An Efficient CWDM Demultiplexing Design for Optical Systems: Exploiting Spatial-Beam Shifting

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***Abstract*— a compact low-cost simple –to- fabricate demultiplixer is proposed for Coarse Wavelength Division Multiplexing (CWDM). The device consists of two layers of the same semi-conductor material; the first layer is homogeneous medium with a given refractive index n_2, while the second layer is an inhomogeneous medium, where its refractive index is graded according to a creation profile. The proposed design exploits the ray's spatial shift that results from material dispersion as difference wavelengths propagate through the structure. Through analytical analysis and numerical evaluation, we investigate the effects of the various design parameters on the amount of achieved spatial shift between the adjacent wavelengths and the size of the device. The results show promising results for 4- and 8-channel devices operating on the standard CWDM wavelength grid.**

I. INTRODUCTION

With the increasing demand for high-speed data communication, transmission systems of higher capacity that can support high data rate are needed. Optical fiber can provide huge Terahertz bandwidth, and hence it can support a very high data rate. However, this huge bandwidth cannot be fully exploited using single wavelength carrier because the switching speed of the available electronics is limited to less than 1% of this bandwidth. Therefore, different multiplexing techniques have been developed to effectively exploiting the enormous Terahertz bandwidth of fibers by transmitting multiple optical channels over a single fiber. Recently, Wavelength Division Multiplexing (WDM) has been used very extensively for various applications in optical fiber communication systems [1-4]. There are two main types of WDM techniques: dense WDM (DWDM) and coarse WDM (CWDM). DWDM systems are widely used in long-haul optical transmission networks. In DWDM, the channel separation can be as small as 0.8 nm, resulting in a large number of multiplexed wavelengths. However, increasing the number of wavelengths is constrained by the availability of very stable tunable lasers and very narrowband optical filters, which makes the cost of DWDM components is expensive. In addition, the use of DWDM system is unnecessary for most of the short-haul optical networks (e.g., local area networks (LANs)). Based on the above facts, CWDM provides an efficient solution for short-haul networks with a fewer number of channels but wider channel passband and lower cost. Typically, in CWDM systems, four-to-eight different channels are available for optical communications [4,5]. WDM multiplexers and demultiplexers are critical components in enabling efficient CWDM communications. While multiplexing of different wavelengths into a single fiber is quite simple process where inexpensive fiber directional couplers are used to combine these wavelengths into the fiber, the demultiplexing process is a challenging problem since it requires very narrowband optical filters to separate the different wavelengths from the received multiplexed optical signal. Several optical filtering techniques are used for the CWDM demultiplexing process such as Thin Film Filters (TFFs), Array Waveguide Gratings (AWGs), integrated optics Concave Grating (CG), 3D Optics Filter (OF), 3D Optic Grating (OG) and Fiber Bragg Gratings (FBGs) [3,4,6,7]. In this paper, we propose a novel demultiplixer for CWDM using two dielectric layers of graded index planar structure. The proposed design exploits the ray's spatial shift that results from material dispersion as difference wavelengths propagate through the graded-index structure. The amount of spatial shift is determined by a number of design parameters; it is found that any spatial shift can be obtained by determining the best graded-index profile that gives the maximum spatial shift for a fixed device thickness, increasing the thickness for a fixed graded-index profile, or increasing the incident angle for a fixed device thickness and graded-index profile. Unlike most of previously proposed WDM demultiplexing devices, which are constructed from a large number of different thin-film layers with very precise thicknesses, our device is simple to fabricate using the well-established technologies of manufacturing graded-index fiber as it constructed using the same bulk material that is graded according to a specific refractive index profile. Thus, the proposed design has many attractive features such as the simplicity, the small size, the low cost and the good thermal stability. The rest of the paper is organized as follows. Section II presents the structure of our proposed design. In Section III, we mathematically describe the ray propagation through the proposed structure. Section IV provides a mathematical expression for the spatial shift between any adjacent wavelengths. We then investigate the effect of the various design parameters on the amount of spatial shift between adjacent wavelengths in Section V. In Section VI, we illustrate the design of CWDM demultiplexers operating on the standard ITU CWDM wavelength range. Finally, Section VII concludes the paper.

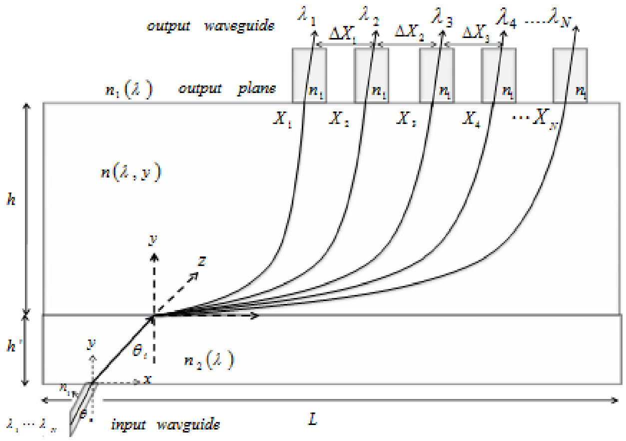


Figure 1. Geometry of the N-channel CWDM demultiplixer.

II. STRUCTYRE OF THE PROPOSED CWDM DEMULTIPLIXER

Figure.1 shows a schematic diagram for our proposed CWDM demultiplixer. In our design, we exploit the spatial shift that results from the material dispersion found in different dispersive media. The proposed device consists of two layers. The lower layer is a homogeneous medium with refractive index n_2. The upper layer is an inhomogeneous medium that is doped gradually such as the refractive index increases with the thickness of this layer according to the following refractive index profile (α -profile):

$$n(y) = n_1\left[1-\Delta\left(\frac{h-y}{h}\right)^{\alpha}\right] \quad 0 < y < h \tag{1}$$

where $\Delta = \frac{n_1 - n_2}{n_1}$, h is the thickness of the graded index layer, α is the parameter that describes the refractive-index profile index, and n_1, n_2 are the refractive indices at $y = 0$ and $y = h$, respectively. In our design, the light ray that carriers the multiplexed wavelengths is incident into the graded-index planer structure from the bottom left corner at an incident angle of θ_x. Thus, the light ray travels in a path from a low index of refraction to a higher index, and hence continuously travels until exiting the upper layer of the structure. We note that the angle of refraction θ_h continuously decreases as the ray propagates through the structure. Due to material dispersion, each of the multiplexed wavelengths has its own propagation path and exit position, which allows separating the different wavelengths at the upper layer of the proposed device.

III. RAY PROPAGATION THROUGH THE GRADED INDEX STRUCTURE

In this section, a mathematical expression for the path profile followed by a given wavelength λ as it propagates through the graded-index layer is derived. Figure 2 shows a generalized shape for the path profile as it propagates through the graded- index structure. The path profile can be described through the structure using a single wave-vector number k, which can be written as [1]:

$$\vec{k}(y) = B_x a_x + k_y(y) a_y \tag{2}$$

where $B_x = k(y)\sin(\theta) = n_2 k_o \sin(\theta_i)$ and $k_y(y) = \sqrt{k^2(y) - \beta^2} = \sqrt{k_o^2 n^2(y) - \beta^2}$ are the x- and y-component of k, k_o is the free space propagation constant, and β is the propagation constant. Since the direction of the propagation lies on the x-y plane, there is no component of propagation in z-direction, so the ray velocity has just two components in the x and y-directions, which can be written as:

$$v_x \overset{\Delta}{=} \frac{dx}{dt} = v\sin(\theta) = \frac{w}{n(y)k_0}\sin(\theta) = \frac{c}{n(y)}\sin(\theta) \tag{3}$$

$$v_y \overset{\Delta}{=} \frac{dy}{dt} = v\cos(\theta) = \frac{w}{n(y)k_0}\cos(\theta) = \frac{c}{n(y)}\cos(\theta) \tag{4}$$

Using a simple geometric optics (by considering the velocity components of the ray into the x and y directions) and following the same methodology in [1], we arrive at the following expression for the ray path profile:

$$x(y) = \int_y \frac{v_x}{v_y}dy = \int_y \frac{\sin(\theta)}{\cos(\theta)}dy = \int_y \tan(\theta)dy \tag{5}$$

Using Snell's law, we show that $n(y)\sin(\theta) = n_2\sin(\theta_i)$. Based on this fact and after some algebraic manipulations, the $\tan(\theta)$ term can be written as:

$$\tan(\theta) = \frac{1}{\sqrt{\left[\frac{n(y)}{n_2\sin(\theta_i)}\right]^2 - 1}} \tag{6}$$

Let $(x_o(\lambda), h)$ represent the exit position point from the structure associated with wavelength λ. To find $x_o(\lambda)$ at y=h, we integrate (6) from 0 to h. Formally, $x_o(\lambda)$ is given by:

$$x_o(\lambda) = \frac{h\sin(\theta_i)}{\alpha\Delta^{1/\alpha}} \int_{1-\Delta}^{1} \frac{1}{\sqrt{m^2 - \left(\frac{n_2 \sin(\theta_i)}{n_1}\right)^2}} (1-m)^{\left(\frac{1}{\alpha}-1\right)} dm \qquad (7)$$

$$= \frac{h\, n_2 \sin(\theta_i)}{\alpha\, n_1\, \Delta^{1/\alpha}(\lambda)} f_\alpha(\theta_i)$$

where $m = 1 - \Delta\left(\frac{h-y}{h}\right)^\alpha$ and $f_\alpha(\theta_i)$ is the integral part of (7).

IV. DISPERSION IN THE PROPOSED STRUCTURE

The spatial shift between any two adjacent wavelengths λ_k and λ_{k+1} at the output of the upper layer of the proposed device can be obtained using (7) as:

$$\Delta x(\lambda_{k+1}, \lambda_k) \overset{\Delta}{=} x_0(\lambda_{k+1}) - x_0(\lambda_k)$$
$$= \frac{h\, n_2 \sin(\theta_i)}{\alpha\ n_1\, \xi} f_\alpha(\theta_i) \left[n_1^{1/\alpha}(\lambda_{k+1}) - n_1^{1/\alpha}(\lambda_k) \right] \qquad (8)$$

where k=1, 2, N, N is the number of multiplexed optical channels (wavelengths), and $\xi = n_1(\lambda_k) - n_2(\lambda_k) \approx n_1(\lambda_{k+1}) - n_2(\lambda_{k+1}) = n_1 - n_2$ is the refractive-index difference, which is approximately constant for the different wavelengths [1].

It is worth mention that the material type used in fabricating the demultiplexing device determines the refractive index values for the various wavelengths. Because Silica (SiO_2) is widely used in fabricating optical fiber waveguides and devices, we consider it in our design. The refraction index as a function of λ for SiO_2 is given by the following empirical formula [2, 8]:

$$n_1(\lambda) = 2.478881 - 0.55555\lambda^2 . \qquad (9)$$

Although, the material dispersion in Silica is not that high, it was used successfully in conventional prisms to analyze coarsely monochromatic light into its components using angular dispersion. But the resolving power of prisms is not sufficient to analyze light having a separation between wavelengths in the order of nanometer (i.e., 20 nm) as it is the case in CWDM systems. The low resolving power of glass prism is due to the fact that the refraction in the prism occurs at two points only, which are the entrance and exit surfaces of the prism. To increase the resolving power one needs to increase the number of refractions of the light wave to be analyzed as it propagates through the dispersive material. In this proposed device, a graded-index structure is used to increase the number of refractions inside the structure to infinity which may result in more spatial separation between wavelengths.

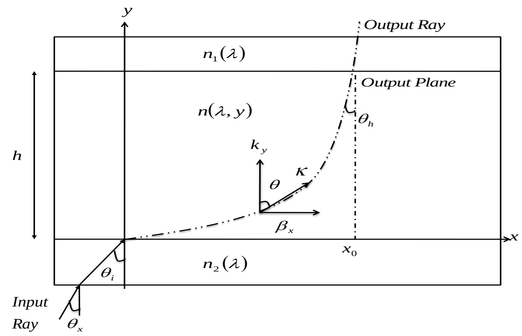


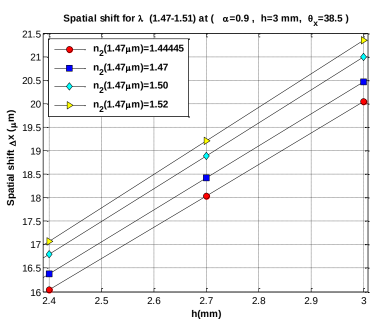
Figure 2. Ray path profile.

V.DESIGN PARAMETERS

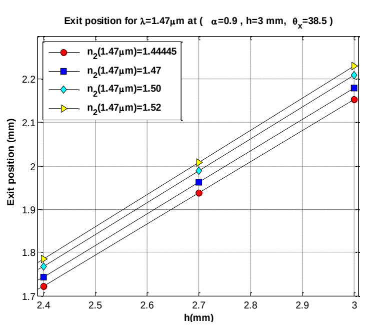
In this section, we investigate the various design parameters that determined the amount of achieved spatial separation between the various wavelengths at the output of the structure. These parameters are the thickness of the structure h , the refractive index profile parameter α , the incident angle θ_x , the refractive index difference $n_1 - n_2$ and the wavelength spacing between adjacent wavelengths (CWDM systems use 4 or 8 channels with channel spacing of 20 nm [1, 8, 10]). We note here that the minimum required spatial shift is mainly determined by the diameter of the optical fiber wave guides used to collect the light rays from the output of the demultiplixer. For example, the required spatial shift between the different wavelengths for a single-mode and multi-mode optical fibers should be larger than $20\mu m$ and $125\mu m$, respectively [9]. We first study the effect of the refractive index difference ξ on the spatial shift by examining Figure 3 (a) for $n_1 = 1.55$ at $1470\,nm$, different values of n_2 , fixed channel spacing, thickness, incident angle, and profile index. This figure shows that the spatial shift increases with increasing n_2 . The effect of the refractive index difference ξ on the exit position is shown in Figure 3(b). This figure shows that the exit position increases as the refractive index increases. We now study the effect of the value of the wavelength on the exit position. Figure 4 shows that the larger the value of the wavelength is, the larger will be the exit position for a fixed thickness h . The spatial separation between adjacent wavelengths for different values of α is shown in Figure 5. This figure reveals that the spatial shifts between all adjacent wavelengths are approximately the same. Thus, we can study the spatial shift between any two adjacent wavelengths without loss of generality. Figure 6 (a) investigates the effect of the thickness of the upper layer h on the amount of achieved spatial shift. This figure reveals that the spatial shift increases with increasing h for a fixed value of α . This figure also shows that the spatial shift between adjacent wavelengths for a given h increases as the refractive index parameter α increases and has a maximum value at $\alpha = 0.9$. Figure 6 (b) shows the exit position as a function of α for different values of h. It is clear from the figure that the exit position decreases as the profile index increases for a given h. To determine the size of the device, we note that the thickness of the device is mainly determined by the thickness of the graded-index upper layer h (since $h >> h'$, where h' is the thickness of the homogeneous lower layer), while the length of the device is mainly determined by the incident angle θ_x. We note that to ensure no total internal reflection occurs at the lower layer of the structure θ_x should be selected such that $\theta_x > \sin^{-1}(n_2 / n_1)$. For a given thickness h and a selected θ_x that provides the required spatial shift, the length of the proposed structure (L) that ensures that the ray will not penetrate the side of the graded-index layer before reaching y=h is given by [11, 12]:

$$L = x_0(\lambda_{\max}) + \ell \qquad (10)$$

where $x_0(\lambda_{\max})$ is the maximum exit point among the different wavelengths and ℓ is a design margin. Figure 7 shows the spatial shift as a function of θ_x for different values of α and fixed thickness and channel spacing $\Delta\lambda$. This figure shows that the spatial shift increases as θ_x increases.



(a) Spatial Shift



(b) Exit Position

Figure 3. The spatial shift and exit position as a function of ξ for $\Delta\lambda = 40\eta m$.

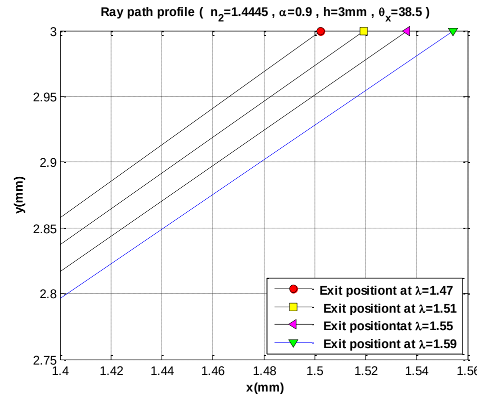


Figure 4. Ray path profile for $\alpha = 0.9$.

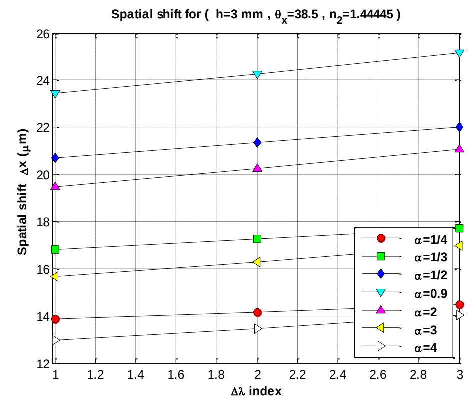
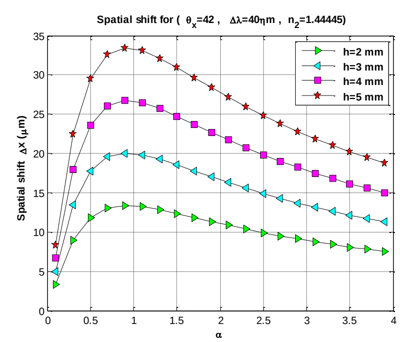
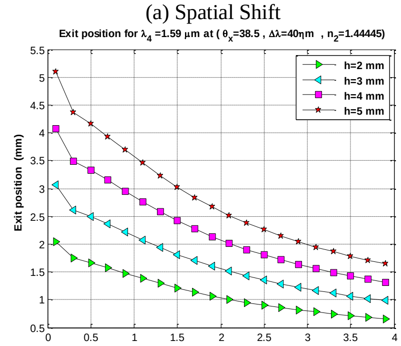


Figure 5. The spatial shift as a function of $\Delta\lambda$ for different values of α.



(a) Spatial Shift



(b) Exit Position

Figure 6. The spatial shift and exit position as a function of α for different values of h.

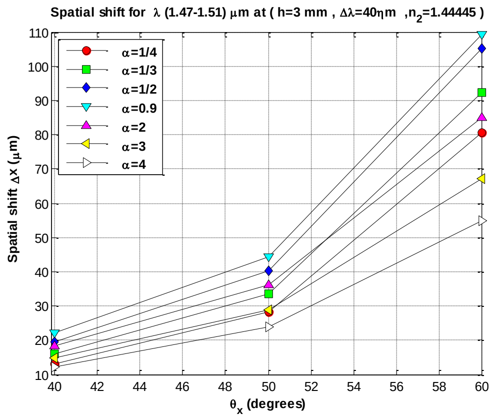


Figure 7. Spatial shift as a function of θ_x for different values of α .

VI. NUMRICAL EXAMPLE

In this section, we investigate the design of 4- and 8-channel CWDM demultiplexers for single mode and multi mode design. Table.1 shows the design parameters of the 4- and 8 channel demultiplixer for refractive index $\alpha = 0.9$ and n_1 =1.55, n_2 =1.44445 that achieves the minimum required spatial shift.

Table 1. Illustrative Examples for CWDM multiplexers

CWDM Design	***Spatial shift*** (Δx_n)	***Channel spacing*** $(\Delta\lambda)$	***Device size***	***Input angle structure*** (θ_x)
4-channels single mode	20 μm	40 nm	3× 2.4 mm	38.5^0
4-channels multi mode	130 μm	40nm	3×6 mm	61.5^0
8-channels single mode	20 μm	20 nm	5×4.4 mm	42^0
8-channels multi mode	130 μm	20 nm	5×10.9mm	63^0

VII. CONCLUSION

In this paper, a novel design for optical demultiplixer is proposed. The proposed design exploits the ray's spatial shift that result from material dispersion between the adjacent wavelengths as they propagate through the proposed graded-index structure. There are different parameters that determine the amount of achieved spatial shift. These parameters are the thickness of the structure, the refractive index profile of the graded layer, the incident angle, the refractive index difference and the wavelength spacing between adjacent wavelengths. Unlike most of previously proposed WDM demultiplexing devices, which are constructed from a large number of different thin-film layers with very precise thicknesses, our device is simply constructed using the same bulk material which is graded according to a specific refractive index profile. The device can be built using the well-established technologies of manufacturing graded-index fiber. Numerical results show promising results in terms of the device size and achieved spatial shift for 4- and 8-channel devices operating on the standard CWDM wavelength grid.

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