# Fiber optic multiple-wavelength filter based on one dimensional photonic bandgap structures with defects

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***Abstract*—A theoretical analysis is given of an optical fiber multiple wavelength tunable filter based on a one-dimensional PBG structure with four defects. To understand the positioning of the modes in the bandgap a previous analysis of structures with one and two defects is performed. By adequate parameterization it will be possible to control the central wavelengths of the various filters of the device. Parameters responsible for this effect are the contrast of refractive indices of high and low index layers, the optical thickness of the defects and the number of layers stacked among the defects related to those stacked at the extremes. In addition to this, the finesse of the filters can be controlled by adequate addition of layers among defects. As a result, a simple one-dimensional PBG structure with defects will permit designing almost any multiple wavelength filter, with immediate application in treatment of WDM signals. The possibility of tunability of this device can be introduced if materials are included whose refractive index changes with some parameter such as temperature, voltage or strain. As an example, liquid crystals change its refractive index with an applied voltage, leading to a shift of the central wavelengths of the filters.**

***Index Terms*— Diffraction; Optical fiber filters; Coupled mode analysis; Non-homogeneous media**

## I. INTRODUCTION

A lot of research both theoretically and experimentally has been devoted during the last years concerning periodic dielectric structures known as photonic bandgap (PBG) structures. The breakage of the periodicity of these structures by inclusion of a defect has been analyzed thoroughly in the literature because of the property it presents that a defect mode is allowed inside the range of forbidden wavelengths [1-6]. This property is more often exploited in one-dimensional PBGs because of its much easier fabrication. Many authors consider the one-dimensional PBG structure in terms of Bragg gratings [7-8], but in this paper considerations will be taken from the point of view of PBG structures in order to facilitate its potential extrapolation to 2D and 3D structures, leaving the possibility of a later analysis with the former theory. The position of the defect mode inside the bandgap is determined by the thickness and the refractive index of the defect, being it possible that it leaves the bandgap or that more than one defect mode be created if the thickness of the defect exceeds a limit value [6,9-10]. In this paper the inclusion of several defects in a one-dimensional PBG structure will be analyzed for the purpose of designing a multiple wavelength filter (MWF). Each defect origins a defect mode, which can be controlled if adequate parameterization is selected. To explain this, the remainder of this paper is organized as follows. In Section II a PBG structure with two defects is analyzed for the purpose of understanding the general case of four defects. Later on, in Section III, an analysis will be performed of the structure with four defects that will constitute the basis of the MWF design. In Section IV the possibilities of design will be shown, where parameters such as the refractive index of high or low index layers, the refractive index of the defects, the number of layers among the defects and so on will permit designing almost any MWF. If some materials are used whose refractive index changes with temperature, strain or voltage, the possibility of tunability of the device will be added. In this case the device is a tunable multiple wavelength filter (TMWF). To finish, concluding remarks are given in Section V.

## II. ANALYSIS OF 1D-PBG STRUCTURES WITH TWO DEFECTS

It is well known from the literature that if the optical thickness of a defect layer in a 1D-PBG with quarter-wave reflector (QWR) configuration is an even multiple of $\lambda_0/4$ (the optical thickness of each layer), the wavelength of the defect mode is exactly $\lambda_0$ due to interference conditions [6,11]. Furthermore, if the thickness of the defect is increased there is a limit value, where additional pairs of defects modes are included symmetrically around the defect mode of $\lambda_0$ wavelength [6,9-10]. On the other hand, if the optical thickness of the defect layer is and odd multiple of $\lambda_0/4$ there is destructive interference for all defect modes of the previous case, and new modes appear between the modes that disappear under this configuration [6]. The same effect occurs if the optical thickness of a defect layer is an even multiple of $\lambda_0/4$

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Manuscript received June 3, 2003. This work was supported by Spanish Ministerio de Ciencia y Tecnologia and FEDER Research Grants CICYT-TIC 2003-00909 and CICYT-TIC 2001-0877-C02-02; Gobierno de Navarra and FPU MECD Grant.

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but there is a displacement of high and low index layers. In other words, low index layers replace high index layers after the defect and the opposite is true for low index layers. To show an example, the one-dimensional PBG structure represented in Fig. 1a will be analyzed with a program based on the Rigorous Coupled Wave Analysis [12]. This is a modal method by Fourier expansion that permits to simulate PBG structures formed by stacks of homogeneous, grating and bi-grating layers. A plane wave with any polarization and angle of incidence impinges on the structure, and accurate transmission and reflection coefficients are obtained in the range of wavelengths desired. The resolution used for all simulations is sufficient to guarantee no changes in the results if higher resolution is applied. And the CPU time for the most complex structure analyzed in this work (Fig. 1c) with a sweep in wavelength of 100000 points is of about 14.5 minutes in a Pentium IV processor at 2.4 GHz. Other numerical methods could be applied for the same purpose presented in this work such as Finite Difference Time Domain (FDTD) or C-matrix Method, but RCWA has been selected because of its good accuracy, versatility and efficiency in computation time.

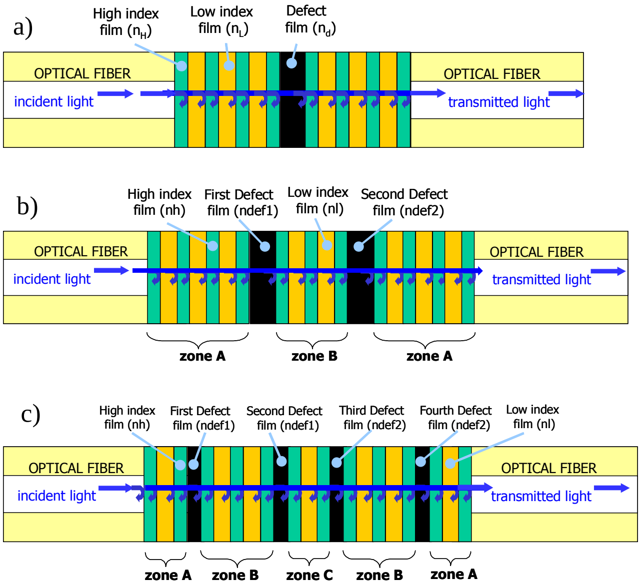

Fig. 1. Different one-dimensional PBG structures: a) PBG with one defect in the middle. There is the same stack of layers at each side of the defect. b) PBG with two defects symmetrically placed and separated by a stack of layers (Zone B) different to those at each extreme (Zone A). c) PBG with four defects symmetrically placed and separated by stacks of layers. The stacks at the extremes are the same (zone A), the stacks separating the first and the second defect, and the third and the fourth are the same (zone B), and the central stack is zone C. All structures are symmetrical.

The fabrication of this device would consist in joining two fiber pigtails to each other by the extreme where there has been a deposition of layers of high and low refractive index materials. The fibers must be single mode so as to avoid the creation of a set of wave vectors. The inclusion of the defect will be performed in one of the fibers. The structure presents 59 layers and it has been designed so that the main bandgap is centered at the standard wavelength of 1550 nm. Taking as a reference the Electrostatic Self-Assembly (ESA) fabrication method [13], which is the most adequate for structures with layers of nanometer size, the two types of layers present apart from the defect have a refractive index of $n_H$=1.8 (corresponding to $[Au:PDDA^+/PSS^-]_n$ bilayers) [14] and $n_L$=1.424 (corresponding to $[PDDA^+/Pss^-]_n$ bilayers) [15]. Regarding the defect layer, another material must be selected whose refractive index varies related to the one of the layer it replaces. If a material is chosen whose properties do not show a change with parameters such as temperature, strain or voltage, the design will be fixed. Nonetheless, there is a possibility of including a material that changes its refractive index. Concretely in this work, a BDH764E liquid crystal has been selected that varies the refractive index with the voltage applied. The refractive index for the $\theta$ =10 state is 1.65 [16]. The thickness of the defect will be 10 times $\lambda_0/4$ to assure a defect mode at 1550 nm and at the same time to achieve a good sweep in wavelength as the refractive index of the defects is changed [10]. The input and output media are the own optical fiber. The transmission plot of this structure is compared in Fig. 2 with that where low index layers replace high index layers after the defect in the one-dimensional PBG structure of Fig. 1a. The opposite is done for low index layers, leading to the same effect produced when the phase of the light trapped in a defect layer experiments a $\pi$ shift because the thickness of the defect is an odd multiple of $\lambda_0/4$ [6]. In this case the two defect modes will be placed between the position of a structure with a defect of 9 and 11 times $\lambda_0/4$.

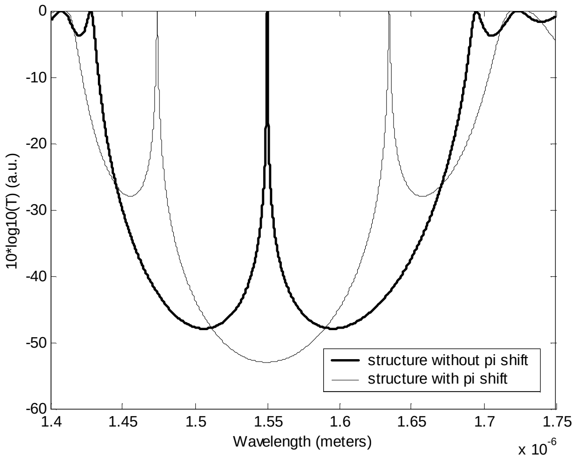

Fig. 2. 1D-PBG structure of 59 layers with one defect with or without replacing high index layers with low index layers and vice versa after the defect layer.

This effect will permit understanding the creation and shift of defect modes inside the bandgap in a one-dimensional PBG structure with two defects represented in Fig. 1b. In this case there are two different regions of stacked layers: the extremes (Zone A), and the zone between the first defect and the second defect (Zone B). First of all, the defects are symmetrically placed around the middle of the structure in order to permit that complete resonance takes place. The ratio of layers in Zone B and Zone A ($R_{B/A}$) will determine the position of the defect modes. Departing from the analysis of Ref. 5, if $R_{B/A}$ is 2, the structure will be composed of two mirrors stacked or, in terms of this work, of two 1D-PBG structures with one defect in the middle. Consequently, the resonant mode exiting the first 1D-PBG structure with one defect in the middle will enter the second one, and couples with the same one created in the second 1D-PBG. In this way a unique defect mode is obtained thicker than the one created by a unique defect. If $R_{B/A}$ increases the defect mode will decrease its transmitted power due to the attenuation introduced by the additional layers before it enters the second mirror or 1D-PBG structure with one defect. On the other hand, if $R_{B/A}$ decreases, a separation of the thick modes into two symmetric defect modes starts, which reaches the same transmission plot as a structure with a unique defect of double thickness, and where high index layers after the defect are replaced by low index layers and vice versa. This last structure is the limit case when no layers are placed between the defects, and the replacement between high and low index layers is performed in order to assure the maintenance of the order in high and low index layers throughout the structure. Otherwise different interferences will take place and other defect modes can be created, which is not the purpose of the analysis of this work. In Fig. 3 four plots are obtained that correspond with different values of $R_{B/A}$. The values expressed in layers in Zone B / layers in Zone A are: 59/29 (coupling of modes), 19/29 9/29 and 0/29 (unique defect of double thickness). Between the two limit cases of coupling of modes and complete separation, the two modes shift in wavelength in opposite direction as the number of layers between the two defects is reduced, till the case of a unique defect of double thickness is reached.

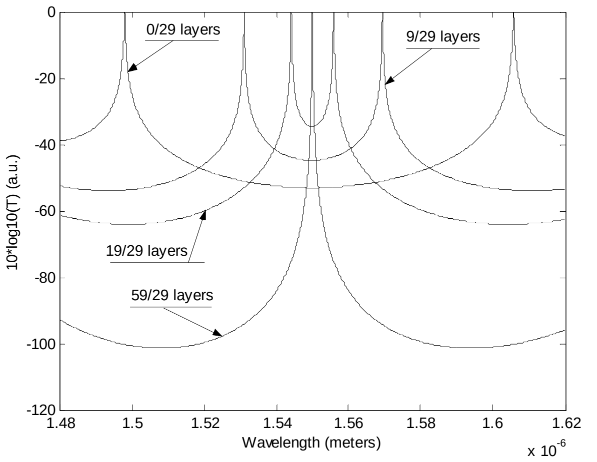

Fig. 3. 1D-PBG structure with two defects for different ratios between the number of layers between the first defect and the second defect (Zone B of Fig. 1b), and the number of layers stacked at the extremes (Zone A of Fig. 1b).

## III. ANALYSIS OF 1D-PBG STRUCTURES WITH FOUR DEFECTS

Departing from the analysis of a one-dimensional PBG with two defects of previous section, the same structure with four defects will be explained for the purpose of designing a WDM device. In Fig 1c three different regions of stacked layers will be distinguished: the extremes (Zone A), the zone between the first defect and the second defect and the third and the fourth defect (Zone B), and the zone between the second and the third defect (Zone C). By analogy with the analysis of two defects, if the number of layers stacked in zones B and C is two times that of zone A, four mirrors will be stacked, leading to the coupling of the four defect modes corresponding with the four defects. Increasing the number of layers will lead, like in the previous section, to a reduction in the transmitted power of the defect modes due to the attenuation introduced by additional layers among the mirrors. On the other hand, if layers of zones B and C are reduced to the limit of zero, two effects will be produced that lead to the creation of four well differentiated defect modes. The first one is that the transmission plot is the same as that of a unique defect of four times the thickness of an individual defect and where high index layers after the defect are replaced by low index layers and vice versa. Consequently, two defect modes should appear symmetrically placed in reference to the centre of the bandgap. And as it was explained in previous section, this change in the position of high and low index layers after the defect produces the same effect as the π shift of the light phase trapped in a defect layer whose thickness is an odd multiple of $\lambda_0/4$. The creation of two more defect modes is justified this time because the thickness of the defect is four times that of an individual defect, which permits the trapping of two more defect modes. As the thickness of a defect mode is increased, more and more modes appear inside the bandgap [2]. In Fig. 4 the transmission corresponding with a structure with 29 layers in zone A, 59 layers in zone B and 59 layers in zone C is compared to another structure with 29 layers in zone A and 0 layers in zones B and C. The first structure shows one defect mode because of the coupling of the four mirrors and the second one shows the four defect modes position the transmission of the structure trends to as the number of layers in zones B and C is reduced.

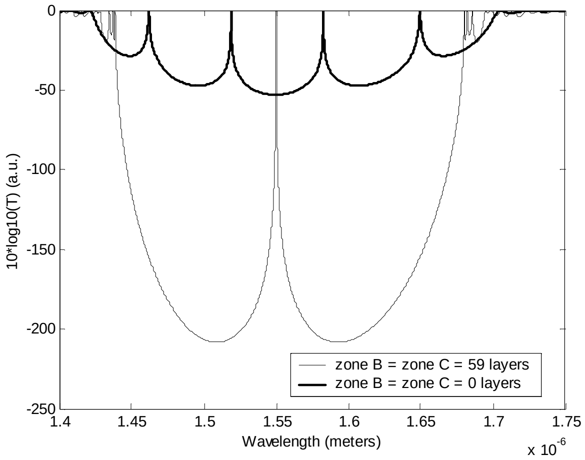

Fig. 4. 1D-PBG structure with four defects for 29 layers stacked at the extremes (Zone A of Fig. 1c), but different number of layers stacked between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c), and different number of layers stacked between the second and the third defect (Zone C of Fig. 1c).

Between the two extreme cases presented so far there are a wide range of possibilities. In the case of 0 layers in zones B and C, the separation between defect modes is nearly the same, but there is a difference that can be avoided if the rules of separation are known. First of all, the effect of varying the numbers of layers in zone B will be explained. It will be departed from the structure where the number of layers of zones B and C is 59. If the number of layers in zone B is reduced, the tendency will be towards a structure with two defects of double thickness separated by the layers of zone C. In other words, the structure is a stack of two mirrors like that of Fig. 1b, but with a defect of double thickness and the substitution of high index layers after the defect by low index layers and vice versa. As a result the four modes coupled will be separated into two pairs of modes symmetrically placed around 1550 nm. On the other hand the reduction of layers in zone C will permit the separation of each of these two pairs of modes. If the four modes are ordered according to its wavelength it can be concluded that a reduction of the number of layers in zone B leads to a displacement of the first and the second mode towards left and the third and the fourth towards right. The relative displacement between the first and the second mode, or the third and the fourth one is dependent on the reduction of layers in zone C. In Fig. 5 it can be visualized the displacement provoked in a structure of four defects with zone A = 29 layers zone C = 9 and zone B with theses values: 0, 9, 19. When the number of layers reaches the value of 59 the central defect modes couple.

On the other hand, the relative displacement between the first and the second mode, and the third and the fourth mode is shown in Fig. 6 for a structure with zone A = 29 layers, zone B = 9 layers and zone C with theses values: 0, 9 and 19. If the separation introduced by the number of layers of zone B is not sufficient the central modes will trend to couple if the number of layers in zone C is low, as it happens in the case of Fig. 6.

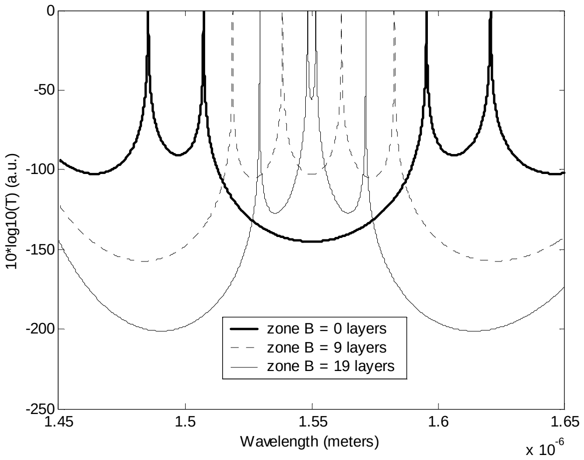

Fig. 5. 1D-PBG structure with four defects for 29 layers stacked at the extremes (Zone A of Fig. 1c), 9 layers stacked between the second defect and the third defect (Zone C of Fig. 1c), but different number of layers stacked between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c).

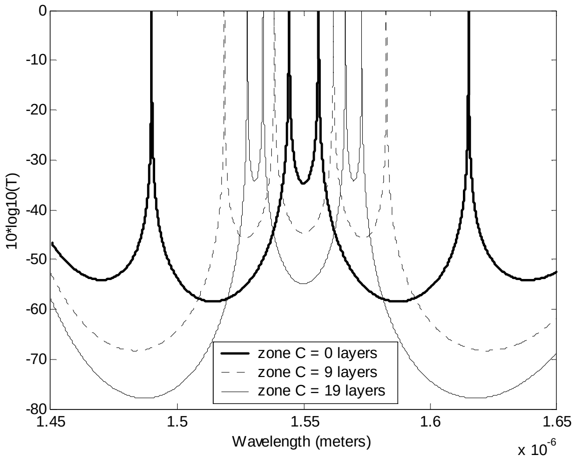

Fig. 6. 1D-PBG structure with four defects for 29 layers stacked at the extremes (Zone A of Fig. 1c), 9 layers stacked between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c), but different number of layers stacked between the second and the third defect (Zone C of Fig. 1c).

## IV. DESIGN POSSIBILITIES OF 1D-PBG STRUCTURES WITH FOUR DEFECTS

Once it has been explained the position of the defect modes in a one-dimensional PBG structure with defects, depending on the number of layers stacked among the defects, a wide range of different designs can be obtained. In this section other parameters are shown that also permit the design of the MWF.

First of all, it is important to note the influence of the position of the four defect modes that constitute the MWF in the bandgap. As a defect mode is shifted in frequency by a parameter such as the thickness or the refractive index, the shift decreases as the defect mode approximates to the edges of the bandgap [2]. As a result, the defect modes symmetrically placed around the middle of the bandgap of the designs selected in this paper will not show problems of asymmetries like those represented in Fig. 7. In this case the optical thickness of the defects is not a multiple of $\lambda_0/4$ as it was the case in the rest of designs. The structure is that of previous section with 29 layers in zones A, B and C. The different values for thickness of the defects analyzed are: $11.5\lambda_0/4$ and $11.9\lambda_0/4$, being the separation in the last case more accused due to the fact that it is nearer the edge of the bandgap, where the shifting in frequency is non linear and causes important differences in relative positions of the defect modes. This case is nearly an even multiple of $\lambda_0/4$, and indeed if a plot of the whole bandgap was given another group of four defect modes is close to the middle. This is because for thicknesses of the defect layer greater than $10\lambda_0/4$, two groups of defect modes apart from the middle one appear at the edge of the bandgap, because the increase in thickness of a defect layer implies the creation of more defect modes [2]. The purpose is actually to show an extreme case of a group of defect modes close the bandgap edge where the symmetry in wavelength position is broken. That is the reason why ESA method will permit accurate control of the thickness of layers, avoiding in this way effects like that of Fig. 7.

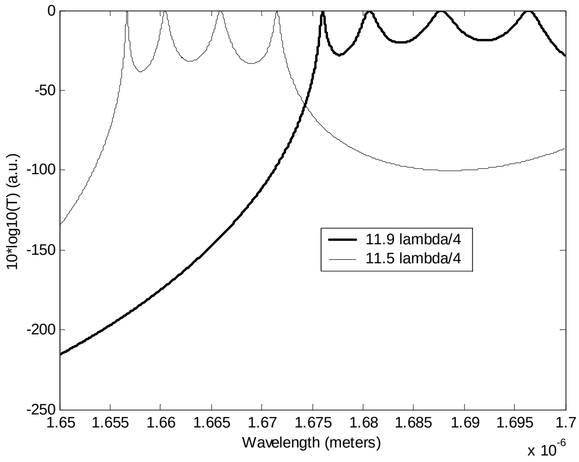

Fig. 7. 1D-PBG structure with four defects for 29 layers stacked at the extremes (Zone A of Fig. 1c), between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c), and between the second and the third defect (Zone C of Fig. 1c). Two different optical thicknesses of the defects near the edge of the bandgap are analyzed.

After assuring that the symmetry is achieved, by selecting thicknesses multiple of $\lambda_0/4$, the contrast of refractive indexes between high and low index layers will define both the MWF width (separation between the central wavelengths of the first and last defect modes in the bandgap), and the sweep in wavelength that can be achieved by choosing a material whose refractive index changes with some parameter. Again the liquid crystal BDH764E will be selected. The refractive index of the defects changes between its two extreme values 1.6301 ($\theta$ state= -10) and 1.65 ($\theta$ state = 10) [16]. To analyze these two effects, the same structure as in section III will be selected, with 29 layers in zones A, B and C, and with an optical thickness the media between 10 times $\lambda_0/4$ for both 1.6301 and 1.65 refractive indexes, which is 2362.8 nm.

In Fig. 8 one of the plots corresponds with the shift in wavelength achieved by varying the state of the liquid crystal as a function of the contrast of indexes between high and low index layers. In fact low index layers maintain its refractive index of 1.424 and high index layers vary its index between 1.5 and 3. The conclusion is that higher contrast of indexes means wider sweep in wavelength. This is because the wider bandgap created by a PBG structure permits that the rest of groups of four defect modes are more separated from each other, which implies a faster displacement of the modes as the optical thickness changes. The other plot in Fig. 8 represents the variation in width of the MWF as a function of the contrast of indexes between the high and low index layers.

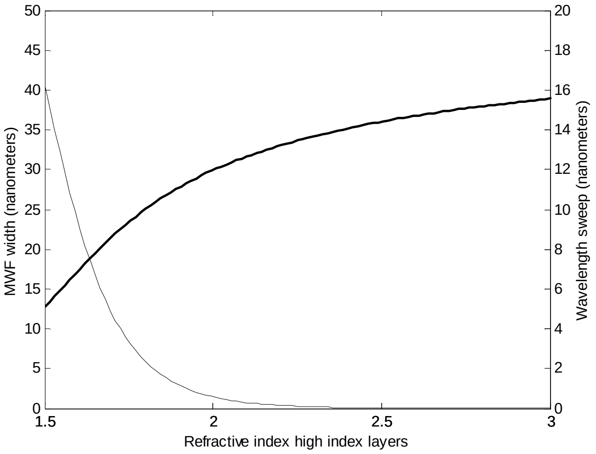

Fig. 8. 1D-PBG structure with four defects. Thin line: evolution of the MWF width (separation between the central wavelengths of the first and the last defect modes in the bandgap) for different refractive indexes of high index layer. Thick line: wavelength sweep introduced by changing the state of the liquid crystal for different refractive indexes of high index layer.

Taken in logarithmic scale, Fig. 8 shows a really good linearity, which can show important advantages in applications such as controlling the width of a MWF with structures where high or low refractive index layers are made of a material whose refractive index changes with a parameter. The conditioning of the applied signal can be achieved with a simple logarithmic circuit. The conclusion is that higher contrast of indexes means thinner MWF width. The reason is that a wider and deeper bandgap is created by a structure with a bigger contrast of indexes. As a result, with very few layers among the defects the coupling between them is very strong, and the wavelength separation is lower, but when the number of layers between the defects approximates zero the modes separate and this separation is higher than that achieved by a structure with a lower contrast of indexes. In the limit, the structure is constituted by a one-dimensional PBG with a defect with a thickness of four times that of a single defect, and the four modes inside the bandgap will be more separated from each other in case the contrast of indexes of the structure is higher. This has been explained in the same way for the first plot of Fig. 8. The result is that the non-linear shift of modes depending on the number of layers between the defects is more accused in a structure with a higher contrast of indexes. This effect is represented in Fig. 9, where a one-dimensional PBG with two defects has been analyzed for the sake of simplicity. The structure analyzed presents 29 layers in each extreme, and departs from the case of 0 layers between the two defects till 59 to show the wavelength separation for three cases: a structure where the refractive index of high index layers is 1.6, another one where the refractive index is 1.8 and a final case for 2. The non-linear shift is more accused when the contrast is higher because only when there are very few layers among the defects the effect of the bandgap created by these layers disappears. Nonetheless, for the structure with refractive index 1.6 the bandgap created is quite weak, which permits that as the number of layers among the defects is slightly reduced, the shape of the transmission plot trends to the case where there is a defect of double thickness in the middle and high index layers after the defect are replaced by low index layers and vice versa.

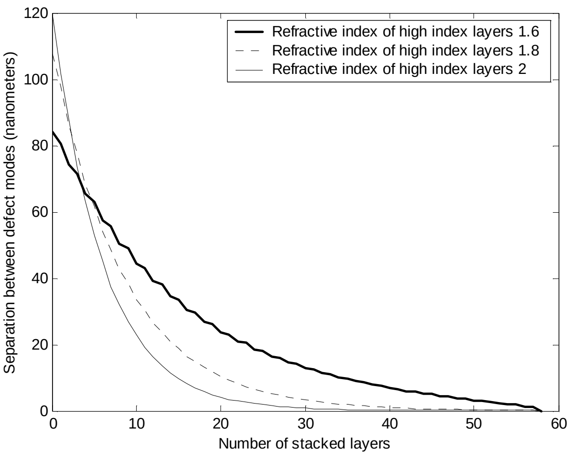

Fig. 9. 1D-PBG structure with two defects. Evolution of the wavelength separation between the two defect modes depending on the number of stacked layers between the defects for three different refractive indexes in high index layers. Number of layers at stacked at both extremes 29.

Finally if it is desired to obtain finer filter functions for the MWF, the number of layers stacked between the defects must be increased. If number of layers in zones B and C is zero and the number of layers in zone A is increased, the filter functions will be sharper as it is represented in Fig. 10 for 29 and 59 layers. This is because the structure is actually a one-dimensional PBG with one defect [3,9-10]. However, if zones B and C present layers, the idea should be to maintain the ratios between zones leading to sharper filters. In Fig. 11 this assumption is discarded. Two different structures: one with zone A = 29, zone B = 25 and zone C = 21; and another one with zone A = 59, zone B = 49 and zone C = 43 are represented. Filter functions are sharper in the second case, but the position of defect modes has changed. The reason is that the bandgap created by each stack of layers is deeper, and consequently the defect modes are more attached to each other. Consequently the shifting of modes will be more non-linear in this last structure. The non-linearity should be studied for this case, and in this way the defect modes could be positioned exactly in the wavelengths of the first structure.

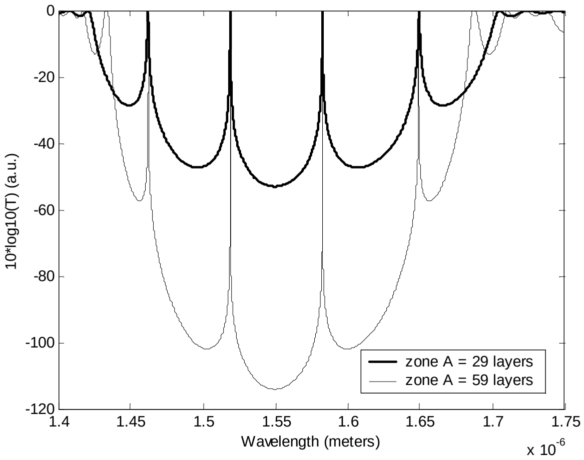

Fig. 10. 1D-PBG structure with four defects for zero layers stacked between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c), zero layers between the second and the third defect (Zone C of Fig. 1c) but different number of layers stacked at the extremes (Zone A of Fig. 1c). The structure can be considered a 1D-PBG with one defect of four times the thickness of an individual defect. The filter functions are sharper if more layers are stacked in zone A with no shift in wavelength.

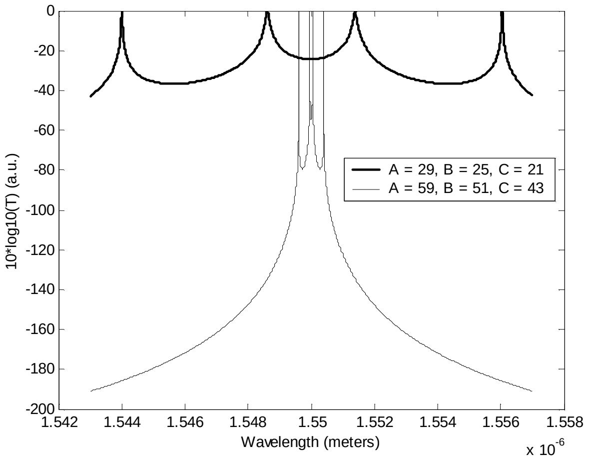

Fig. 11. Two 1D-PBG structures with four defects are compared. The first one has 29 layers stacked at the extremes (Zone A of Fig. 1c), 25 layers stacked between the first defect and the second defect and the third and the fourth defect (Zone B of Fig. 1c), and 21 layers between the second and the third defect (Zone C of Fig. 1c). The second one owns proportional number of layers for each region: Zone A = 59 layers, Zone B = 51 and Zone C = 43. The filter functions are sharper if more layers are stacked, but there is a shift in wavelength of the defect modes due to the greater confinement produced by the greater bandgap created.

## V. CONCLUSIONS

It has been analyzed in this paper the application of a one-dimensional PBG structure with four defects for the purpose of designing a Multiple Wavelength Filter (MWF). Understanding the influence in the position of the defect modes, in a one-dimensional PBG structure with two defects, of the number of layers stacked between the two defects related to those stacked at the extremes permits understanding the behavior of the defect modes in this more complex structure. In the future it will be possible to apply the rules explained here for more complex structures with even more defects.

Apart from the influence of the number of layers stacked among the defects there are other important parameters. The thickness of the defect must be chosen a multiple of $\lambda_0/4$ in order to avoid that modes be placed close to bandgap edge, which can cause asymmetries in the position of the modes of the MWF. On the other hand, the contrast of the refractive index between high and low index layers rules the separation among the defect modes, and at the same time changes the shift in wavelength achieved by varying the refractive index of the defects in case they are dependent on a parameter. Finally, the number of layers stacked will permit designing finer or wider filter functions in the transmission plot provided adequate changes are performed in the ratios between stacks of layers among the defects.

To our knowledge this is the first time a PBG structure with several defects has been analyzed for the purpose of designing a MWF. The rules given will permit almost any design. It will be also possible that, instead of a fixed design, a tunable MWF can be obtained if a material for the defects, or one of the two different materials for the layers stacked, changes its refractive index with a parameter. In this work it has been suggested the inclusion of liquid crystals, whose refractive index changes with the voltage applied.

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