A New Optical Waveguide for Implementation of Multi-wavelengths Narrowband Filters for DWDM Systems

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Summary
We investigate the possibility of optical waveguide with multi-levels index of refraction in the core region (more than two-levels) for multi-wavelengths applications analytically and numerically. We show that with slowly varying apodization all of dense wavelength division multiplexing (DWDM) applications with 30-dB sideband suppression and insertion losses of less than 1-dB can be implemented. The coupled wave equations and coupling coefficient for general treatment and approximated cases are reviewed. The apodization functions for obtaining narrowband filtering especially for DWDM filters are determined. Also, the capability of our proposal for implementation of superimposed gratings with constant geometry and only with suitable apodization is illustrated. Finally, some DWDM filters based on our proposal are designed.

Key words
Optical waveguide, Superimposed Gratings, Multi-wavelengths Filters, Optical waveguide with multi-levels index of refractions

1. Introduction

The rapid development of dense wavelength division multiplexing (DWDM) system, which is a necessary demand of optical communication, has produced great demand for compact and re-configurable selective multi-wavelengths tuning elements. Where high efficiency and selectivity are required, an interesting alternative is the Bragg Gratings. The Bragg Gratings have important applications in optical communications including sensors, signal conditioners such as filters, mode converters, splitters and many other applications and signal generation such as distributed feedback lasers [1-4]. Multi-band optical filters have key role in DWDM systems. Also, optical signal processing, computing and communication are depends on progress in easy implementation of multi-wavelength building blocks. There are many alternatives for realization of multi-band optical filters based on quasi-periodic structures and ring resonators [5,6]. Also, recently implementation of multi-band optical filters based on superimposed gratings has been discussed [7,8], owing to its powerful capacity offering a high number of channels of identical spectral performance for filtering or chromatic dispersion compensation in the existing long-haul fiber link. Currently, there is a high level of interest in the fabrication of filters to provide wavelength selectivity and noise filtering in DWDM systems. The tight specifications of these filters, regarding the required near square amplitude response and the extremely low group delay variations in the pass-band, pose a technological challenge to any of the available technologies, for example, multi-layer dielectric thin film filters, arrayed waveguide gratings or fiber Bragg Gratings. In this direction, superimposed Bragg Gratings has been found important and key role in realization of multi-channel DWDM applications and many research reports presented for description of these applications [9-14]. But, all of these researches limited to constant predefined superimposing components and the resulting waveguiding structures for two different designs are different from together from structural point of view. Finally, they couldn't present a unified waveguiding structure for implementation of superimposed gratings at least for special applications without geometry changing. In this field of research, for each case, there is an algorithm for inscription on optical mediums.
In this paper, a novel optical waveguide structure including multi-levels index of refraction in the core region with constant geometry and possibility for easy apodization to obtain all DWDM applications and especially from narrowband optical filters design point of view and many other interesting optical transfer functions is presented. In the proposed waveguide, we have more than 2-levels (maximum five levels without apodization in each period) of the index of refraction, which looks different from traditional gratings. Based on this

proposal, we show the capabilities of this waveguide for DWDM and general optical applications. Here, we present a design procedure for obtaining special apodization functions for a given multi-wavelengths reflection profile. Our method is based on discrete inverse Fourier Transform of the desired output Fourier domain components and re-construction of the index of refraction in position domain. Using the obtained index of refraction, we determine the apodization functions for the proposed grating. Also, our proposed method can be implemented using Electro-optically within the integrated circuits.

Our approach is presented in the following sections with different topics as follows. In section II, the mathematical modeling and formulation is presented. Also, simulation and results of designed examples are presented in section III.

2. Mathematical Modeling

Fig. 1 shows an especial optical slab waveguide. In this figure, $\Lambda_0 = 4(d_1 + d_2), d_1, d_2, 2h, F_j$ and n_j are grating period, duration of high and low levels of the index of refraction in the grating, duration of constant index of refraction, height of slab, amplitudes of high and low levels of the index of refraction and the index of refractions for substrate, core and cladding regions respectively. As it is shown in this case we have more than 2-levels of the index of refractions even in the same amplitudes ($F_1 = F_2 = F_3 = F_4$) compared to two levels for traditional case.

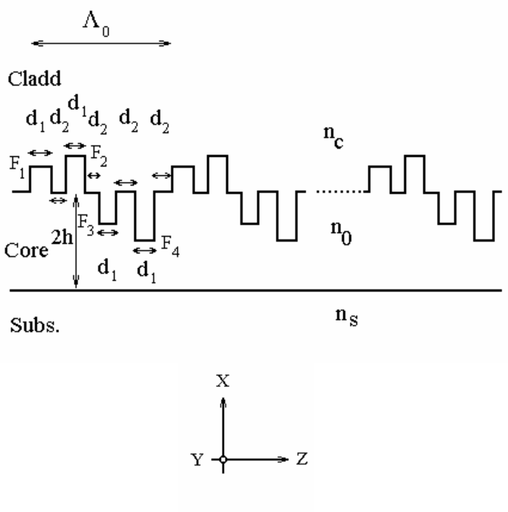


Fig. 1. A proposal for optical waveguide with multi-levels index of refractions

In this case we assume that there is only one mode for propagating through core in the forward and backward directions, for simplicity of formulation and we ignore from all radiation modes. The amplitudes are small and can be considered as perturbation. Now, in this section for this special case we review the Maxwell equations and coupled mode theory for analysis of our proposed optical waveguide. The Maxwell wave equation for without perturbation and time harmonic case is as follows.

$$[\nabla^2 + K^2 n_0{}^2(x, y)]\Psi(x, y, z) = 0 , \qquad (1)$$

where n_0 and K are the index of refraction without perturbation and wave vector respectively.

With assuming single mode and traveling wave in Z-direction, we have

$$[\nabla_t{}^2 + K^2 n_0{}^2(x, y) - \beta^2]\Psi_t(x, y) = 0 , \qquad (2)$$

where index t shows transverse component and frequency dependent β is the propagation wave vector. If we consider TE mode for investigation, for example, in presence of perturbation we have

$$E_Y(x, y, z, t) = e^{i\omega t}[A(z) + B(z)]\Psi_t(x, y), \qquad (3)$$

where

$A(z), B(z) \propto e^{\mp i\beta(\omega)Z}$ and $\beta(\omega) = n_{eff} \dfrac{\omega}{c} = n_{eff} K$.

If we apply this grating as perturbation into Maxwell equations, we obtain the following coupled wave equations as

$$\begin{aligned} &\frac{dA(z)}{dz} - i(\beta + D(z))A(z) = iD(z)B(z), \\ &\frac{dB(z)}{dz} + i(\beta + D(z))B(z) = -iD(z)A(z), \end{aligned} \qquad (4)$$

where D(z) is given in the following relation.

$$D(z) = 2\delta n K, \qquad (5)$$

where δn is perturbation and shown in Fig. 2. According to Fig. 2, δn can be written in different regions in terms of relevant apodization functions. For $0 \le z \le \dfrac{d_2}{2}$, $\dfrac{d_2}{2} \le z \le d_1 + \dfrac{d_2}{2}$,

$$d_1 + \frac{d_2}{2} \le z \le d_1 + d_2 + \frac{d_2}{2} ,$$

$$d_1 + d_2 + \frac{d_2}{2} \le z \le 2d_1 + d_2 + \frac{d_2}{2} ,$$

$$2d_1+d_2+\frac{d_2}{2}\le z\le 2d_1+2d_2+\frac{d_2}{2},$$
$$2d_1+2d_2+\frac{d_2}{2}\le z\le 3d_1+2d_2+\frac{d_2}{2},$$
$$3d_1+2d_2+\frac{d_2}{2}\le z\le 3d_1+3d_2+\frac{d_2}{2},$$
$$3d_1+3d_2+\frac{d_2}{2}\le z\le 4d_1+3d_2+\frac{d_2}{2},$$
$$4d_1+3d_2+\frac{d_2}{2}\le z\le 4d_1+4d_2$$

the perturbed index of refraction are $\delta n=0$, $F_1(z)$, 0, $F_2(z)$, 0, $F_3(z)$, 0, $F_4(z)$ and 0 respectively. Where F_j and d_j are constant amplitudes within each period and the index of refraction characteristics, which are introduced in Fig. 1 respectively.

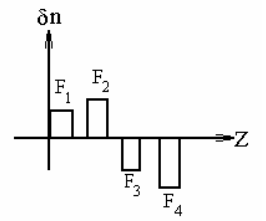


Fig. 2 The index of refraction as Perturbation

If we have periodic grating with amplitudes F_j, which are constant in whole grating, the Fourier expansion can be used. Else the Fourier transform or discrete Fourier Transform can be used. However δn should be expanded in terms of harmonic functions. Since δn is small and operates as perturbation and for $Max\left|F_j-F_i\right|<<F_0$, then, it can be expressed as follows.

$$\delta n=\eta(z)e^{i\frac{2\pi}{\Lambda_0}Z}+\eta^*(z)e^{-i\frac{2\pi}{\Lambda_0}Z}, \qquad (6)$$

where $\eta(z)$ and F_0 are slowly varying amplitudes (it can be determined for especial and given F_j cases) and the average amplitude in whole grating. Now, if Eq. (6) substituted into Eq. (5), we obtain the following relation as

$$D(Z)=\xi(z)e^{i\frac{2\pi}{\Lambda_0}Z}+\xi^*(z)e^{-i\frac{2\pi}{\Lambda_0}Z}, \qquad (7)$$

where $\xi(z)=2K\eta(z)$. Using Eq. (8), and new variables, which are given in Eq. (9),

$$A(z)=a(z)e^{i\frac{\pi}{\Lambda_0}z},\quad B(z)=b(z)e^{-i\frac{\pi}{\Lambda_0}z}, \qquad (8)$$

Eq. (4) can be simplified as

$$\frac{da(z)}{dz}=i\delta\beta.a(z)+i\xi(z).b(z),\quad \frac{db(z)}{dz}=-i\delta\beta.b(z)-i\xi^*(z).a(z), \qquad (9)$$

where $\delta\beta=\beta-\frac{\pi}{\Lambda_0}$. For obtaining multi-wavelengths reflection profile, it is necessary that the coupling coefficient $\xi(z)$ or $\eta(z)$ can be superposition of slowly varying envelop harmonic functions, in which each of them can be in resonant with incident special wavelengths. So, $\eta(z)$ should have the following form generally as

$$\eta(z)=.......+\eta_{-1}e^{i\alpha_{-1}z}+\eta_0 e^{i\alpha_0 z}+\eta_1 e^{i\alpha_1 z}+.......,\qquad (10)$$

where η_j and α_j are coupling strength for each wavelength and small and fixed numbers demonstrating the resonant frequencies respectively. Using this equation for $\eta(z)$ the output peaks can be obtained in the reflection coefficient at

$$\Lambda_j=\Lambda_0(1-\alpha_j\frac{\Lambda_0}{2\pi}). \qquad (11)$$

In the section III, we illustrate the suitable apodization functions for obtaining specials Λ_j's. Now, based on coupled wave equation, which is obtained and given by Eq. (9), we can introduce a differential equation including the reflection coefficient as follows.

$$r=\frac{b}{a}\bigg|_Z, \qquad (12)$$

$$\frac{dr}{dZ}=-i2\delta\beta.r-i\xi.r^2-i\xi^*. \qquad (13)$$

Using this equation, we can obtain the proposed optical waveguide reflection and transmission coefficients based on exact or numerical methods.
Now, for designing a special multi-wavelengths reflection profile the following procedure should be performed. For this purpose, we should obtain the Fourier domain necessary information for these multi-wavelengths. So, the Fourier component

should be determined precisely (amplitudes and bandwidths). Thus, using inverse Fourier Transform, the position distribution of the index of refractions can be obtained as

$$\delta n(n) = \sum_{k=0}^{N-1} \delta nn(k) e^{i2\pi \frac{kn}{N}} , \qquad (14)$$

where δnn and N are the Fourier domain component (determined from reflection profile, which is necessary in design) and number of samples respectively. The following procedure can be applied to design of multi-wavelengths narrowband filters based on our proposed grating.

1. According to multi-wavelengths reflection profile (as an input to design problem) the Fourier domain peaks, and wavelengths can be determined. Using these information and Eq. (2-10) η or ξ can be calculated. Using Eq. (2-6), the δn in the Fourier domain (δnn) can be obtained and can be converted to discrete form with imagination of the amplitudes in the grating structure as discrete samples.
2. Using inverse Fourier Transform, the position dependent perturbed index of refraction should be calculated.
3. Using our introduced Grating structure, the amplitudes (F_1, F_2, F_3, F_4) are obtained.

Using proposed algorithm, the index of refraction in position and finally the apodization functions could be determined.

3. Results and discussion

In this section, we will derive some of especial features of our proposed optical waveguide. In this investigation, we consider two general cases.

1. Constant Amplitudes ($F_1 = F_2 = F_3 = F_4$)
2. Modulated Amplitudes (Similar or different reflection profiles) ($F_1 \neq F_2 \neq F_3 \neq F_4$)

Case 1) In this case we consider the same amplitudes for all high and low levels of the index of refractions and is given in the following, as design examples. This is three levels optical waveguide and similar to traditional case.

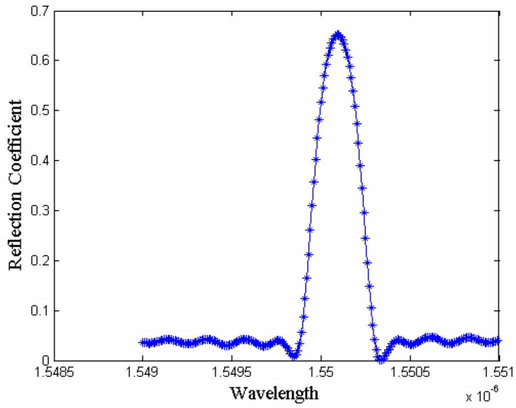
$F_1 = F_2 = F_3 = F_4 = 0.000325, 0.00075$

In this case, the perturbed index of refraction could be expanded in terms of Fourier series and first harmonic, which is dominant in our consideration and calculations, can be determined as follows.

$$n(z) = 1.5 + \delta n_1 \sin(\frac{2\pi}{\Lambda_0} z) , \qquad (15)$$

where δn_1 for these cases are obtained as $\delta n_1 = 0.00027095, 0.00062528$.

If we apply the Transfer Matrix Method (TMM) or any other numerical methods, the following results can be obtained. Fig. (3-1) shows our simulated results for this case with constant amplitudes. Fig. (3-1-a) shows example for 0.000325, which is narrowband filter and Fig. (3-1-b) is correspond to second example for 0.00075, which is wideband compared to first example.



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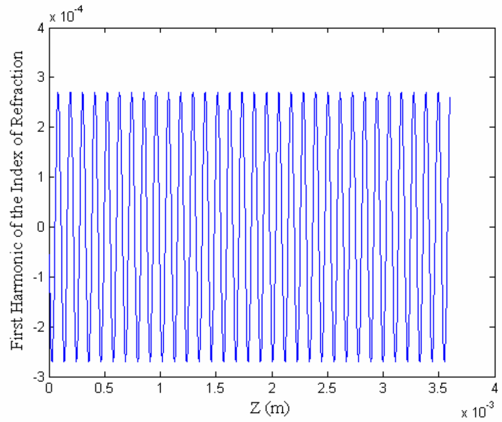
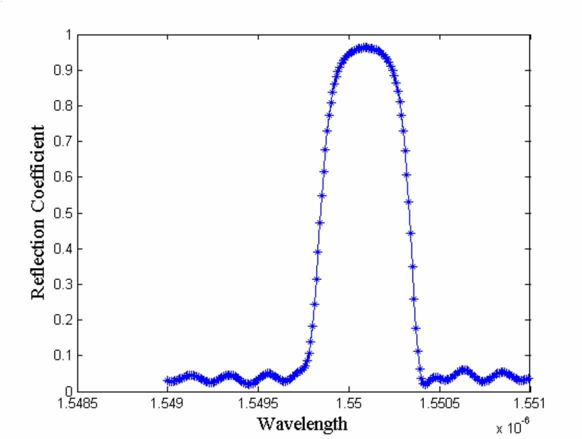


b

Fig. 3 a)- The Reflection Coefficient for constant Amplitudes (Grating Length =3.6 mm, and Amplitudes: $F_1 = F_2 = F_3 = F_4 = 0.000325$, Period of Grating = 0.5167 um, Reflection Peak= 0.65189 and BW (-1dB)=0.15 nm)
b)- The first harmonic of the index of refraction profile



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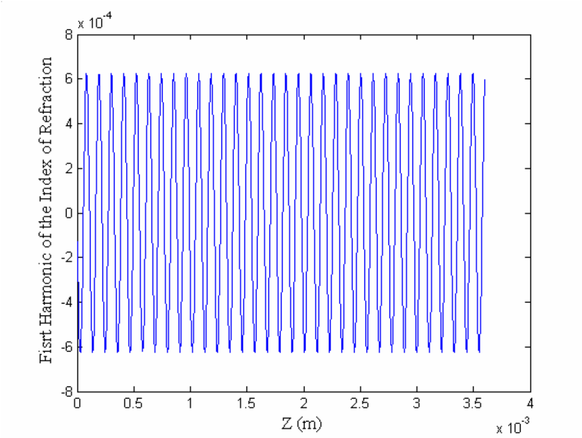


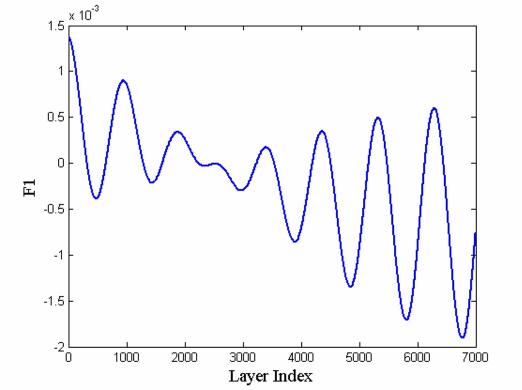
b

Fig. 4 a)- The Reflection Coefficient for constant Amplitudes (Grating Length =3.6 mm, and Amplitudes: $F_1 = F_2 = F_3 = F_4 = 0.00062528$, Period of Grating = 0.5167 um, Reflection Peak= 0.96241 and BW (-1dB)=0.3250 nm) b)- The first harmonic of the index of refraction profile

In Figs. 3 the reflection coefficients (a, b) and first harmonic of the index of refractions (a, b) for these cases are illustrated. As it is shown in Fig. 3, with suitable amplitude for perturbed index of refraction for our proposed optical waveguide, many desired filters profile can be obtained, which is important in optical communications, especially for DWDM applications.

Case 2) Modulated amplitudes for similar profiles- In this case we consider the different amplitudes for each high and low levels of the perturbed index of refractions for generation of multi-wavelengths in the reflected signal with similar profiles. For first example in this case, the following curves are accepted for amplitudes, which are given in Fig. 5. Using these figures for amplitudes, in our proposed grating, of the index of refractions, we simulate the reflection coefficient based on TMM method and obtained the multi-wavelengths reflection profile, which is given in Fig. 5.

How, we can determine these amplitudes, which are so complicated. For this purpose, we used our procedure, which is given in section II. For example, here, we consider the reflection coefficient profile with three peaks at 3-wavelengths from DWDM system standard with approximately (for satisfying the DWDM demands specifications, exact similarity is impossible) similar characteristics (from reflection peaks and Bandwidths point of views and) at $\lambda_1 = 1.55\mu m - 2\times 0.80129nm$, $\lambda_2 = 1.55\mu m$ and $\lambda_3 = 1.55\mu m + 2\times 0.80129nm$, which is converted to discrete form with imagination of the amplitudes are our samples and illustrated in Fourier domain in Fig. 5. According to our procedure presented in section II, after selecting the frequencies including bandwidths (0.2750 nm) and amplitudes (Reflection peaks = 0.93460) (Fig. 5), the inverse Fourier Transform can be calculated and the position dependent index of refraction can be determined and illustrated in Fig.5. As it is shown, the amplitudes are superposition of three sinusoidal functions for generating three peaks in frequency domain. In the next example, we will illustrate the different reflected multi-wavelengths profiles.



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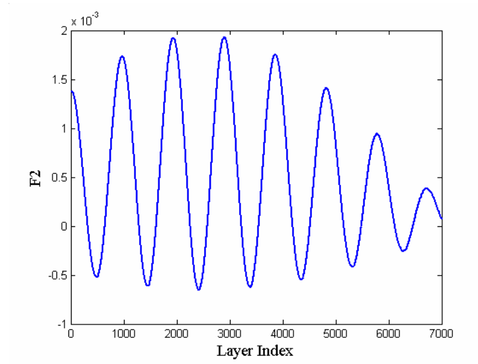

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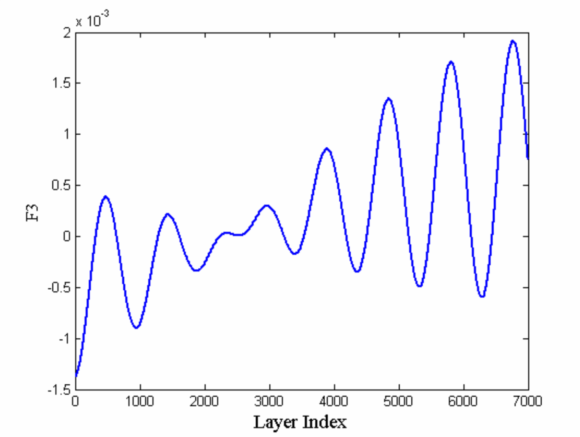

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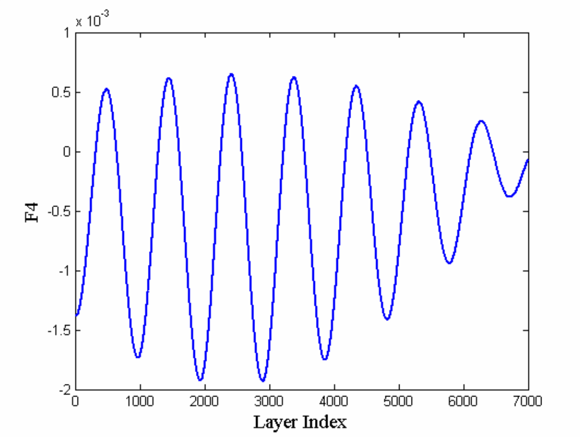

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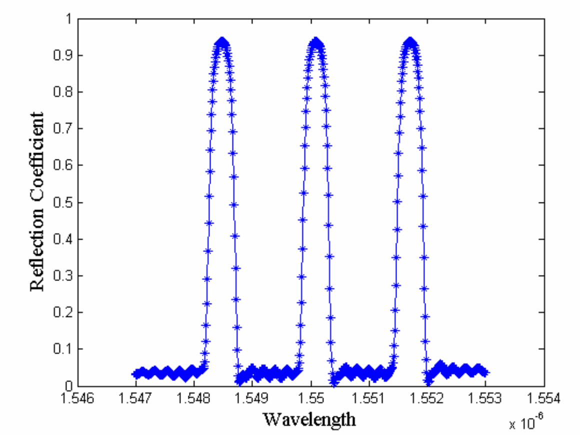

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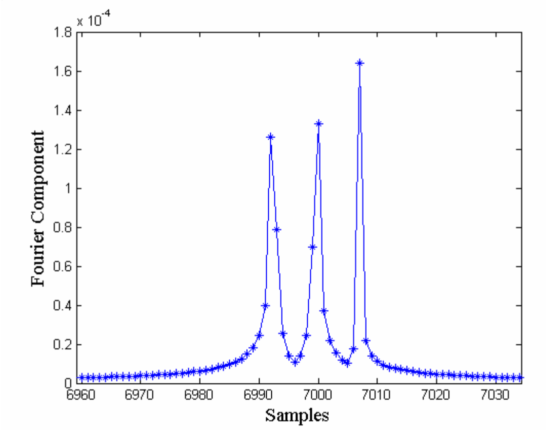
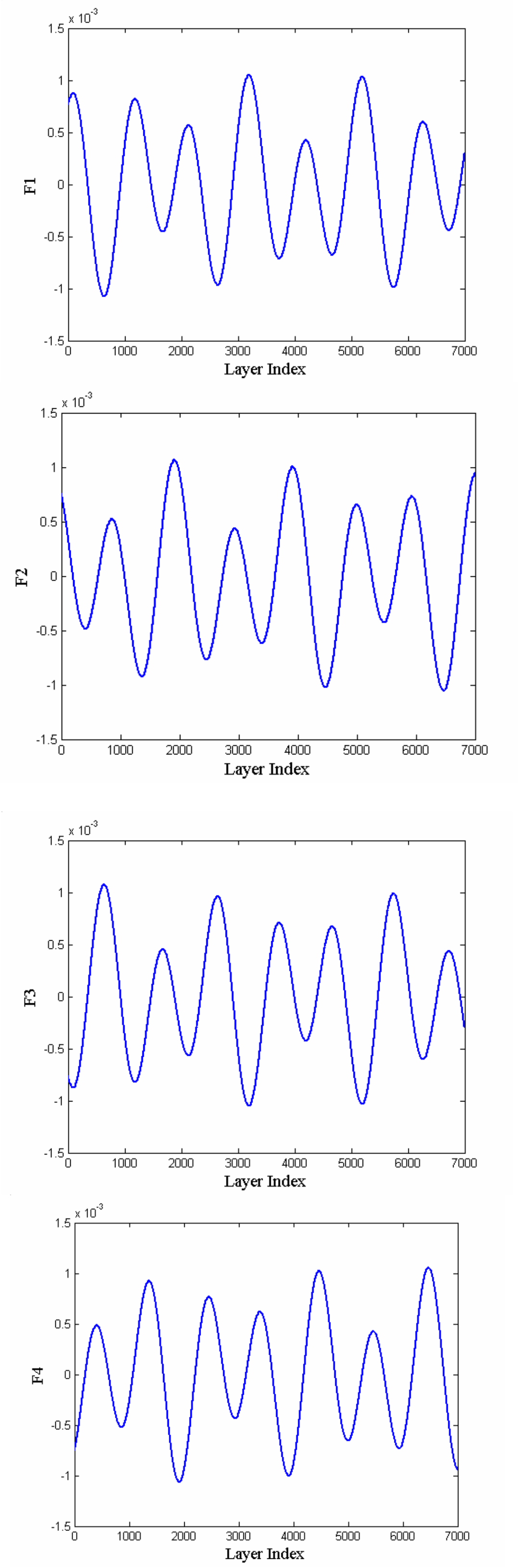


f

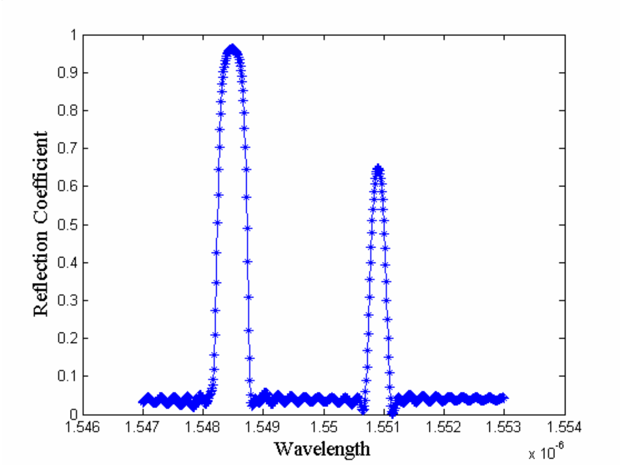
Fig. 5 a,b,c,d)- Amplitudes of Grating e)- The reflection coefficient and f)- The Spectral Characteristic in discrete Fourier domain (Period of Grating = 0.5167 um, Reflection Peak= 0.9346 and BW (-1dB)=0.2750 nm)

Case 2) Modulated amplitudes for different profiles- According to our treatment for similar profiles in the previous example, here, we will design two wavelengths reflection with different characteristics (reflection peaks and bandwidths). For second example in this case, the following curves (Fig. 6-a) are accepted for amplitudes. With these selections, we simulated the reflection coefficient and obtained the multi-wavelengths reflection profile with different shapes, which is given in Fig. 6-b. For determination of amplitudes, our procedure, which is discussed in section II, can be used.

For example, here, we consider 2-wavelengths components, which is presented in discrete Fourier domain in Fig. 6-c with different spectral shapes and characteristics (reflection peaks and Bandwidths) for having the reflection peaks at $\lambda_1 = 1.55\mu m - 2\times 0.80129nm$ and $\lambda_2 = 1.55\mu m + 0.80129nm$. According to our procedure presented in section II, after selecting the frequencies including bandwidths (0.3250 and 0.15 nm) and amplitudes (Reflection peaks = 0.96241 and 0.65189) the inverse Fourier Transform can be calculated and the position dependent index of refraction can be obtained and illustrated in Fig 6-a. As it is shown, the amplitudes are superposition of two sinusoidal functions.



a



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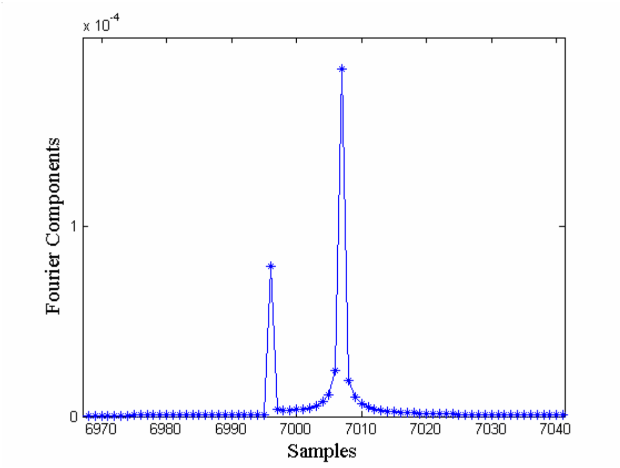

c

Fig. 6 a)- Amplitudes of Grating b)- The reflection coefficient (Period of Grating = 0.5167 um, Reflection Peak= 0.96241,0.65189 and BW (-1dB)=0.3250, 0.15 nm)
c)- The Spectral characteristic in discrete Fourier domain

So, the multi-wavelengths filter design based on our proposed grating presented. It is explained that based on our proposed procedure, the narrowband filter design for optical applications generally and DWDM especially is possible. Our proposal is suitable for integrated systems and optical integrated circuits design. Also, our presented optical waveguide introduces a special waveguide for the first time with constant geometry for realization of superimposed gratings with different combinations, in which there isn't a traditional structure for realization of more than two components with soft control. So, our method is general and can implement all superimposed gratings. Here, we introduced an optical waveguide including multi-levels index of refractions with constant geometry and capable for implementation of a large number of superimposed gratings only with soft control (apodization). This is a novel result, which presented in this paper and illustrated with some examples in section III. Our proposed waveguide will introduce soft controllable optical devices and systems.

Conclusion

Here, a new structure for optical waveguide including multi-levels index of refraction with constant geometry and easy capability for implementation of multi-wavelengths transfer functions and especially narrowband optical filters has introduced. The capability of our proposal with three designs in section III has demonstrated. Our proposal can be used in optical DWDM systems as well as for realization of interesting optical engineering transfer functions. The similar and different reflection peaks easily can be realized only with obtained amplitude profiles (soft control). So, the proposed structure is new and will introduce soft control based optical devices and systems and will be basis for reconfigurable devices. Also, this structure can be integrated easily and can be used in optical integrated circuits as basic blocks for complex optical system implementation. The proposed structure can be realized using electro-optically.

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