order Gaussian filters

In order to characterize the network performance is necessary to consider the performance given for the Gaussian filters concatenation. To simulate this effect in an accurate way we have considered the non-ideal misalignment in the real world. Fig. 9 shows the amplitude transfer function of 1st and 3rd of order of the Gaussian filter when the signal passes through 30 concatenated

Gaussian filters. We can see that in 3rd order filters the amplitude transfer function of Gaussian filter is much closer to the ideal rectangle transfer function than the 1st order. In other words, when the bandwidth is fixed, with the order increasing the flat top region is wider. Fig.10 shows the effective bandwidth changing with the number of cascaded filters. It can be seen that the effective bandwidth becomes smaller with the filters increasing.

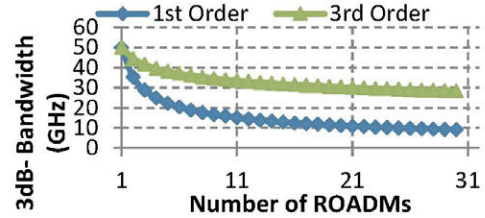


Fig.10. Bandwidth evolution depending on number of ROADMs

VIII. CONCLUSION

This paper explains the design of equalized holographic LCoS ROADMs with flexible bandwidth for the use in DWDM optical networks. By using a mixed hologram and due to the small size of micropixels in LCoS technology, the device is able to route whatever DWDM signal with any central wavelength and any bandwidth from the input fiber to the output fibers depending on the bandwidth. The losses of the designed ROADM have been minimized by choosing a “4f-folded” instead of a “lineal-2f” for the optical structure. The device is able to cover the complete DWDM band, 1530.0413 - 1624.8914nm by using groups of 4 inputs wavelengths and considering spectral bandwidths (12.5GHz, 25GHz, 50GHz or 100GHz) according to ITU-T G.694.1. A SOA is included in the design to compensate the intrinsic losses of the device and also to maintain a fixed output power level obtaining an equalized device. It is highlighted the importance and effects of cascaded ROADM in optical networks. This effect produces a narrowed passband filtering and clipping signal effect mainly and it will be necessary to consider the maximum number of ROADMs which the signal is able to pass through without impairments in the quality of the optical network.

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